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Neo-Totalitarian Transformation of the Political Regime in Russia under Vladimir Putin: Democratic Institutional Degradation, Elite Militarisation, and Manipulative Legitimation of the War against Ukraine ^[1]

Abstract:

The article examines the neo-totalitarian transformation of the Russian political regime under Vladimir Putin in the context of democratic degradation, elite militarisation, manipulative legitimation, and the war against Ukraine. The relevance of the study is determined by the need to explain how a formally constitutional state, preserving elections, parliament, courts, parties, official statistics, and diplomatic rhetoric, can progressively convert these institutions into instruments of authoritarian control, coercive governance, and wartime mobilisation. The central research problem lies in the contradiction between the formal preservation of democratic and legal structures in Russia and their functional transformation into mechanisms of regime reproduction. The article advances the hypothesis that the war against Ukraine is not an external deviation from the internal development of the Russian regime, but both a consequence and an instrument of its neo-totalitarian transformation. The object of the research is the political regime of contemporary Russia under Vladimir Putin. The study aims to identify how democratic erosion, personalisation of power, elite subordination, information manipulation, statistical representation, and militarisation contribute to the consolidation of a neo-totalitarian model of governance. The study demonstrates that the degradation of democratic institutions created the structural preconditions for personalist and coercive rule; the war against Ukraine intensified repression, disciplined elites, and legitimised the expansion of security-state mechanisms; peace rhetoric and socio-economic statistics became instruments of perception management; and the militarisation of new elites contributed to the long-term institutionalisation of war. The article concludes that contemporary Russia should be analysed not merely as an authoritarian regime, but as a neo-totalitarian system in which war, propaganda, institutional conversion, elite loyalty, and managed reality operate as interconnected mechanisms of political domination.

Keywords: neo-totalitarianism, democratic erosion, authoritarianism, Russia, Vladimir Putin, political regime, elite militarisation, war against Ukraine, political legitimacy, propaganda, statistical manipulation, managed reality.

Introduction

The transformation of the Russian political regime under Vladimir Putin represents one of the most significant cases of democratic erosion, authoritarian consolidation, and militarised state transformation in contemporary political science. Since the early 2000s, Russia has moved from a formally pluralistic but institutionally fragile post-Soviet political order towards an increasingly centralised, repressive, and militarised system of rule. This transformation has not occurred through the immediate abolition of constitutional institutions, political parties, elections, courts, federal structures, or formal legal procedures. Rather, it has taken place through their gradual functional conversion: institutions that formally imitate democratic mechanisms have been progressively deprived of autonomous political meaning and subordinated to the logic of executive dominance, elite loyalty, coercive control, information management, and regime reproduction.

This article examines this process as a neo-totalitarian transformation of the Russian political regime. The concept of neo-totalitarianism is used here not as a direct reproduction of the classical totalitarian models of the twentieth century, but as an analytical category describing

a contemporary form of authoritarian rule in which formal institutions, electoral procedures, legal norms, propaganda systems, security agencies, economic resources, digital instruments, and war mobilisation are integrated into a single structure of political control. Unlike classical totalitarianism, such a regime does not necessarily require permanent mass ideological mobilisation in its earlier party-state form. However, it seeks to monopolise the political interpretation of reality, restrict autonomous civic action, discipline elites, suppress alternative sources of legitimacy, and transform war into a central mechanism of domestic consolidation.

The Russian case is especially important because it demonstrates how democratic backsliding may develop not as a single rupture, but as a cumulative process of institutional hollowing-out. Contemporary theories of democratic erosion emphasise that democratic regimes often decline gradually, through legal, electoral, administrative, and discursive mechanisms, rather than through abrupt coups or formal constitutional collapse (*Bermeo, 2016*). In hybrid and competitive authoritarian regimes, elections may continue to exist, opposition parties may formally participate in politics, courts may preserve their institutional appearance, and parliaments may continue to legislate; yet the competitive substance of these institutions becomes systematically distorted (*Levitsky & Way, 2002; Schedler, 2002*). Russia's political trajectory illustrates this dynamic with particular clarity. The formal architecture of constitutional democracy has been preserved, but its core democratic functions—political competition, accountability, representation, judicial independence, federal pluralism, media freedom, and civil society autonomy—have been progressively weakened, neutralised, or transformed into instruments of controlled legitimisation.

A significant body of scholarship has analysed Russia as an authoritarian, hybrid, patronal, or personalist political regime. Fish (*2005*) explained the derailment of democratic development in Russia through the failure of open politics and the rise of super-presidential dominance. Gel'man (*2015*) interpreted post-Soviet Russian politics through the lens of authoritarian regime change and the institutionalisation of non-democratic rule. Hale (*2015*) emphasised the role of patronal networks in structuring power relations across Eurasian political systems, while Reuter (*2017*) analysed the origins and functions of dominant-party institutions in post-Soviet Russia. These approaches remain essential for understanding the earlier stages of Russia's authoritarian consolidation. However, the full-scale war against Ukraine and the subsequent militarisation of domestic politics require an expanded analytical framework capable of connecting democratic erosion, personalist authoritarianism, elite coercion, propaganda, war legitimisation, and statistical manipulation into a unified model of regime transformation.

The personalisation of power is central to this transformation. Research on authoritarian rule shows that personalist dictatorships tend to weaken institutional constraints, reduce elite autonomy, increase the unpredictability of decision-making, and rely more heavily on coercion and loyalty-based governance (*Geddes et al., 2018; Svoblik, 2012*). The Russian political system under Putin has increasingly reflected these features. Decision-making has become concentrated around the presidential centre, while political, administrative, economic, security, and regional elites have become dependent on access to state-controlled resources and symbolic recognition from the regime. In such a system, elite survival is determined less by institutional competence, electoral accountability, or policy effectiveness than by demonstrated loyalty. The increasing role of the security apparatus and the growing political value of military experience further

deepen this transformation, linking elite reproduction to coercive and militarised forms of state power.

The war against Ukraine must therefore be analysed not only as a geopolitical event, but also as a structural outcome of Russia's internal authoritarian evolution. The absence of effective institutional checks, the marginalisation of independent expertise, the suppression of pluralistic public debate, and the personalisation of strategic decision-making created a political environment in which aggressive external policy became more probable. At the same time, the war has become a mechanism for further consolidating the regime domestically. It has allowed the authorities to intensify repression, narrow the space for dissent, justify censorship, expand the role of the security services, mobilise society around narratives of external threat, and impose collective responsibility on political and administrative elites. In this sense, war is not external to the regime's domestic logic; it is one of the instruments through which that logic is reproduced.

The full-scale invasion of Ukraine in 2022 made visible a deeper transformation that had been developing for many years. The annexation of Crimea in 2014, the conflict in eastern Ukraine, the growing repression of domestic opposition, and the increasing ideological emphasis on historical grievance, sovereignty, and civilisational confrontation all contributed to a gradual militarisation of Russian political discourse and state practice. Plokhyy (2023) interprets the Russo-Ukrainian war as a return of imperial history, while Snyder (2018) analyses Russia's confrontation with Ukraine and the West through the broader logic of authoritarian politics, disinformation, and anti-liberal ideological revisionism. Laruelle (2021) cautions against simplistic classifications of Russia as fascist, yet her analysis also demonstrates the importance of examining the ideological, symbolic, and propagandistic dimensions of the regime. Taken together, these approaches suggest that the war cannot be reduced to a single geopolitical cause. It should be examined as part of the long-term transformation of state power, political identity, and authoritarian legitimization.

This article also focuses on the manipulative legitimization of war. Authoritarian regimes do not rely exclusively on coercion; they also construct narratives that explain, justify, normalise, and moralise their policies. The contemporary Russian regime combines coercive repression with what Guriev and Treisman (2022) define as the logic of "spin dictatorship": the management of public perception through information control, selective visibility, symbolic performance, and the manipulation of political meaning. In the Russian case, this logic has become inseparable from militarised propaganda. Official discourse presents the war not as aggression, but as defence; not as imperial expansion, but as historical correction; not as a crisis of regime legitimacy, but as a test of national unity. The rhetoric of peace is used in a similarly manipulative manner. Declarations of readiness for negotiations may function not as evidence of genuine de-escalation, but as communicative devices aimed at shifting responsibility, influencing external audiences, and sustaining domestic belief in the rationality of state policy.

A further dimension of this legitimization concerns the political use of socio-economic and military data. In a neo-totalitarian system, statistics cease to function merely as instruments of public knowledge and become part of the regime's symbolic infrastructure. Economic indicators, employment data, inflation figures, military reports, and claims about battlefield developments are selectively emphasised, restricted, reframed, or embedded in official

narratives of stability and resilience. The manipulation of information does not necessarily require the complete fabrication of all data. More often, it operates through selective publication, methodological opacity, omission of politically damaging indicators, asymmetrical access to information, and the saturation of public discourse with state-approved interpretations. In this way, statistical governance becomes a mechanism of political legitimisation: it produces a managed image of reality in which war, sanctions, repression, and institutional degradation appear controllable, rational, and historically justified.

The object of this research is the political regime of contemporary Russia under Vladimir Putin.

The subject of the research is the set of institutional, elite, informational, and legitimising mechanisms through which democratic institutions have been degraded, political authority has been personalised, elites have been subordinated and militarised, and the war against Ukraine has been incorporated into the domestic logic of regime reproduction.

This focus makes it possible to analyse the Russian case not merely as an example of authoritarian consolidation, but as a more complex process in which institutional decay, coercive governance, propaganda, war mobilisation, and statistical manipulation operate as mutually reinforcing elements of neo-totalitarian transformation.

The article aims to identify how democratic erosion, the personalisation of power, the weakening of institutional constraints, the coercive control of elites, and the manipulative management of public perception have contributed to the neo-totalitarian transformation of the Russian political regime and to the legitimisation of the war against Ukraine.

To achieve this aim, the article pursues several research objectives:

- it clarifies the theoretical relationship between democratic backsliding, competitive authoritarianism, personalist rule, and neo-totalitarianism;
- it analyses the degradation of democratic institutions in Russia, including elections, parliamentarism, judicial independence, federalism, media freedom, and civil society;
- it examines the mechanisms through which political, administrative, economic, regional, and security elites have been incorporated into a system of loyalty-based governance;
- it explains the war against Ukraine as both a consequence of the regime's internal authoritarian evolution and an instrument of its further consolidation;
- it investigates the rhetoric of peace as a form of manipulative political communication;
- it considers the political use of socio-economic and military data as a means of constructing an image of stability, resilience, and controlled reality;
- it explores the militarisation of new elites and the long-term institutionalisation of war as defining features of the current stage of Russian regime transformation.

The hypothesis of the article is that the war against Ukraine is not an external deviation from the internal development of the Russian political regime, but a logical consequence and an instrument of its neo-totalitarian transformation. The degradation of democratic institutions, the concentration of power in the presidential centre, the reduction of elite autonomy, and the suppression of political pluralism created the structural preconditions for aggressive foreign policy. After the beginning of the full-scale war, the conflict itself became a mechanism of regime reproduction, enabling the authorities to strengthen domestic control, militarise elite

recruitment, legitimise repression, and manage public perception through propaganda and selective statistical representation.

The theoretical significance of the article lies in its attempt to integrate several strands of contemporary political science into a single explanatory framework. Existing literature has examined democratic erosion, personalist authoritarianism, Russian patronal politics, propaganda, and the war against Ukraine as important but often analytically separate phenomena. This article argues that these dimensions should be understood as interconnected components of a broader neo-totalitarian transformation. By doing so, it contributes to the study of modern authoritarianism by showing how a regime may preserve formal constitutional, electoral, legal, and administrative structures while transforming them into instruments of coercion, mobilisation, elite discipline, and manipulated legitimacy.

The practical significance of the research is determined by the need to understand the political mechanisms that allow authoritarian regimes to adapt, radicalise, and reproduce themselves under conditions of war, sanctions, international pressure, and internal social tension. The findings may be useful for experts in political science, international relations, security studies, democratic resilience, and post-Soviet studies. They may also contribute to the development of analytical tools for assessing the risks of authoritarian militarisation, identifying manipulative forms of peace rhetoric, evaluating the political use of official statistics, and interpreting the relationship between domestic regime transformation and external military aggression.

The article makes three main contributions to the existing literature. First, it integrates theories of democratic backsliding, competitive authoritarianism, personalist dictatorship, and neo-totalitarian control into a single explanatory model of contemporary Russian regime transformation. Second, it interprets the war against Ukraine not only as a foreign policy outcome, but also as a domestic political technology of authoritarian consolidation. Third, it highlights the role of socio-economic and military data in the legitimisation of authoritarian governance, showing that statistical manipulation is not peripheral to the regime, but one of its key instruments of reality management.

The structure of the article follows the IMRaD model. The literature review examines the main theoretical approaches to democratic erosion, personalist authoritarianism, neo-totalitarianism, wartime legitimisation, propaganda, and information manipulation. The methodology section explains the use of historical-political, institutional, comparative, systemic, discourse, and content analysis. The results section presents seven interconnected analytical findings: the theoretical foundations of democratic erosion and neo-totalitarianism; the degradation of democratic institutions in Russia; elite control as a mechanism of regime reproduction; the war against Ukraine as an outcome of the regime's internal logic; the rhetoric of peace as a manipulative communicative strategy; socio-economic statistics as an instrument of political legitimisation; and the militarisation of new elites as a step towards the long-term institutionalisation of war. The discussion section interprets these findings in relation to broader theories of authoritarian resilience and regime transformation, while the conclusion summarises the article's theoretical and practical implications.

Methods

This study is designed as a qualitative political science inquiry into the neo-totalitarian transformation of the Russian political regime under Vladimir Putin. The methodological logic of the article is based on the assumption that the transformation of political regimes cannot be adequately explained through a single institutional, ideological, military, or communicative variable. The Russian case requires an integrated analytical approach that connects democratic erosion, personalist authoritarianism, elite subordination, coercive governance, wartime mobilisation, propaganda, and the political use of socio-economic and military data. For this reason, the study combines historical-political analysis, institutional analysis, comparative political analysis, systemic analysis, discourse analysis, content analysis, and interpretive analysis of political legitimization.

The research is based on a qualitative single-case study design. Russia under Vladimir Putin is treated as an analytically significant case of long-term authoritarian consolidation and post-democratic regime transformation. The single-case design is justified by the exceptional political relevance of the Russian case for contemporary studies of democratic backsliding, authoritarian resilience, militarisation of state power, and war legitimization. The purpose of the study is not to produce a statistical generalisation across a large number of regimes, but to develop an explanatory model of how formal democratic institutions can be gradually converted into mechanisms of authoritarian and neo-totalitarian control.

The chronological focus of the research covers the period from the early 2000s to the current stage of the Russian-Ukrainian war. This period allows the article to trace the movement from the early consolidation of executive power and the construction of “managed democracy” to the later development of personalist authoritarianism, the suppression of political pluralism, the militarisation of public discourse, the full-scale invasion of Ukraine in 2022, and the subsequent institutionalisation of war as a domestic political mechanism. At the same time, the article refers to the annexation of Crimea in 2014 and the war in eastern Ukraine as critical turning points that connected domestic authoritarian consolidation with external military aggression.

The theoretical framework of the study draws on several interrelated fields of contemporary political science. The first is the theory of democratic erosion and democratic backsliding, which explains how democratic institutions may decline gradually while preserving their formal constitutional appearance (*Bermeo, 2016; Lührmann & Lindberg, 2019*). This framework is necessary for analysing how elections, parliamentarism, judicial independence, media pluralism, federalism, and civil society in Russia have been weakened without the complete formal abolition of democratic institutions. The second theoretical field is the theory of competitive and electoral authoritarianism, which explains the persistence of elections and other nominally democratic procedures under conditions of unequal competition, institutional manipulation, and administrative domination (*Levitsky & Way, 2002; Schedler, 2002*). This perspective is essential for interpreting the Russian regime not as an absence of institutions, but as a system of controlled and politically subordinated institutions.

The third theoretical field concerns personalist authoritarianism and the politics of authoritarian rule. Studies of personalist regimes show that the concentration of decision-making around a single political centre weakens institutional constraints, reduces elite autonomy,

increases the role of loyalty, and expands the use of coercive mechanisms (*Geddes et al., 2018; Svolik, 2012*). This framework is applied to the Russian case in order to analyse the progressive concentration of power around the presidency and the transformation of political, administrative, regional, economic, and security elites into actors dependent on the regime's system of patronage and coercive discipline. The fourth theoretical field concerns patronal politics and authoritarian institutions in post-Soviet contexts, which helps to explain the role of informal networks, resource distribution, dominant-party structures, and loyalty-based governance in Russia (*Hale, 2015; Reuter, 2017*).

The fifth theoretical component concerns propaganda, information manipulation, and the communicative dimension of authoritarian rule. The study uses the concept of “spin dictatorship” to explain how contemporary authoritarian regimes combine coercion with the management of public perception, selective visibility, symbolic performance, and manipulation of political meaning (*Guriev & Treisman, 2022*). This framework is especially relevant for analysing Russian official discourse on the war against Ukraine, the rhetoric of peace, the representation of external threats, and the use of socio-economic and military data as instruments of political legitimization.

The empirical basis of the research consists of several categories of sources. The first category includes legal and institutional materials: constitutional provisions, federal legislation, electoral regulations, laws affecting media, civil society, public assembly, political opposition, and the legal treatment of dissent. These sources are used to analyse the institutional transformation of the Russian political system and the legalisation of repressive governance. The second category includes official political discourse: presidential speeches, public statements by senior state officials, policy documents, strategic narratives, and official explanations of the war against Ukraine. These sources are used for discourse and content analysis of legitimization strategies.

The third category consists of international democracy and governance assessments, including reports and indices produced by organisations and research projects that monitor political rights, civil liberties, democracy, corruption, repression, and institutional change. These materials are used not as mechanically definitive classifications, but as comparative indicators that help situate Russia within broader patterns of authoritarian consolidation and autocratisation. The fourth category includes analytical reports, scholarly studies, and expert assessments concerning the Russian political regime, the Russian-Ukrainian war, elite politics, propaganda, and socio-economic governance under wartime conditions. The fifth category includes open socio-economic and military-related data, where available, as well as secondary analyses of restrictions, omissions, changes in accessibility, and selective representation of such data.

The study uses historical-political analysis to reconstruct the main stages of Russia's regime transformation. This method makes it possible to identify the sequence through which formal pluralism gave way to managed democracy, then to consolidated authoritarianism, and finally to a more militarised and neo-totalitarian model of political control. Historical-political analysis is applied not only to major events, but also to institutional trajectories: changes in electoral competition, party development, media regulation, relations between the federal centre and

regions, judicial dependence, civil society restrictions, and the expansion of security-state influence.

Institutional analysis is used to examine the transformation of formal political institutions. The study analyses elections, parliament, courts, political parties, federal structures, media regulation, and civil society organisations as institutions whose formal existence does not automatically imply democratic functionality. The key methodological task is to distinguish between institutional form and institutional function. This distinction is essential for understanding how the Russian regime preserves constitutional and legal structures while transforming their practical role. Elections, for example, are analysed not only as procedures of vote aggregation, but as mechanisms of symbolic confirmation, administrative mobilisation, elite discipline, and managed legitimacy.

Comparative political analysis is used to relate the Russian case to broader theories of authoritarianism, democratic backsliding, competitive authoritarianism, personalist rule, and neo-totalitarian control. The purpose of comparison is not to equate contemporary Russia mechanically with classical totalitarian regimes or with all other authoritarian systems. Rather, comparison is used to identify both common features and specific differences. The Russian case is compared conceptually with existing regime types in order to clarify whether the concept of neo-totalitarian transformation captures features that are not fully explained by the categories of hybrid regime, electoral authoritarianism, or personalist dictatorship alone.

Systemic analysis is applied to the Russian political regime as an interconnected structure of institutions, elites, coercive agencies, propaganda mechanisms, legal instruments, economic resources, and war mobilisation. This method is important because the article does not treat democratic erosion, elite control, propaganda, statistical manipulation, and the war against Ukraine as isolated phenomena. Instead, they are analysed as mutually reinforcing elements of a single regime logic. Systemic analysis allows the study to explain how institutional degradation creates conditions for external aggression, while war in turn strengthens domestic repression, elite militarisation, and the manipulation of public perception.

Discourse analysis is used to examine the official rhetoric of the Russian authorities concerning democracy, sovereignty, national security, historical memory, Ukraine, the West, peace, and war. The analysis focuses on recurrent semantic patterns, legitimising narratives, binary oppositions, historical analogies, and moral justifications. Special attention is given to the rhetoric of peace, which is treated as a potentially manipulative communicative strategy when it coexists with continued military escalation, refusal to recognise responsibility, and the preservation of maximalist political goals. Discourse analysis makes it possible to identify how the regime constructs meanings that frame aggression as defence, coercion as stability, and repression as national necessity.

Content analysis is used as a supplementary method for identifying repeated themes and justificatory formulas in official statements, state-controlled media narratives, and public communication concerning the war and the socio-economic situation. The analysis pays attention to recurring categories such as “sovereignty”, “security”, “historical justice”, “external threat”, “stability”, “resilience”, “peace negotiations”, “national unity”, and “economic adaptation”. This method supports the interpretation of propaganda not as random messaging, but as a structured system of political meaning production.

A separate methodological component concerns the analysis of socio-economic and military data as instruments of political legitimisation. The study does not treat official statistics as neutral or self-sufficient evidence. Instead, it analyses the political conditions under which data are produced, selected, published, restricted, reframed, or embedded in official narratives. This approach is especially important in wartime conditions, when access to certain categories of information may be limited and when official indicators may be used to construct an image of economic resilience, social stability, military effectiveness, and administrative control. The methodological emphasis is placed not only on what data show, but also on what data are excluded, how they are communicated, and how they are used to legitimise regime performance.

The key analytical categories of the study are operationalised as follows. “Democratic degradation” refers to the weakening of the substantive functions of democratic institutions, including political competition, accountability, judicial independence, media freedom, federal pluralism, and civil society autonomy. “Personalisation of power” refers to the concentration of strategic decision-making around the presidential centre and the reduction of effective institutional constraints on executive authority. “Militarisation of elites” refers to the increasing incorporation of military, security, veteran, and war-related actors into political representation, administrative governance, symbolic hierarchy, and elite recruitment. “Manipulative legitimisation” refers to communicative, legal, symbolic, and statistical practices through which the regime constructs public acceptance or passive compliance without relying solely on direct coercion. “Neo-totalitarian transformation” refers to the integration of institutional control, elite discipline, coercion, propaganda, war mobilisation, and reality management into a consolidated system of political domination.

The validity of the study is strengthened through methodological triangulation. Legal and institutional materials are interpreted alongside official discourse, international indices, scholarly literature, expert analyses, and available socio-economic data. This triangulation is necessary because no single category of source is sufficient for analysing an authoritarian regime under wartime conditions. Official sources reveal the regime’s self-presentation and formal legal architecture, but they must be critically compared with independent assessments and scholarly interpretations. International indices provide comparative indicators, but they require contextual interpretation. Scholarly literature offers theoretical depth, but it must be connected to current empirical developments. The use of multiple source categories therefore reduces the risk of one-sided interpretation and strengthens the explanatory coherence of the study.

The study also recognises several limitations. First, the analysis is constrained by the limited transparency of authoritarian governance and by restrictions on access to reliable political, military, and socio-economic information. Second, the wartime context complicates the verification of certain data, especially those related to military developments, casualties, public opinion, elite conflict, and economic costs. Third, official statistics may be incomplete, selectively published, or methodologically adjusted. Fourth, the concept of neo-totalitarianism remains analytically contested and must therefore be used with caution. In this article, it is not applied as a rhetorical label, but as a theoretical category whose usefulness depends on its ability to explain the integration of institutional degradation, coercion, propaganda, elite militarisation, war mobilisation, and manipulated legitimacy.

Ethically, the research is based exclusively on publicly available materials, published academic studies, official statements, legal documents, and open analytical sources. No private personal data, interviews with vulnerable individuals, or non-public materials are used. The article does not aim to reproduce propaganda narratives as factual claims, but to analyse their political function within the regime's system of legitimation. For this reason, official discourse is treated as an object of analysis rather than as neutral evidence. This distinction is essential for maintaining analytical distance when studying authoritarian communication under conditions of war.

Overall, the methodological design allows the article to move from description to explanation. It does not merely document the degradation of democratic institutions in Russia, but reconstructs the mechanisms through which this degradation has contributed to a broader neo-totalitarian transformation. By combining institutional, historical, comparative, systemic, discourse, content, and data-oriented analysis, the study provides a methodological basis for understanding the war against Ukraine as both an outcome of Russia's internal authoritarian evolution and an instrument of its further consolidation.

Literature Review

The literature on the transformation of the Russian political regime under Vladimir Putin can be situated at the intersection of several major fields of contemporary political science: democratic erosion, competitive and electoral authoritarianism, personalist rule, patrimonial politics, neo-totalitarian control, authoritarian legitimation, propaganda, and the relationship between domestic regime dynamics and external military aggression. Each of these fields explains an important dimension of the Russian case. However, taken separately, they do not fully capture the systemic character of the current transformation, in which institutional degradation, elite subordination, militarisation, war mobilisation, and manipulated representations of reality operate as mutually reinforcing mechanisms. This literature review therefore examines the main theoretical traditions relevant to the study and identifies the analytical gap that the present article seeks to address.

Democratic erosion and the hollowing-out of institutions

The first theoretical foundation of the study is the literature on democratic erosion and democratic backsliding. Contemporary research has moved beyond the earlier assumption that democracies usually collapse through abrupt coups, revolutions, or openly anti-constitutional seizures of power. Bermeo (2016) argues that democratic backsliding increasingly takes place through more gradual and legally ambiguous processes, including executive aggrandisement, election manipulation, and strategic harassment of opposition forces. This approach is particularly relevant to the Russian case because the country's authoritarian consolidation did not occur through the immediate abolition of democratic forms. Instead, elections, courts, parties, parliaments, and federal arrangements remained formally present while their substantive democratic functions were gradually weakened.

Lührmann and Lindberg (2019) develop this argument further by conceptualising the contemporary period as a "third wave of autocratisation". Their contribution is important because it situates the Russian case within a broader global trend in which democratic decline is often incremental, institutional, and discursively justified. Autocratisation does not necessarily

require the formal rejection of democratic language. On the contrary, regimes undergoing democratic erosion may continue to use constitutional, electoral, legal, and even democratic terminology while transforming these mechanisms into instruments of control. This insight is essential for analysing Russia's movement from post-Soviet pluralism to managed democracy and subsequently to a more repressive and militarised form of authoritarian rule.

Theories of competitive and electoral authoritarianism provide a second crucial layer of explanation. Levitsky and Way (2002) define competitive authoritarianism as a regime type in which formal democratic institutions exist and are widely viewed as the principal means of gaining power, but incumbents violate these rules so extensively that the regime fails to meet conventional democratic standards. Schedler (2002) similarly emphasises the “menu of manipulation” available to authoritarian incumbents, including institutional engineering, control over the media, restrictions on opposition activity, administrative pressure, and manipulation of electoral competition. These concepts are highly applicable to Russia because they explain how elections may continue to occur without functioning as mechanisms of genuine accountability or alternation in power.

The Russian case, however, also reveals the limits of the competitive authoritarian framework. In the earlier stages of Putin's rule, the category of competitive authoritarianism helped explain the coexistence of formal elections, limited opposition, media pluralism under pressure, and a dominant executive. Over time, however, the space for meaningful political competition narrowed so significantly that the regime's institutional logic shifted beyond competitive authoritarianism towards a more closed and coercive model. The increasing repression of opposition actors, legal restrictions on civil society, criminalisation of dissent, and militarisation of official discourse indicate that the Russian regime has moved from manipulated competition to a system in which political alternatives are not merely disadvantaged but increasingly excluded from legitimate public existence.

Fish's (2005) analysis of Russia's failed democratic development remains one of the most important early contributions to understanding this trajectory. He identifies super-presidentialism and the weakness of institutional constraints as central causes of democratic derailment. This argument remains relevant because it shows that Russia's later authoritarian consolidation was rooted in institutional imbalances established in the post-Soviet period. However, the subsequent evolution of the regime suggests that super-presidentialism alone is not sufficient to explain the current system. What began as executive dominance developed into a broader structure of institutional subordination, elite discipline, ideological mobilisation, and coercive control.

Gel'man (2015) provides a more direct analysis of authoritarian regime change in post-Soviet Russia. His work is especially significant because it conceptualises Russian authoritarianism not as a temporary deviation from democratisation, but as a purposeful and institutionalised political order. Gel'man's approach helps explain how political institutions in Russia became instruments of non-democratic governance rather than defective versions of democratic institutions. This perspective is crucial for the present article, which interprets the degradation of democracy not as institutional failure alone, but as institutional conversion: the transformation of democratic forms into authoritarian functions.

Patronal politics, dominant-party institutions, and elite control

The second body of literature concerns patronal politics, dominant-party systems, and the mechanisms of elite management. Hale's (2015) theory of patronal politics is particularly important for understanding the informal foundations of power in post-Soviet political systems. According to this approach, political authority in many Eurasian regimes is structured through networks of personal dependency, resource distribution, and informal hierarchy. Formal institutions matter, but they are deeply embedded in patron-client relations. This framework is useful for analysing the Russian regime because it explains why elite loyalty, access to resources, and proximity to the presidential centre have often mattered more than programmatic competition or institutional accountability.

Reuter's (2017) study of dominant-party institutions in post-Soviet Russia further clarifies how authoritarian regimes use parties not primarily as vehicles of ideological representation, but as instruments of elite coordination and electoral management. In this interpretation, the ruling party serves several functions: it signals loyalty, organises electoral mobilisation, distributes access to political careers, integrates regional elites, and reduces uncertainty within the authoritarian system. This analysis is central to understanding how United Russia and associated political structures have contributed to the reproduction of Putin's regime. The party does not operate as an autonomous representative institution; rather, it functions as part of the administrative and symbolic infrastructure of regime stability.

The literature on patronal and dominant-party politics is particularly useful for analysing the earlier and middle stages of Russian authoritarian consolidation. Yet the militarisation of elite recruitment after the full-scale invasion of Ukraine requires additional conceptual development. The regime's increasing emphasis on loyalty, patriotic performance, military participation, and symbolic association with the war suggests that elite reproduction is no longer based only on patronage, administrative utility, or electoral management. It is increasingly linked to participation in or endorsement of the war project. This development indicates a shift from patronal authoritarianism towards a more militarised and coercively integrated model of elite control.

Belton (2020) offers an important account of the relationship between the security services, state capitalism, and political power in Putin's Russia. Her analysis shows how networks connected to the security apparatus became central to the reconstitution of state authority and the consolidation of power. Although her work is journalistic in style rather than strictly theoretical, it is valuable for understanding the sociological and institutional foundations of the regime's coercive elite structure. Mommsen (2017) similarly emphasises the role of secret-service networks in shaping Putin's Russia. These perspectives contribute to the argument that the Russian regime cannot be understood solely through electoral or constitutional analysis; it must also be examined as a security-centred system of elite domination.

Personalist authoritarianism and the concentration of decision-making

The third theoretical tradition relevant to this study concerns personalist authoritarianism. Geddes, Wright, and Frantz (2018) provide a systematic account of how different types of dictatorships function, emphasising the distinctive features of personalist regimes. In such regimes, power becomes concentrated around the ruler, institutional constraints weaken, elite autonomy declines, and decision-making becomes more dependent on the preferences, perceptions, and strategic calculations of a narrow ruling circle. This framework is essential for

analysing the Putin regime, especially in its later stages, when decision-making became increasingly centralised and insulated from institutionalised deliberation.

Svolik (2012) offers a complementary analysis by focusing on the internal politics of authoritarian rule, particularly the dilemmas of power-sharing and control. Authoritarian rulers must manage both mass threats and elite threats. They must prevent popular opposition while also ensuring that insiders do not defect or challenge the ruler. In personalist systems, this often produces a combination of patronage, surveillance, coercion, and loyalty tests. The Russian case reflects this logic. The regime has increasingly narrowed the space for independent elite behaviour, while also using legal vulnerability, economic dependency, symbolic rewards, and coercive pressure to maintain elite discipline.

Frantz, Kendall-Taylor, Wright, and Xu (2020) further show that the personalisation of power is associated with increased repression in dictatorships. Their argument is particularly relevant to Russia because the personalisation of Putin's rule has coincided with the expansion of repressive legislation, restrictions on independent media, criminalisation of opposition activity, and intensified coercive practices under wartime conditions. This literature supports the claim that personalisation is not merely a stylistic feature of leadership; it has institutional consequences. It reduces the resilience of formal constraints and increases the probability that the regime will rely on coercive instruments to manage uncertainty.

Frye (2021) adds nuance to this discussion by challenging overly simplified images of Putin as an all-powerful ruler. His concept of the "weak strongman" highlights the limits, vulnerabilities, and constraints faced by personalist leaders even in highly centralised systems. This perspective is valuable because it prevents the analysis from reducing Russian politics to personal will alone. The Putin regime is not simply the expression of one individual's preferences; it is also a system of incentives, dependencies, institutional distortions, elite fears, and social adaptation. Nevertheless, the personalisation of power remains central because it shapes how these structural elements are coordinated and how strategic decisions are made.

Greene and Robertson (2019) also complicate the analysis of Putinism by examining the relationship between society and the regime. Their work demonstrates that Russian politics cannot be reduced to coercion alone. Public attitudes, social divisions, regime narratives, and managed participation are all part of the system. This insight is important for the present study because neo-totalitarian transformation is not interpreted as a purely top-down apparatus of repression. It also involves the production of consent, resignation, conformity, or passive acceptance through narratives of stability, external threat, national unity, and controlled normality.

Neo-totalitarianism and the transformation of authoritarian control

The concept of neo-totalitarianism requires careful theoretical positioning. Classical totalitarianism, as analysed by Arendt (1951), referred to political systems that sought comprehensive domination over society through ideology, terror, mass mobilisation, and the destruction of autonomous social life. The Soviet and Nazi cases shaped the classical understanding of totalitarian rule. However, contemporary authoritarian regimes often operate differently. They may preserve markets, private consumption, legal forms, selective openness, digital communication, and formal elections while simultaneously expanding coercive and

informational control. For this reason, the term “neo-totalitarianism” should not be used as a rhetorical synonym for dictatorship. It must be analytically specified.

In the context of this article, neo-totalitarianism refers to a contemporary configuration of authoritarian power in which formal institutions, coercive agencies, propaganda, legal repression, elite discipline, economic management, statistical representation, and war mobilisation become integrated into a unified system of political control. This differs from classical totalitarianism because it does not necessarily require permanent mobilisation through a single mass party or a fully coherent official ideology. However, it resembles totalitarian logic in its ambition to monopolise political meaning, eliminate autonomous sources of legitimacy, define enemies, criminalise dissent, and subordinate public reality to the interpretive authority of the state.

Applebaum (2024) contributes to this discussion by situating contemporary autocracies within transnational networks of mutual support, corruption, repression, and information manipulation. Although her work addresses a broader global phenomenon, it is relevant to the Russian case because it highlights how modern authoritarian systems adapt to global capitalism, digital media, and international institutions while undermining liberal-democratic norms. Contemporary autocracies do not always isolate themselves from the world; they may use global financial systems, technological tools, and information networks to strengthen domestic control and external influence. This is important for understanding the adaptive nature of Russia’s authoritarianism.

Guriev and Treisman (2022) provide one of the most influential recent frameworks for analysing contemporary authoritarian communication. Their distinction between “fear dictators” and “spin dictators” helps explain why many modern autocrats rely less on mass terror than on image management, selective repression, and manipulation of public perception. In the Russian case, however, the full-scale war against Ukraine suggests a partial transformation of this model. The regime has not abandoned the instruments of spin, but it has combined them with more overt coercion, censorship, repression, and militarisation. This hybridisation of spin and fear is one of the reasons why the concept of neo-totalitarian transformation is analytically useful.

Snyder (2018) contributes another important dimension by analysing the ideological and informational foundations of Russia’s anti-liberal politics. His account of the “politics of eternity” is relevant because it shows how historical myth, grievance, civilisational rhetoric, and disinformation can be used to undermine liberal democratic temporality and justify aggression. In this framework, politics is no longer oriented towards institutional improvement or accountable governance, but towards permanent conflict with constructed enemies. This is directly relevant to the Russian regime’s use of Ukraine, the West, and domestic dissent as interconnected objects of political mobilisation.

Laruelle (2021) offers a more cautious and analytically differentiated interpretation of Russian ideology. She warns against simplistic claims that Russia is fascist, arguing instead for a more careful analysis of the ideological plurality, symbolic repertoires, and propagandistic flexibility of the regime. This caution is methodologically important for the present article. The concept of neo-totalitarianism should not collapse all forms of authoritarian ideology into a single label. Instead, it should capture the functional integration of ideological ambiguity,

coercion, propaganda, elite discipline, and war mobilisation. The Russian regime may not possess a fully coherent ideology in the classical totalitarian sense, but it has developed a powerful system of ideological instruments capable of legitimising repression and war.

War, regime survival, and authoritarian legitimation

The literature on war and authoritarian politics provides another essential theoretical foundation. The article treats the war against Ukraine not only as an external geopolitical conflict, but also as a domestic mechanism of regime consolidation. This approach is supported by broader theories of authoritarian legitimation, which show that regimes may use external threats, military conflict, and nationalist mobilisation to strengthen internal cohesion, justify repression, and redirect social discontent.

Plokhyy (2023) interprets the Russo-Ukrainian war as a return of history, emphasising the imperial, national, and historical dimensions of the conflict. His analysis is important because it places the war within a longer historical context of Russian imperial identity and contested Ukrainian sovereignty. However, for the purposes of this article, the war must also be understood as part of contemporary regime dynamics. Historical narratives matter not only because they shape elite beliefs, but also because they are politically mobilised by the regime to legitimise present actions.

Snyder (2018) similarly links Russia's war against Ukraine to a broader anti-liberal and anti-democratic project. His analysis suggests that the external aggression of the Russian state is inseparable from its internal politics of disinformation, historical myth, and authoritarian consolidation. This perspective supports the argument that the war should not be interpreted solely as a geopolitical reaction to external stimuli. It is also a product of domestic regime transformation: the weakening of institutional constraints, the exclusion of alternative voices, the concentration of strategic decision-making, and the use of imperial narratives to legitimise violence.

Horvath (2011) offers an earlier but still relevant interpretation of Putinism as a form of "preventive counter-revolution". His argument focuses on how the Russian regime responded to the perceived threat of democratic revolutions in the post-Soviet space by developing strategies of authoritarian defence. This framework is highly relevant to Ukraine, because democratic mobilisation in neighbouring countries was interpreted by the Kremlin not merely as a foreign policy problem, but as a potential domestic threat. From this perspective, aggression against Ukraine can be understood partly as an externalised form of regime security: a way to prevent the consolidation of an alternative democratic and geopolitical model in the post-Soviet region.

Eltchaninoff (2015) contributes to the analysis of Putin's worldview by exploring the intellectual and ideological influences that shape the Russian president's political imagination. Although such interpretations must be treated with caution, they help illuminate how civilisational rhetoric, historical grievance, and anti-Western narratives became part of the regime's legitimising vocabulary. Milosevich (2024) and Taibo (2022) similarly examine Russia's confrontation with Ukraine and the international order from European analytical perspectives, highlighting the relationship between Russian imperial thinking, authoritarian adaptation, and geopolitical revisionism.

The literature on war legitimisation also intersects with the study of elite politics. War changes the criteria of loyalty. It creates new symbolic hierarchies, elevates military actors, expands the role of the security apparatus, and transforms participation in or support for war into a marker of political reliability. This process is central to the militarisation of elites. In Russia, the war against Ukraine has not only intensified repression against opponents; it has also created new channels of elite incorporation for military personnel, veterans, propagandists, and administrators connected to occupied territories or wartime governance. This development suggests that war is becoming institutionalised within the domestic structure of political authority.

Propaganda, information control, and the manipulation of reality

The literature on propaganda and information manipulation is indispensable for understanding the Russian regime's capacity to legitimate authoritarian governance and war. Authoritarian regimes do not govern by coercion alone. They also construct political realities in which repression appears necessary, war appears defensive, economic hardship appears manageable, and loyalty appears patriotic. Guriev and Treisman's (2022) work is especially useful in this regard because it shows how contemporary autocrats often rely on perception management rather than permanent visible terror. However, the Russian case demonstrates that spin and coercion can coexist and reinforce each other.

Sharafutdinova (2020) provides an important account of identity politics in Putin's Russia. Her concept of the "red mirror" highlights how the regime appeals to insecure national identity, Soviet nostalgia, emotional belonging, and status anxiety. This is important because propaganda does not operate only through false information. It also works through identity, emotion, memory, humiliation, pride, and fear. The regime's narratives about Ukraine, the West, sovereignty, and historical justice draw on these affective resources. They create a symbolic framework in which war can be presented as restoration, defence, or national survival.

Laruelle (2021) again provides a useful corrective by demonstrating that Russian propaganda is ideologically flexible rather than doctrinally uniform. It combines conservative, imperial, Soviet, Orthodox, anti-liberal, anti-Western, and civilisational motifs without necessarily resolving their internal contradictions. This flexibility is a strength rather than a weakness. It allows the regime to address different audiences, adapt to changing circumstances, and maintain interpretive dominance without committing itself to a single coherent ideological system. In a neo-totalitarian framework, the goal is not necessarily ideological consistency, but monopolisation of permissible meaning.

The manipulation of peace rhetoric is a specific aspect of this broader communicative strategy. Official declarations of readiness for negotiations may serve multiple political functions: shifting blame to Ukraine or the West, presenting the regime as rational and responsible, reducing domestic anxiety, influencing international publics, and obscuring the continuation of maximalist war aims. The literature on authoritarian communication helps explain why such rhetoric should not be analysed only at the level of stated intention. It must be interpreted as part of a wider system of symbolic governance in which language is used to manage perceptions, distribute responsibility, and legitimise policy continuity.

The political use of statistics and socio-economic data is less developed in the literature on Russian authoritarianism, but it is crucial for understanding the current stage of regime

transformation. Official data in authoritarian systems may perform a dual function. On one level, they provide administrative information necessary for governance. On another level, they serve as instruments of political representation, constructing an image of competence, stability, resilience, and control. Under wartime conditions, this second function becomes especially important. Economic indicators, employment figures, inflation data, budgetary categories, and military claims may be selectively published, methodologically reframed, or rhetorically embedded in narratives of national endurance.

This does not mean that all official data are necessarily fabricated. A more sophisticated approach recognises that manipulation often occurs through selection, omission, opacity, timing, contextual framing, and asymmetrical access. The state may emphasise indicators that support the narrative of resilience while limiting access to data that reveal structural costs. It may present adaptation as success, militarised spending as economic strength, and restricted transparency as national security. In this sense, statistics become part of the regime's broader reality-management apparatus. They help produce a public image in which war, sanctions, repression, and institutional degradation appear governable and historically justified.

Russia between fascism, authoritarianism, and neo-totalitarianism

A major analytical challenge in the literature concerns the classification of the contemporary Russian regime. Some interpretations emphasise authoritarianism, others personalism, patrimonial politics, fascist tendencies, imperial nationalism, or totalitarian revival. Each concept captures part of the phenomenon, but each also has limitations. The category of authoritarianism is broad and analytically flexible, but it may understate the extent to which the Russian regime has integrated coercion, ideology, propaganda, war, and elite militarisation. The category of competitive authoritarianism explains earlier stages of regime development, but it becomes less adequate as genuine competition disappears. The concept of personalism captures the concentration of power, but it does not by itself explain the regime's ideological, informational, and wartime dimensions.

The debate over whether Russia should be described as fascist is particularly contested. Laruelle (2021) argues that the fascism label often obscures more than it clarifies, especially when applied without attention to ideological complexity and historical specificity. At the same time, Snyder (2018) and other scholars emphasise the importance of imperial myth, anti-liberalism, violence, and the politics of historical grievance in Russian state ideology. The present article does not seek to resolve this debate by replacing one label with another. Instead, it proposes the concept of neo-totalitarian transformation as a way to analyse the functional integration of several processes: democratic degradation, personalist centralisation, elite subordination, security-state expansion, propaganda, statistical manipulation, militarisation, and war legitimisation.

Arendt's (1951) classical theory of totalitarianism remains important because it directs attention to the relationship between ideology, terror, atomisation, and the destruction of autonomous political life. However, contemporary Russia differs from classical totalitarian systems in significant ways. It does not reproduce the exact institutional structure of Stalinism or Nazism. It retains market mechanisms, consumer practices, formal elections, private property, digital communication, and selective international engagement. Yet these differences do not mean that totalitarian logics are entirely absent. The regime's attempt to define legitimate

reality, criminalise dissent, mobilise society around constructed enemies, discipline elites, and subordinate institutions to a single centre of power demonstrates a partial reactivation of totalitarian mechanisms in a new historical form.

For this reason, the term neo-totalitarianism is used in this article not as a moral metaphor, but as an analytical category. It refers to a regime trajectory in which authoritarianism becomes increasingly comprehensive, militarised, and reality-controlling while retaining some formal and adaptive features of contemporary governance. This concept allows the article to move beyond the limitations of static regime typologies. It focuses not only on what the Russian regime is, but on how it is transforming and through which mechanisms this transformation occurs.

Research gap and analytical contribution

The reviewed literature provides a rich foundation for analysing Russia's political development. Studies of democratic erosion explain the hollowing-out of institutions. Theories of competitive authoritarianism clarify the manipulation of elections and formal democratic procedures. Research on patronal politics and dominant-party systems explains elite coordination and resource distribution. The literature on personalist authoritarianism highlights the concentration of decision-making and the weakening of institutional constraints. Studies of propaganda and spin dictatorship explain the manipulation of public perception. Historical and geopolitical analyses of the Russo-Ukrainian war illuminate the imperial, ideological, and international dimensions of the conflict.

However, several gaps remain. First, much of the literature treats these dimensions as analytically separate. Democratic backsliding, elite politics, propaganda, war, and statistical manipulation are often studied in different subfields or with different methodological tools. Second, existing analyses sometimes explain the war against Ukraine primarily through geopolitics, ideology, imperial history, or security dilemmas, while insufficiently integrating it into the domestic logic of regime reproduction. Third, the political use of socio-economic and military data as part of authoritarian legitimation remains underdeveloped compared with the literature on propaganda and censorship. Fourth, the militarisation of elites after the full-scale invasion requires more systematic analysis as a mechanism of long-term regime transformation.

This article addresses these gaps by proposing an integrated explanatory model of Russia's neo-totalitarian transformation. It argues that the degradation of democratic institutions, the personalisation of power, the subordination and militarisation of elites, the war against Ukraine, the rhetoric of peace, and the manipulation of socio-economic and military data should be understood as interconnected elements of a single political process. The war is not treated merely as an external policy outcome; it is analysed as both a consequence of internal authoritarian evolution and an instrument of further domestic consolidation. Similarly, propaganda and statistics are not treated as secondary instruments of communication; they are analysed as central mechanisms through which the regime constructs legitimacy and manages reality.

The contribution of the article therefore lies in its synthesis. It brings together theories of democratic erosion, authoritarian institutions, personalist rule, patronal politics, propaganda, wartime legitimation, and neo-totalitarian control to explain the current stage of Russian political development. This synthesis is necessary because the Russian regime has itself become increasingly synthetic: it combines formal institutions with informal dependency, electoral

procedures with coercive exclusion, legalism with repression, diplomacy with war, peace rhetoric with militarisation, and statistical representation with reality management. A fragmented theoretical approach cannot fully explain such a regime. An integrated framework is required to capture the systemic logic of its transformation.

Results

Theoretical Approaches to Democratic Erosion and Neo-Totalitarianism

The analysis of the Russian political regime under Vladimir Putin requires a conceptual framework that goes beyond the binary distinction between democracy and dictatorship. The Russian case demonstrates that democratic degradation may unfold through a prolonged process of institutional conversion rather than through a sudden formal abolition of constitutional structures. Elections, courts, parliaments, political parties, federal institutions, and public rhetoric of legality may persist, while their substantive democratic functions are gradually emptied and replaced by mechanisms of control, loyalty production, symbolic legitimation, and coercive administration. This result is consistent with contemporary theories of democratic backsliding, which emphasise gradual executive aggrandisement, manipulation of institutions, and erosion of accountability rather than abrupt regime collapse (*Bermeo, 2016; Lührmann & Lindberg, 2019*).

The first theoretical result of this study is that Russia's trajectory can be interpreted as a sequence of regime mutations: from post-Soviet institutional fragility to managed democracy, from managed democracy to consolidated authoritarianism, and from consolidated authoritarianism to a neo-totalitarian form of political control. The concept of "managed democracy" captures the earlier phase in which political competition was limited but not entirely eliminated, opposition existed but was structurally disadvantaged, and the state increasingly controlled electoral and media environments. Theories of competitive authoritarianism and electoral authoritarianism are particularly useful for analysing this phase, since they explain how incumbents use formal democratic institutions while undermining the fairness, openness, and uncertainty that make democratic competition meaningful (*Levitsky & Way, 2002; Schedler, 2002*).

However, the Russian regime has progressively moved beyond the logic of competitive authoritarianism. In competitive authoritarian regimes, opposition actors are disadvantaged but may still possess some meaningful capacity to compete, mobilise, litigate, communicate, and win limited political victories. In contemporary Russia, the sphere of permissible political action has narrowed to such an extent that political competition has largely become ritualised. Opposition has been fragmented, exiled, criminalised, co-opted, or symbolically tolerated only where it does not threaten the ruling centre. As a result, the regime no longer relies primarily on manipulation of competition; it increasingly relies on the exclusion of alternative political legitimacy.

This shift makes it necessary to introduce the category of neo-totalitarian transformation. The concept does not mean that contemporary Russia mechanically reproduces the institutional structure of classical totalitarian regimes analysed by Arendt (*1951*). It does not possess the same type of mass-party mobilisation, universal ideological coherence, or total social penetration characteristic of Stalinist or Nazi systems. Yet it increasingly displays a neo-totalitarian logic: the state seeks to monopolise the interpretation of political reality, define legitimate and illegitimate

speech, construct enemies, discipline elites, criminalise dissent, and integrate war, propaganda, coercion, law, statistics, and institutional control into a single structure of domination.

The neo-totalitarian character of the regime lies not in the complete elimination of social complexity, but in the political subordination of complexity. Markets may continue to function, private consumption may remain possible, formal elections may be held, courts may issue decisions, and official statistics may be published. However, these mechanisms are embedded within a political order in which their function is subordinated to regime survival. Legal procedures become tools of repression, elections become instruments of plebiscitary confirmation, public data become elements of symbolic governance, and political language becomes a mechanism of reality management.

This transformation also reflects the evolution from “spin dictatorship” to a more coercive and militarised model. Guriev and Treisman (2022) argue that many contemporary autocrats seek to govern through image management, manipulation, selective repression, and the performance of competence rather than through visible mass terror. Russia retains many features of this model, especially in its management of economic indicators, media narratives, and official claims of stability. Yet the full-scale war against Ukraine has intensified the role of fear, coercion, censorship, military mobilisation, and criminalisation of dissent. Therefore, the Russian case demonstrates not the replacement of spin by fear, but their integration. Spin legitimises coercion, while coercion protects the communicative monopoly of the regime.

The theoretical result of this subsection is that the Russian regime should be analysed as a dynamic and hybridised neo-totalitarian formation. It combines electoral authoritarian procedures, personalist decision-making, patronal elite management, coercive legislation, militarised propaganda, selective statistical visibility, and wartime mobilisation. This synthesis explains why narrower concepts—hybrid regime, competitive authoritarianism, personalist dictatorship, or patronal politics—are useful but insufficient when used separately.

Thus, the theoretical analysis shows that contemporary Russia represents not merely an authoritarian regime with weakened democratic institutions, but a regime undergoing neo-totalitarian transformation. Its central feature is the conversion of formal democratic, legal, informational, and administrative structures into instruments of political control, elite discipline, manipulated legitimacy, and wartime mobilisation.

Degradation of Democratic Institutions in Russia: From Managed Democracy to Repressive Autocracy

The degradation of democratic institutions in Russia has followed a cumulative and systemic logic. It did not begin with the full-scale invasion of Ukraine in 2022, although the war accelerated and radicalised the process. The foundations of this degradation were laid much earlier through the centralisation of executive power, the weakening of federalism, the subordination of national television, the transformation of party politics, and the reduction of meaningful electoral competition. Fish (2005) identified super-presidentialism as one of the core institutional sources of Russia’s democratic derailment. Gel’man (2015) later demonstrated that post-Soviet Russian authoritarianism was not simply the result of institutional weakness, but also the result of purposeful political construction.

The first institutional sphere affected by democratic degradation was electoral competition. Elections in Russia continued to be held regularly, but their democratic function changed. Instead of serving as mechanisms of uncertainty, representation, and accountability, they became procedures of controlled legitimisation. Administrative resources, restrictions on candidates, control over electoral commissions, media imbalance, legal pressure on opposition actors, and the strategic use of loyal systemic opposition narrowed the field of political alternatives. This corresponds to Schedler's (2002) concept of electoral manipulation, in which authoritarian incumbents do not necessarily abolish elections but transform them into instruments of domination.

The second sphere was parliamentarism. The Federal Assembly formally retained its legislative role, but the real capacity of parliament to constrain the executive declined significantly. The State Duma became increasingly aligned with presidential initiatives, while the legislative process increasingly served the political priorities of the executive centre. In this context, parliamentarism was not destroyed formally; rather, it was converted into a mechanism of legal authorisation for executive power. This is an important feature of authoritarian legalism: the regime governs through law, but law ceases to function as a constraint on power.

The third sphere was the judiciary. Judicial independence is central to democratic accountability because courts can constrain arbitrary power, protect rights, and resolve political conflicts according to legal norms. In Russia, however, the judiciary became increasingly dependent on executive priorities, especially in politically sensitive cases. Courts have been used to sanction opposition figures, suppress civil society, enforce media restrictions, and legitimise repressive legislation. This transformation illustrates the distinction between legal form and legal function. The presence of courts does not guarantee the rule of law if judicial institutions operate as instruments of political control.

The fourth sphere was media freedom and information pluralism. Independent media were gradually marginalised through ownership pressure, regulatory constraints, labelling practices, criminal prosecutions, blocking of platforms, and the expansion of state-controlled narratives. The degradation of media pluralism is particularly important because democratic institutions require a public sphere in which citizens can access competing interpretations of political reality. Under Putin, the media environment increasingly shifted from pluralistic contestation to state-centred narrative management. After 2022, this process intensified as the war created a justification for censorship, criminalisation of alternative descriptions of the conflict, and the narrowing of permissible public language.

The fifth sphere was civil society. Non-governmental organisations, independent associations, protest movements, human rights groups, and foreign-linked institutions faced increasing pressure through restrictive legislation, financial controls, administrative harassment, and reputational delegitimation. The classification of organisations and individuals as "foreign agents" or "undesirable" contributed to the transformation of civic activity into a legally vulnerable sphere. This degradation weakened the autonomous social foundations of democracy and increased the state's capacity to isolate citizens from independent political organisation.

The sixth sphere was federalism. Although Russia remains formally federal, political centralisation has significantly reduced the autonomy of regions. Regional governors and elites

became increasingly dependent on the federal centre, while fiscal, administrative, and political mechanisms strengthened vertical control. Hale's (2015) theory of patronal politics helps explain this process: formal federal institutions are embedded in networks of dependency, resource distribution, and loyalty. As a result, federalism becomes not a mechanism of pluralism and territorial representation, but a system of administrative transmission from the centre to the periphery.

The degradation of democratic institutions was not accidental or fragmented. It was cumulative and mutually reinforcing. Electoral control weakened accountability; parliamentary subordination legalised executive dominance; judicial dependence protected repression; media control shaped public perception; civil society restrictions prevented autonomous mobilisation; and federal centralisation reduced territorial pluralism. Together, these processes transformed managed democracy into repressive autocracy.

Thus, the degradation of democratic institutions in Russia occurred through functional conversion rather than formal disappearance. Elections, parliament, courts, media regulation, civil society law, and federal institutions remained visible, but their democratic functions were replaced by mechanisms of control, confirmation, repression, and loyalty management. This institutional hollowing-out created the domestic foundation for the regime's later neo-totalitarian transformation.

Elite Control as a Mechanism of Regime Reproduction

The reproduction of the Putin regime depends not only on mass control, electoral manipulation, or propaganda, but also on the systematic management of elites. Political regimes endure when they solve two interconnected problems: controlling society and controlling insiders. Svoboda (2012) argues that authoritarian rulers face a permanent dilemma of power-sharing with elites. They need elites to govern, administer, finance, repress, and legitimise the regime, but they must also prevent elites from becoming autonomous centres of power. In Russia, the solution to this dilemma has been the construction of a loyalty-based elite order.

The Russian elite system combines formal hierarchy, informal patronage, resource dependency, legal vulnerability, and coercive discipline. Hale's (2015) theory of patronal politics is particularly useful here. Russian elites are not organised primarily through programmatic political parties, ideological competition, or institutional accountability. They are embedded in networks of dependency centred on access to state resources, administrative protection, political status, and personal connections. In such a system, loyalty is not simply a moral expectation; it is a survival mechanism. Political, administrative, economic, regional, and security elites depend on their perceived reliability in relation to the presidential centre.

Dominant-party institutions play an important role in this system. Reuter (2017) shows that dominant parties in authoritarian contexts often serve as tools for elite coordination, candidate selection, electoral mobilisation, and administrative integration. United Russia has performed these functions in the Russian political system. It does not operate as an autonomous party representing social interests against the state. Rather, it functions as a political-administrative mechanism that organises loyalty, channels political careers, manages regional elites, and produces an image of national consensus around the executive.

The personalisation of power has intensified elite dependency. In personalist authoritarian regimes, elite autonomy declines because institutional rules become less important than proximity to the ruler and alignment with the ruler's political priorities (*Geddes et al., 2018*). Under Putin, strategic decision-making has become increasingly centralised, while elite access to influence has become more dependent on presidential trust and loyalty. This does not mean that all elites are powerless or identical. Economic groups, security agencies, regional administrators, technocrats, party officials, and propagandists occupy different positions within the regime. However, their autonomy is limited by their dependence on the centre and by the risks of disloyalty.

The role of the security apparatus is especially significant. Belton (*2020*) and Mommsen (*2017*) emphasise the importance of security-service networks in shaping Putin's Russia. The strengthening of the *siloviki* is not merely a personnel issue; it reflects the broader transformation of the state's governing logic. Security thinking has become central to domestic politics, economic control, foreign policy, and elite discipline. Political loyalty is increasingly evaluated through the language of security, sovereignty, threat, and betrayal. This creates a regime environment in which dissent is not treated as legitimate disagreement, but as a security problem.

The war against Ukraine has further transformed elite control. Before 2022, elite discipline was largely maintained through patronage, selective coercion, political exclusion, and control over resources. After the full-scale invasion, loyalty became more explicitly tied to the war. Silence, compliance, public support, participation in patriotic rituals, involvement in wartime administration, and acceptance of sanctions became mechanisms through which elites demonstrated reliability. The war imposed collective responsibility on elites: even those who may privately doubt the war's rationality are publicly bound to the regime by complicity, fear, dependency, and lack of exit options.

This logic also explains why elite fragmentation has not automatically produced regime breakdown. Personalist regimes may be vulnerable when elites coordinate against the ruler, but coordination becomes difficult when elites lack trust, fear repression, depend on state resources, and are publicly implicated in regime decisions. The war increases the cost of defection because disloyalty can be framed as betrayal during national struggle. Thus, militarised crisis strengthens the disciplinary environment in which elites operate.

At the same time, the regime faces a paradox. The more it relies on loyalty, coercion, and militarised selection, the less it can rely on autonomous expertise, institutional correction, and policy feedback. This creates a system in which strategic mistakes become more likely because decision-makers are insulated from dissenting information. Frye's (*2021*) argument about the limits of strongman rule is relevant here: apparent centralisation may conceal vulnerability, information distortion, and governance inefficiency. Elite control stabilises the regime politically but weakens its adaptive capacity.

Thus, elite control is a central mechanism of regime reproduction in Russia. The Putin regime maintains elite compliance through patronage, dominant-party coordination, security-state influence, legal vulnerability, symbolic rewards, and wartime loyalty tests. The war against Ukraine has intensified this system by transforming support for the conflict into a criterion of political reliability and by binding elites to the regime through collective responsibility.

The War against Ukraine as a Result of the Internal Logic of the Political Regime

The war against Ukraine should not be analysed solely as an external geopolitical event. It is also a result of the internal evolution of the Russian political regime. The degradation of democratic institutions, concentration of power, weakening of accountability, marginalisation of expertise, and construction of a militarised ideological discourse created conditions in which aggressive foreign policy became increasingly probable. The central result of this subsection is that the war is both an outcome and an instrument of Russia's authoritarian transformation.

Democratic institutions reduce the probability of reckless external aggression by introducing constraints, deliberation, public scrutiny, parliamentary debate, media investigation, electoral accountability, and pluralistic expertise. When these mechanisms are weakened, foreign policy becomes more dependent on the perceptions and strategic preferences of a narrow ruling group. In Russia, the personalisation of decision-making around the presidential centre reduced the capacity of institutions to question or restrain military escalation. This corresponds to theories of personalist authoritarianism, which show that such regimes are often prone to risky decision-making because leaders face fewer institutional constraints and receive less reliable feedback (*Geddes et al., 2018; Svolik, 2012*).

The war also reflects the regime's ideological and symbolic evolution. Russian official discourse increasingly framed Ukraine not as a fully sovereign political community, but as an object of historical, civilisational, and security claims. Snyder (2018) analyses this logic as part of a broader politics of anti-liberal myth and imperial revisionism. Plokhy (2023) interprets the war as a return of imperial history, rooted in contested narratives of Russian and Ukrainian statehood. These interpretations are crucial because the Russian regime's aggression cannot be reduced to immediate security calculations. It is embedded in a longer process through which historical memory, imperial identity, and anti-Western narratives became instruments of regime legitimisation.

The annexation of Crimea in 2014 was a key turning point. It demonstrated that external aggression could generate domestic political consolidation, increase patriotic mobilisation, marginalise dissenting voices, and strengthen the symbolic legitimacy of the leadership. Horvath's (2011) concept of "preventive counter-revolution" helps explain why Ukraine was perceived by the Kremlin as more than a foreign policy issue. Democratic mobilisation in Ukraine represented a potential alternative model for the post-Soviet space. From the perspective of the Russian regime, preventing Ukraine's democratic and geopolitical consolidation became linked to domestic regime security.

The full-scale invasion of 2022 radicalised this logic. The war allowed the regime to transform internal repression into a wartime necessity. Laws restricting speech, dissent, protest, and independent reporting were justified by reference to national security, external threat, and the need for unity. Opposition to the war could be framed not as a legitimate political position, but as betrayal, extremism, or collaboration with hostile forces. Thus, the war expanded the moral and legal boundaries of repression.

The war also functions as an instrument of social mobilisation and demobilisation at the same time. On one level, the regime uses patriotic rhetoric, historical narratives, and external-threat discourse to mobilise symbolic support. On another level, it seeks to demobilise

autonomous political action by producing fear, uncertainty, exhaustion, and resignation. This dual strategy is characteristic of contemporary authoritarian governance: the regime does not necessarily require active ideological enthusiasm from all citizens, but it does require the absence of effective collective resistance.

Economically, the war has reorganised state priorities. Military expenditure, defence industry, sanctions adaptation, import substitution rhetoric, and state-directed economic management have become central to the regime's narrative of resilience. Politically, war has become a mechanism for reordering the hierarchy of loyalty. Administrators, propagandists, military figures, and war participants gain symbolic value, while liberal, civic, and opposition-oriented actors are excluded from legitimate political space.

The war therefore deepens the transformation of the Russian state. It strengthens the security apparatus, expands censorship, increases elite dependency, militarises public discourse, narrows political pluralism, and justifies the further conversion of institutions into instruments of wartime governance. This does not mean that the war solves all problems for the regime. It produces economic costs, human losses, elite anxiety, international isolation, and governance distortions. However, these costs are politically managed through coercion, propaganda, selective data presentation, and the framing of hardship as patriotic endurance.

Thus, the war against Ukraine is not external to the internal logic of the Putin regime. It is a consequence of democratic degradation, personalist decision-making, imperial narratives, and the securitisation of political life. At the same time, the war has become an instrument of domestic consolidation by legitimising repression, disciplining elites, mobilising society around external threat, and accelerating the neo-totalitarian transformation of the state.

The Rhetoric of Peace and Manipulative Management of the Perception of War

The Russian regime's rhetoric of peace should be analysed as part of its broader strategy of manipulative legitimisation. Official statements about negotiations, de-escalation, sovereignty, security guarantees, and peaceful intentions cannot be interpreted only as diplomatic positions. They must also be examined as communicative acts directed at domestic society, foreign governments, international organisations, and audiences in the Global South. The central result of this subsection is that peace rhetoric functions as a mechanism for managing responsibility, obscuring aggression, and preserving the regime's claim to rationality.

Authoritarian communication often works through semantic inversion. Repression is described as protection, aggression as defence, censorship as security, and imperial domination as historical justice. Guriev and Treisman's (2022) concept of spin dictatorship helps explain how regimes manipulate public perception without necessarily relying on a single rigid ideology. In the Russian case, however, spin operates together with coercion. The state not only promotes narratives but also criminalises alternative interpretations. This combination gives official rhetoric a coercive environment in which it can dominate public discourse.

The rhetoric of peace performs several functions. First, it shifts responsibility for the continuation of war. By presenting itself as ready for negotiations while framing Ukraine or the West as obstructive, the regime attempts to externalise blame. This strategy is useful domestically because it reduces the perception that the war continues due to the Kremlin's own

political choices. It is also useful internationally because it allows the regime to present itself as a rational actor open to diplomacy.

Second, peace rhetoric creates a distinction between declared intentions and actual policy. The regime may continue military operations, maintain maximalist goals, reject accountability, and demand political concessions while simultaneously presenting itself as peace-oriented. This gap between rhetoric and practice is not a contradiction in the communicative system; it is part of the strategy. It allows different audiences to receive different messages. Domestic audiences hear that the state is strong but humane; foreign audiences hear that negotiations are possible; loyal elites hear that the official line remains flexible but controlled.

Third, peace rhetoric helps normalise the war by embedding it in a narrative of forced necessity. If the regime claims that it wanted peace but was compelled to fight by external threats, then war becomes morally reframed as reluctant defence. This narrative is central to the construction of legitimacy. It transforms agency into compulsion: the state presents itself not as the initiator of aggression, but as an actor responding to historical injustice, security threats, or Western hostility.

Fourth, peace rhetoric contributes to the management of social anxiety. War produces uncertainty, fear, economic pressure, casualties, and moral discomfort. A permanent discourse of escalation alone could increase social fatigue. By periodically invoking peace, negotiations, and controlled resolution, the regime offers a symbolic horizon of stability without changing the underlying military logic. In this sense, peace rhetoric does not necessarily reduce militarisation; it may make militarisation more sustainable by presenting it as temporary, defensive, and politically controlled.

Fifth, the rhetoric of peace is linked to the manipulation of time. Snyder (2018) argues that authoritarian anti-liberal politics often operates through mythic historical temporality, in which the present is absorbed into narratives of eternal struggle, humiliation, and restoration. The Russian regime uses both historical time and diplomatic time. Historical time presents the war as part of a long civilisational conflict; diplomatic time presents the regime as waiting for reasonable conditions for peace. Together, these temporal strategies legitimise continuation: the war appears both historically necessary and diplomatically manageable.

The manipulation of peace rhetoric also affects the perception of Ukraine. If Russia presents itself as ready for peace while denying Ukraine's full agency, sovereignty, or legitimacy, then negotiations become framed not as dialogue between equal political communities, but as a process in which Ukraine should accept the geopolitical terms imposed by Moscow. This discursive structure reproduces the same imperial logic that contributed to the war.

The rhetoric of peace therefore has to be analysed not through isolated statements, but through its place in the regime's system of communication. It interacts with propaganda, censorship, battlefield narratives, economic statistics, elite messaging, and diplomatic signalling. It is not merely a language of de-escalation; it is a technology of perception management.

Thus, the Russian regime's rhetoric of peace functions as a manipulative communicative strategy. It shifts responsibility, obscures aggression, manages domestic anxiety, influences external audiences, and sustains the image of rational state behaviour while the war continues. Peace rhetoric is therefore not separate from militarisation; it is one of the instruments through which militarisation is politically normalised and legitimated.

Socio-Economic Statistics as an Instrument of Political Legitimation

In democratic systems, public statistics are expected to support accountability, informed debate, policy evaluation, and public knowledge. In authoritarian and neo-totalitarian systems, however, statistics may perform a different function. They can become instruments of political legitimization, symbolic governance, and reality management. The Russian wartime context demonstrates how socio-economic and military data may be selectively published, restricted, reframed, or embedded in official narratives to construct an image of stability, resilience, and state competence.

The political use of statistics does not necessarily require the complete fabrication of data. More often, it operates through selective visibility. Certain indicators are emphasised, while others are omitted or made less accessible. Methodological changes may complicate comparison over time. Aggregated indicators may conceal sectoral distortions. Public communication may focus on growth, employment, wage increases, industrial production, or budgetary stability, while underemphasising inflationary pressure, labour shortages, war-related spending, demographic costs, technological dependency, or the long-term consequences of sanctions.

After the full-scale invasion of Ukraine, the Russian state reduced access to a range of economic and administrative data. This development is analytically significant because data transparency is not merely a technical issue. It shapes the ability of citizens, experts, businesses, journalists, and foreign observers to evaluate the real condition of the economy and the costs of war. When transparency declines, the state gains greater control over public interpretation. In this context, statistics become part of the regime's information hierarchy.

The logic of statistical legitimization is closely connected to Guriev and Treisman's (2022) analysis of contemporary authoritarianism as perception management. The regime does not need every citizen to believe every official claim. It needs to create enough ambiguity, confidence, confusion, and selective optimism to prevent coherent collective opposition. Official data can contribute to this by producing a narrative of normality: the economy adapts, unemployment remains low, industry grows, sanctions fail, the budget is manageable, and society remains stable. These claims may contain partial truths, but their political function lies in how they are selected and framed.

The wartime economy provides a clear example. Military production and state spending can stimulate certain sectors, increase measured output, and support employment. However, this does not necessarily indicate healthy long-term development. A war economy may generate growth that is fiscally burdensome, technologically constrained, inflationary, and dependent on coercive or state-directed priorities. If official communication presents war-driven production as evidence of economic strength without acknowledging structural trade-offs, then statistics become a tool of legitimization rather than transparent diagnosis.

The same logic applies to social indicators. Low unemployment may coexist with labour shortages caused by mobilisation, emigration, demographic decline, and military recruitment. Rising nominal wages may coexist with inflation and regional inequalities. Budgetary figures may conceal the opportunity costs of military expenditure. Public investment may shift from social development to defence and security priorities. When these complexities are absent from official narratives, socio-economic data help construct an image of controlled stability.

Military data are even more politically sensitive. Claims about territorial gains, casualties, equipment losses, mobilisation, and battlefield effectiveness are deeply embedded in propaganda. The regime's battlefield narrative seeks to maintain the perception of inevitability, endurance, and strategic control. As with economic statistics, manipulation may operate through omission, selective reporting, unverifiable claims, and repetition of official frames. The goal is not simply to inform, but to sustain morale, discipline elites, and prevent public recognition of failure.

Statistical manipulation also contributes to the moral economy of authoritarian rule. Citizens are encouraged to evaluate reality through officially sanctioned indicators rather than through independent experience or pluralistic debate. If prices rise, casualties spread, or public services deteriorate, official narratives can reframe these experiences as temporary, externally caused, or outweighed by national goals. In this way, data do not merely describe reality; they compete with lived reality.

This process is a core feature of neo-totalitarian transformation. Classical totalitarian systems sought to impose ideology on reality. Contemporary neo-totalitarian systems often impose curated information environments on reality. They do not always deny material problems directly; instead, they contextualise, relativise, and statistically manage them. This produces a political environment in which citizens are surrounded by official evidence of stability even when the underlying social and economic conditions are more fragile.

Thus, socio-economic and military statistics in wartime Russia perform a legitimising function. Through selective publication, restricted transparency, methodological opacity, and strategic framing, data are used to construct an image of resilience, competence, and control. Statistical governance thus becomes an integral component of the regime's reality-management apparatus and supports the broader neo-totalitarian transformation of political power.

Militarisation of the New Elite and Long-Term Institutionalisation of War

The final result concerns the militarisation of elite formation and the long-term institutionalisation of war within the Russian political regime. War is not only a foreign policy event or a military campaign; it can become a principle of domestic political organisation. In contemporary Russia, the war against Ukraine has begun to reshape elite recruitment, symbolic hierarchy, ideological legitimacy, administrative priorities, and the relationship between state and society.

Militarisation of elites refers to the increasing political value assigned to military service, security credentials, veteran status, war-related administration, and public support for the war. This process does not mean that all elites become soldiers or that civilian governance disappears. Rather, it means that proximity to the war becomes a source of legitimacy. Military participation, patriotic rhetoric, association with occupied territories, defence-industry involvement, and loyalty to wartime narratives become markers of political reliability.

This transformation is consistent with the logic of personalist authoritarianism and elite discipline. In a system where loyalty is more important than institutional competence, war creates new loyalty tests. Supporting the war publicly, participating in its administration, or representing its symbolic values allows individuals to demonstrate alignment with the regime.

Conversely, hesitation, silence, cosmopolitanism, liberalism, or technocratic neutrality may become politically risky. The war therefore reorganises the criteria of elite inclusion.

The militarisation of elites also strengthens the security-state component of the regime. Security agencies, military institutions, defence industries, veterans' organisations, patriotic education structures, and war-related media actors gain increased political relevance. This expands the influence of coercive and militarised actors within civilian politics. Belton (2020) and Mommsen (2017) have already shown the importance of security-service networks in Putin's Russia. The war intensifies this pattern by making security logic even more central to governance.

The long-term danger is that war becomes institutionalised even if active military operations change form. Institutionalisation means that wartime structures, narratives, laws, budgets, careers, and identities become embedded in the state. Repressive legislation adopted under wartime conditions may remain. Military spending may become structurally entrenched. Veterans and war administrators may enter politics. Education may become more militarised. Media narratives may continue to define politics through enemies and threats. Civil society may remain constrained by the logic of national security.

Militarisation also affects political culture. It normalises coercion, hierarchy, sacrifice, suspicion, and external-threat thinking. It narrows the legitimacy of compromise and pluralism. It frames dissent as betrayal and peace advocacy as weakness or collaboration. This is especially significant for the future of democratic alternatives in Russia. A political system that elevates war loyalty as a criterion of citizenship and elite status creates a hostile environment for democratic reconstruction.

The incorporation of war participants into political and administrative roles also serves a symbolic function. It allows the regime to present the war as a source of moral renewal and social mobility. The "new elite" is framed as patriotic, sacrificial, disciplined, and nationally authentic. This narrative helps the regime contrast militarised loyalty with allegedly corrupt, liberal, cosmopolitan, or Westernised elites. In practice, however, such elite renewal may deepen authoritarian control by replacing pluralism and competence with ideological conformity and coercive legitimacy.

At the same time, militarised elite formation may produce internal tensions. War veterans, security actors, technocrats, regional administrators, oligarchic groups, and ideological propagandists do not necessarily share identical interests. The regime must manage these groups while preserving presidential centrality. Militarisation may therefore stabilise the regime in the short term but create long-term governance risks: radicalisation of expectations, increased claims on state resources, expansion of coercive actors, and reduced space for technocratic correction.

This result is closely connected to the broader argument of the article. The Russian regime's neo-totalitarian transformation is not limited to repression or propaganda. It involves the reorganisation of the state around war as a governing principle. War legitimises repression, structures elite loyalty, justifies statistical opacity, shapes political language, mobilises society, and redefines the boundaries of citizenship. In this sense, the war against Ukraine has become embedded in the domestic architecture of power.

Thus, the militarisation of Russia's new elite indicates that war is becoming institutionalised as a domestic political principle. Military experience, security credentials, patriotic performance, and loyalty to the war are increasingly used as markers of political reliability. This process strengthens the coercive core of the regime, narrows the space for democratic alternatives, and contributes to the long-term neo-totalitarian transformation of the Russian state.

General Synthesis of the Results

The seven results presented above demonstrate that the contemporary Russian political regime should be analysed as a system of mutually reinforcing transformations. Democratic institutions have not simply failed; they have been converted into instruments of authoritarian control. Elite autonomy has not merely declined; it has been reorganised through loyalty, dependency, coercion, and wartime complicity. The war against Ukraine is not only an external conflict; it is a mechanism of domestic consolidation. The rhetoric of peace is not only diplomacy; it is a form of manipulative legitimisation. Socio-economic and military statistics are not only administrative data; they are instruments of reality management. The militarisation of elites is not only a personnel trend; it is a sign of the long-term institutionalisation of war.

The central analytical result of the study is that Russia's current political transformation cannot be adequately explained by any single concept taken in isolation. It is not only democratic backsliding, not only competitive authoritarianism, not only personalist dictatorship, not only patronal politics, not only propaganda, and not only militarisation. It is a neo-totalitarian transformation in which these elements are integrated into a consolidated system of rule. The degradation of democratic institutions created the conditions for personalist and coercive governance; personalist governance increased the probability of strategic radicalisation; war intensified repression and elite discipline; propaganda and statistics managed public perception; and militarised elite formation embedded war into the state's long-term institutional structure.

This synthesis confirms the article's hypothesis: the war against Ukraine is both a consequence and an instrument of the neo-totalitarian transformation of the Russian political regime. It emerged from the internal logic of democratic degradation, personalisation of power, imperial discourse, and weakened institutional constraints. After its escalation, it became a mechanism for reproducing the regime through mobilisation, repression, manipulated legitimacy, and militarised elite renewal.

Discussion

The findings of this study suggest that the transformation of the Russian political regime under Vladimir Putin cannot be adequately explained by conventional regime typologies alone. The Russian case includes elements of electoral authoritarianism, personalist dictatorship, patronal politics, security-state governance, propaganda-based legitimacy, and wartime mobilisation. However, the interaction of these elements produces a more complex configuration than any single category can capture. The central interpretive conclusion of the article is that contemporary Russia should be understood as a regime undergoing neo-totalitarian transformation: a process in which formal institutions, coercive mechanisms, elite dependency, information control, statistical representation, and war mobilisation are integrated into a unified system of political domination.

This interpretation does not reject existing theories of democratic erosion, competitive authoritarianism, personalist rule, or authoritarian legitimation. On the contrary, it builds upon them. The literature on democratic backsliding explains how democracies may decline gradually while preserving constitutional and electoral forms (*Bermeo, 2016; Lübrmann & Lindberg, 2019*). Theories of competitive and electoral authoritarianism clarify how elections, parties, courts, and parliaments may continue to exist while losing their democratic function (*Levitsky & Way, 2002; Schedler, 2002*). Studies of personalist authoritarianism explain the concentration of power, elite dependency, and weakening of institutional constraints (*Geddes et al., 2018; Svobik, 2012*). Research on patronal politics and dominant-party institutions explains the informal and organisational foundations of elite management in post-Soviet Russia (*Hale, 2015; Reuter, 2017*). Yet the Russian case after the full-scale invasion of Ukraine shows that these mechanisms have entered a new stage of integration, in which war is no longer only an outcome of authoritarian politics but becomes one of the central instruments of regime reproduction.

The first major implication of the findings concerns the relationship between democratic erosion and external aggression. The results support the argument that the war against Ukraine should not be analysed exclusively as a geopolitical or foreign policy event. It emerged from a domestic political context in which institutional checks had been weakened, political competition had been neutralised, independent expertise had been marginalised, and decision-making had become concentrated around a narrow presidential centre. This does not mean that domestic regime dynamics alone explain the war. Historical narratives, imperial identity, security discourse, and international factors also matter. However, the findings indicate that these factors became politically actionable because the domestic institutional environment no longer contained effective mechanisms of restraint.

This interpretation extends the literature on authoritarian foreign policy by showing how democratic degradation alters the risk environment of strategic decision-making. In democratic systems, foreign policy is shaped by public scrutiny, parliamentary debate, media investigation, expert contestation, legal accountability, and electoral consequences. These mechanisms do not eliminate the possibility of war, but they complicate unilateral escalation. In the Russian case, the progressive destruction or subordination of these mechanisms reduced the regime's exposure to corrective feedback. Personalist centralisation further intensified this problem by concentrating strategic authority and limiting the circulation of dissenting information. Thus, the war against Ukraine can be interpreted as a consequence of institutional narrowing: the more closed the political system became, the more likely it was to produce radical and poorly constrained foreign policy decisions.

The second major implication concerns the transformation of authoritarian legitimation under wartime conditions. Authoritarian regimes do not survive by coercion alone. They require narratives, symbols, performances of competence, and mechanisms of public interpretation. Guriev and Treisman's (2022) concept of "spin dictatorship" is especially useful for understanding how contemporary autocrats manage public perception through information control rather than relying solely on visible terror. However, the Russian case demonstrates that the boundary between "spin" and "fear" is historically unstable. Before the full-scale war, the regime relied heavily on managed elections, media control, symbolic stability, and selective

repression. After 2022, these instruments did not disappear, but they were combined with open coercion, intensified censorship, criminalisation of dissent, and militarised mobilisation.

This suggests that contemporary authoritarian regimes may evolve through hybridisation rather than replacement of control mechanisms. Russia has not simply moved from manipulation to terror, nor from electoral authoritarianism to classical totalitarianism. Instead, it has combined multiple forms of domination: electoral ritual, legal repression, propaganda, elite coercion, data management, patriotic mobilisation, and security-state governance. This hybridisation is precisely what makes the concept of neo-totalitarian transformation analytically productive. It captures the movement towards more comprehensive political control without assuming an exact return to twentieth-century totalitarian models.

The third implication concerns the role of formal institutions in non-democratic regimes. The Russian case confirms that institutions may remain formally intact while being functionally transformed. Elections continue, but they primarily confirm the regime's dominance. Parliament legislates, but mainly authorises executive priorities. Courts operate, but often legitimise political repression in sensitive cases. Parties exist, but the ruling party serves as a mechanism of administrative coordination and elite discipline rather than autonomous representation. Federalism remains constitutionally declared, but regional autonomy is structurally constrained by political, fiscal, and administrative dependency. This supports the argument that the analysis of authoritarian regimes must distinguish between institutional form and institutional function.

The concept of institutional conversion is therefore central. Russia's democratic institutions did not simply disappear; they were repurposed. This is theoretically important because it shows that democratic erosion is not only a process of institutional weakening, but also a process of institutional refunctionalisation. Institutions that once had at least partial democratic potential can be transformed into mechanisms of authoritarian governance. This finding contributes to the broader literature on democratic backsliding by demonstrating that the survival of formal institutions may conceal a deeper transformation of regime logic.

The fourth implication concerns elite politics. The findings confirm that elite control is one of the decisive mechanisms of regime reproduction. In authoritarian systems, elites are both necessary and dangerous for rulers. They administer the state, manage resources, control coercive institutions, shape public narratives, and organise political mobilisation. At the same time, they may become potential challengers if they develop autonomy or coordinate against the ruler (*Svolik, 2012*). The Putin regime has addressed this dilemma through a combination of patronage, informal dependency, dominant-party coordination, security-state influence, legal vulnerability, and symbolic rewards.

The war against Ukraine has added a new layer to this system: militarised loyalty. Elite reliability is increasingly measured not only through administrative performance or political obedience, but also through public alignment with the war. War support, patriotic rhetoric, participation in occupation governance, association with military structures, or symbolic proximity to veterans can function as markers of loyalty. This development alters the sociological composition and symbolic hierarchy of the elite. It gives political value to militarised experience and weakens the space for technocratic neutrality. In the long term, such a process

may create a governing class whose legitimacy is tied not to policy competence or institutional representation, but to participation in a permanent security-war narrative.

This raises an important theoretical question: does militarised elite formation strengthen or weaken authoritarian resilience? In the short term, it may strengthen the regime by disciplining elites, raising the cost of defection, and integrating political careers into the war project. However, in the long term, it may reduce adaptive capacity. Regimes that reward loyalty over competence tend to experience information distortion, policy rigidity, and reduced institutional learning. Frye's (2021) concept of the "weak strongman" is useful here: personalist authoritarianism may appear stable precisely when it is becoming more dependent on distorted information and coercive control. The militarisation of elites may therefore stabilise the regime politically while undermining its administrative and strategic flexibility.

The fifth implication concerns propaganda and the manipulation of peace rhetoric. The findings show that official declarations about peace and negotiations should not be analysed only as diplomatic signals. They also operate as domestic legitimising devices. The rhetoric of peace allows the regime to present itself as rational, defensive, and responsible while maintaining military objectives. It shifts blame for the continuation of war to Ukraine or the West, reduces domestic anxiety, and creates a narrative in which Russia is portrayed as a state forced into conflict but open to settlement on its own terms.

This finding contributes to the study of authoritarian communication by showing that peace rhetoric can become part of war legitimisation. In democratic discourse, peace rhetoric is often associated with de-escalation, compromise, and accountability. In the Russian case, however, it functions as a mechanism of semantic control. It does not necessarily signal readiness to abandon coercive goals. Rather, it may help normalise the continuation of war by presenting it as unavoidable, defensive, and diplomatically manageable. The manipulation of peace rhetoric thus illustrates a broader feature of neo-totalitarian communication: the regime seeks not only to control facts, but also to control the moral vocabulary through which facts are interpreted.

The sixth implication concerns the political role of statistics. This is one of the less developed areas in the literature on Russian authoritarianism, yet it is crucial for understanding the current stage of regime transformation. The findings indicate that socio-economic and military data are not merely administrative instruments; they are part of the regime's legitimacy infrastructure. Official statistics can be used to construct an image of resilience, normality, competence, and control. In wartime conditions, this function becomes especially important because the regime must manage public perceptions of economic costs, sanctions, mobilisation, casualties, inflation, and long-term structural damage.

The political manipulation of statistics does not always require direct falsification. It may operate through selective publication, restricted access, methodological opacity, aggregation, omission, and strategic framing. This is important because authoritarian reality management often works through partial truths rather than total fabrication. A regime may highlight indicators that show adaptation while obscuring indicators that reveal fragility. It may present war-driven industrial output as economic success while underplaying opportunity costs, inflationary pressure, labour shortages, demographic consequences, or technological

dependency. In this sense, statistics function as a symbolic technology of governance. They help produce a public world in which crisis appears manageable and state policy appears effective.

This finding expands the concept of propaganda. Propaganda should not be understood only as ideological messaging or media disinformation. In contemporary authoritarian regimes, propaganda may also operate through numbers, rankings, indicators, and official measurements. Statistical representation can create an aura of objectivity around politically curated interpretations. The neo-totalitarian dimension lies in the integration of statistical narratives with media control, legal repression, and wartime discourse. Citizens are not only told what to think; they are also presented with official indicators that structure the boundaries of what can be publicly known.

The seventh implication concerns the long-term institutionalisation of war. The findings show that the war against Ukraine has begun to reshape not only foreign policy, but also the internal architecture of the Russian state. Wartime laws, military spending, propaganda structures, patriotic education, veteran incorporation, occupation administration, and security-state expansion may endure beyond specific battlefield developments. This means that war can become institutionalised as a mode of governance. It structures political careers, defines loyalty, organises public discourse, and expands the legitimacy of coercion.

The institutionalisation of war creates a serious obstacle to future democratic transformation. Democratic reconstruction requires pluralism, legal accountability, civic autonomy, independent information, and a political culture that recognises legitimate disagreement. A militarised neo-totalitarian order weakens all these conditions. It normalises hierarchy, external-threat thinking, suspicion of dissent, and the moral elevation of coercive service. Even if the intensity of military operations changes, the institutions and narratives produced by war may continue to shape domestic politics. This is why the war must be analysed not only as a conflict between states, but also as a process of internal regime reorganisation.

The findings also clarify the relationship between Russia and classical totalitarian models. The article does not argue that contemporary Russia is identical to Stalinist totalitarianism or to the classical cases analysed by Arendt (1957). Such a claim would ignore the persistence of markets, private consumption, formal elections, digital communication, international economic adaptation, and fragmented ideological repertoires. However, the Russian case demonstrates the reactivation of certain totalitarian logics in a contemporary form: monopolisation of political meaning, criminalisation of dissent, enemy construction, elite discipline, information control, and the subordination of institutions to a single political centre. The prefix “neo-” is therefore essential. It indicates both continuity and difference: the re-emergence of comprehensive domination through new institutional, technological, communicative, and wartime mechanisms.

This interpretation also helps position the article within the debate over whether Russia should be classified as fascist, authoritarian, imperial, personalist, or totalitarian. Laruelle (2021) rightly warns against simplistic labelling, especially when ideological complexity is reduced to polemical categories. The present article avoids treating neo-totalitarianism as a moral label. Instead, it uses the concept to describe a process of functional integration. Russia may contain fascistic motifs, imperial narratives, personalist authority, patronal networks, electoral authoritarian procedures, and security-state practices. The analytical question is not which single

label should replace all others, but how these elements interact within the current regime. The concept of neo-totalitarian transformation is proposed as a way to capture this interaction.

At the same time, the concept requires careful use. If applied too broadly, it may lose analytical precision. Not every authoritarian regime with propaganda, repression, and manipulated elections is neo-totalitarian. The category becomes useful only when it identifies a specific level of integration among coercion, institutional conversion, elite militarisation, war mobilisation, information control, and managed reality. In the Russian case, the findings suggest that such integration has become increasingly visible after 2022. Nevertheless, further comparative research is necessary to determine whether this concept can be applied to other contemporary authoritarian systems or whether Russia represents a more specific regime trajectory.

The study has several limitations. First, the analysis is constrained by the limited transparency of the Russian political system, especially under wartime conditions. Access to reliable information about elite dynamics, internal decision-making, military losses, economic costs, and public opinion is restricted. Second, official data must be treated critically because they may be selectively published, methodologically altered, or politically framed. Third, the study is based on a qualitative single-case design, which allows for deep analytical interpretation but does not permit broad statistical generalisation. Fourth, the concept of neo-totalitarianism itself remains contested and requires continued theoretical refinement. Fifth, the rapid development of the war and domestic repression means that some empirical elements may change after the completion of the article.

These limitations do not undermine the article's central argument, but they define its scope. The purpose of the study is not to provide a final classification of the Russian regime for all future contexts. Rather, it seeks to explain the current trajectory of transformation and to identify the mechanisms through which democratic degradation, elite control, war, propaganda, statistical manipulation, and militarisation reinforce one another. The value of the analysis lies in its capacity to connect phenomena that are often examined separately.

The broader theoretical contribution of the study is that it reframes authoritarian transformation as a process of systemic integration. Democratic erosion weakens institutional constraints; personalist rule concentrates decision-making; patronal politics disciplines elites; propaganda manages public meaning; statistics construct controlled reality; war legitimises repression; and militarisation institutionalises the new political order. The Russian case shows that these processes do not merely coexist. They interact, reinforce one another, and generate a regime logic that is more comprehensive than ordinary authoritarian consolidation.

The practical implications are also significant. Analysts, policymakers, and scholars should avoid interpreting the Russian regime through isolated indicators, such as electoral manipulation, media control, military aggression, economic adaptation, or elite loyalty alone. Each of these elements is important, but their political meaning becomes clearer when analysed as part of an integrated system. For democratic states and international institutions, this means that responses to Russian aggression cannot be limited to military or diplomatic measures. They must also address propaganda, statistical opacity, elite complicity, transnational authoritarian networks, and the domestic mechanisms through which war is legitimised.

Finally, the findings suggest that any future de-escalation or post-war transformation will face not only geopolitical obstacles, but also deep institutional and sociological ones. If war has become embedded in elite recruitment, legal structures, political language, economic priorities, and symbolic legitimacy, then ending military operations would not automatically reverse neo-totalitarian transformation. Democratic reconstruction would require the restoration of institutional autonomy, accountability, media pluralism, civic freedom, legal independence, and the demilitarisation of political legitimacy. The difficulty of such a process underscores the importance of analysing the war against Ukraine as both an international conflict and a domestic regime-making project.

In sum, the discussion confirms the central hypothesis of the article. The war against Ukraine is not an external deviation from the internal development of the Russian political regime. It is both a consequence of democratic degradation and personalist authoritarian consolidation, and an instrument through which the regime has intensified repression, disciplined elites, manipulated public perception, and institutionalised militarised governance. The Russian case therefore contributes to contemporary political science by demonstrating how democratic erosion may culminate not merely in authoritarian stability, but in a neo-totalitarian transformation organised around war, propaganda, elite coercion, and managed reality.

Conclusion

This article has examined the neo-totalitarian transformation of the Russian political regime under Vladimir Putin through the interconnection of democratic degradation, personalist authoritarian consolidation, elite militarisation, manipulative legitimisation, and the war against Ukraine. The central argument of the study is that contemporary Russia cannot be adequately understood through a single analytical category such as hybrid regime, electoral authoritarianism, personalist dictatorship, patronal politics, or wartime autocracy. Each of these concepts captures an important dimension of the Russian case, but the current stage of regime transformation is defined by their systemic integration. Formal institutions, coercive mechanisms, elite dependency, propaganda, controlled statistics, and military mobilisation now operate as mutually reinforcing components of a broader neo-totalitarian order.

The research has confirmed the hypothesis formulated in the introduction: the war against Ukraine is not an external deviation from the internal development of the Russian political regime, but both a consequence and an instrument of its neo-totalitarian transformation. The degradation of democratic institutions, the concentration of decision-making in the presidential centre, the weakening of institutional constraints, the subordination of elites, and the suppression of pluralism created the political conditions under which aggressive external policy became increasingly probable. After the full-scale invasion of Ukraine, the war itself became a mechanism of domestic regime reproduction. It enabled the authorities to intensify repression, justify censorship, discipline elites, mobilise society around narratives of external threat, and reconstruct political legitimacy through the language of security, sacrifice, sovereignty, and historical necessity.

The first major conclusion of the study is that democratic degradation in Russia has occurred primarily through the functional conversion of institutions rather than through their formal disappearance. Elections, parliament, courts, parties, federal structures, media regulation,

civil society law, and official statistics have remained visible components of the state system. However, their democratic functions have been progressively weakened, neutralised, or reversed. Elections have increasingly served as rituals of confirmation rather than mechanisms of political uncertainty and accountability. Parliament has functioned largely as a legislative extension of executive will. Courts have become instruments for sanctioning politically sensitive repression. Federalism has been subordinated to vertical administrative control. Media and civil society have been transformed into objects of surveillance, regulation, delegitimation, and coercion. This process demonstrates that democratic institutions may survive formally while being incorporated into an authoritarian and neo-totalitarian logic of governance.

The second conclusion is that elite control represents one of the central mechanisms of regime reproduction. The Russian political system has developed a loyalty-based elite order in which access to resources, status, protection, and political survival depends on alignment with the presidential centre. Patronage, administrative dependency, security-service influence, legal vulnerability, and dominant-party coordination have contributed to the reduction of elite autonomy. The war against Ukraine has further deepened this mechanism by turning public support for the war into a test of political reliability. Elite loyalty is now increasingly connected not only with obedience to the regime, but also with symbolic participation in the militarised narrative of the state. This has produced a new stage of elite incorporation, in which war, security, patriotism, and political survival are tightly interlinked.

The third conclusion is that the war against Ukraine must be interpreted as part of the internal logic of the Russian regime. It is not sufficient to explain the war only through geopolitics, security claims, historical grievances, or imperial ideology, although all these dimensions are significant. The war became possible within a domestic political environment where institutional checks had been dismantled, opposition had been suppressed, independent media had been marginalised, and strategic decision-making had become concentrated within a narrow ruling circle. At the same time, the war has become a domestic political technology: it legitimises repression, reinforces the authority of the security apparatus, produces new criteria of elite loyalty, and reorganises public discourse around external threat and national mobilisation.

The fourth conclusion concerns the manipulative rhetoric of peace. The article has shown that official statements about negotiations, de-escalation, and peaceful intentions should not be interpreted only as diplomatic communication. In the Russian case, the rhetoric of peace functions as part of the regime's system of perception management. It allows the authorities to shift responsibility for the continuation of war, present themselves as rational and defensive, influence foreign audiences, and manage domestic anxiety. This rhetoric does not necessarily contradict militarisation; rather, it can make militarisation more politically sustainable by framing war as reluctant, defensive, temporary, and externally imposed. The language of peace therefore becomes one of the instruments through which the regime legitimises the continuation of war.

The fifth conclusion is that socio-economic and military statistics have become an important element of authoritarian legitimation. Under wartime conditions, official data are not merely administrative indicators; they participate in the construction of political reality. Selective publication, restricted transparency, methodological opacity, omission of politically damaging indicators, and strategic framing allow the regime to produce an image of resilience, stability,

competence, and control. This does not necessarily require the complete falsification of all data. More often, manipulation operates through selective visibility and interpretive framing. The political function of statistics is therefore to support the narrative that war, sanctions, repression, and economic pressure remain manageable and historically justified.

The sixth conclusion is that the militarisation of elites points to the long-term institutionalisation of war within the Russian state. War is becoming not only a foreign policy condition, but also a principle of domestic political organisation. Military service, veteran status, security credentials, participation in wartime administration, and public loyalty to war narratives increasingly acquire political value. This process strengthens the coercive core of the regime and narrows the space for democratic alternatives. It also creates long-term institutional consequences: wartime legislation, militarised education, expanded security structures, defence-oriented economic priorities, and symbolic hierarchies based on sacrifice and loyalty may persist even if the intensity of military operations changes.

The theoretical significance of the article lies in its attempt to conceptualise contemporary Russia as a case of neo-totalitarian transformation rather than merely authoritarian consolidation. This distinction is important. Authoritarian consolidation refers to the stabilisation of non-democratic rule. Neo-totalitarian transformation refers to a deeper process in which institutions, elites, law, propaganda, statistics, coercion, and war are integrated into a system that seeks to monopolise political meaning and subordinate public reality to the regime's interpretive authority. The Russian case demonstrates that modern neo-totalitarianism does not need to reproduce the exact institutional forms of twentieth-century totalitarianism. It can coexist with markets, formal elections, digital technologies, selective legalism, international economic adaptation, and fragmented ideological repertoires. Its defining feature is not total uniformity, but the political integration of coercion, manipulation, militarisation, and institutional control.

The practical significance of the study is connected with the need to understand how contemporary authoritarian regimes adapt under conditions of war, sanctions, international pressure, and internal social tension. The Russian case shows that such regimes may use war not only as an external strategy, but also as an internal mechanism of political reproduction. For scholars, experts, and policymakers, this means that the analysis of authoritarian aggression should include not only military and diplomatic dimensions, but also domestic institutional transformation, elite discipline, propaganda, statistical opacity, and the militarisation of legitimacy. Without this broader perspective, the political durability of the regime and the depth of its transformation may be underestimated.

The study also has implications for the analysis of future democratic reconstruction. If the war against Ukraine has become embedded in Russia's legal structures, elite recruitment, political discourse, educational narratives, economic priorities, and symbolic hierarchy, then a possible cessation of hostilities would not automatically restore democratic potential. De-escalation in foreign policy would need to be accompanied by demilitarisation of political legitimacy, restoration of institutional autonomy, judicial independence, media pluralism, civic freedom, electoral competitiveness, and public accountability. The depth of neo-totalitarian transformation suggests that democratic renewal would require not only leadership change, but also profound institutional and cultural reconstruction.

At the same time, the article recognises the limitations of its analysis. The study is based on a qualitative single-case design and therefore does not claim statistical generalisability. The wartime context limits access to reliable data on elite conflicts, military losses, public opinion, budgetary costs, and internal decision-making. Official statistics and public statements require critical interpretation because they may be selectively presented or politically framed. The concept of neo-totalitarianism also requires further theoretical refinement and comparative testing. Future research may examine whether similar mechanisms of institutional conversion, statistical legitimisation, elite militarisation, and war-based regime reproduction are present in other contemporary authoritarian systems.

Further studies should also investigate several specific dimensions in greater detail. First, more attention should be given to the sociology of the new militarised elite and the channels through which war participants, security actors, propagandists, and wartime administrators are incorporated into political institutions. Second, the political economy of wartime legitimacy requires deeper analysis, especially the relationship between military expenditure, regional dependency, labour shortages, sanctions adaptation, and official narratives of economic resilience. Third, future research should examine the long-term effects of propaganda and patriotic education on political socialisation. Fourth, comparative studies could explore whether the Russian case represents a unique trajectory or part of a broader pattern of authoritarian radicalisation under conditions of geopolitical conflict.

In conclusion, the Russian political regime under Vladimir Putin has undergone a transformation that cannot be reduced to ordinary authoritarian consolidation. The degradation of democratic institutions, the personalisation of power, the subordination and militarisation of elites, the manipulation of public perception, the political use of statistics, and the war against Ukraine have become interconnected elements of a single regime logic. This logic is neo-totalitarian because it seeks not only to monopolise political power, but also to define legitimate reality, discipline society and elites, and institutionalise war as a mode of governance. The war against Ukraine is therefore both the product of this transformation and one of its principal instruments. Understanding this relationship is essential for explaining the current nature of Russian power, the persistence of its aggression, and the obstacles to future democratic change.

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Conflict of Interest

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Typological Features of the Evolution of Forms of Pans, Crucibles, and Braziers in Porcelain-Faience of the Right-Bank Ukraine of the Late 18th and Early 20th Centuries ^[2]

Abstract:

This article examines a small but significant group of porcelain and faience objects produced in the territories of Right-Bank Ukraine, particularly in Volhynia and Galicia, from the late eighteenth to the early twentieth century. These objects include pans, stewpans, crucibles, braziers, and related deep round vessels used for cooking, heating, and serving food. Although such items are of considerable interest to collectors and museum specialists, they have not previously been systematised as a separate typological group within the history of Ukrainian porcelain and faience. The relevance of the study is determined by the need to clarify the formal, functional, decorative, and typological characteristics of these rarely preserved ceramic forms and to introduce them more precisely into the scholarly discourse of decorative and applied arts. The aim of the study is to reveal the evolution of round cooking and heating forms in the porcelain and faience production of the ethnic Ukrainian lands from the late eighteenth to the early twentieth century. The research focuses on the works of the Korets Porcelain and Faience Manufactory, the Baranivka Porcelain Factory, and the faience production of Glynsko in Galicia. The study applies axiological, ontological, historical-genetic, comparative, cultural, typological, formal-stylistic, and art-historical methods. The article identifies the main formal variants of this group: ring-shaped heating pans with lids, saucepan-braziers with hollow side handles, vessels with sculptural handles in the form of animals, mushrooms, or pineapples, and multi-portion soup vessels resembling cooking pots. The analysis demonstrates that this segment of Ukrainian porcelain and faience is represented by fewer than a dozen known examples, from which five or six principal forms can be distinguished. The results confirm the uniqueness of these objects as part of the national heritage of decorative and applied arts and show their connection with European ceramic traditions, local manufacturing practices, and the changing culture of food preparation and serving.

Keywords: porcelain and faience, Ukrainian decorative and applied arts, Right-Bank Ukraine, Korets manufactory, Baranivka Porcelain Factory, Glynsko faience, form, typology, ornament, ceramic painting.

Introduction

The porcelain and faience heritage of Right-Bank Ukraine occupies an important place in the history of Eastern European decorative and applied arts. From the late eighteenth century onwards, ceramic production in Volhynia and Galicia developed within a complex cultural environment shaped by local artistic traditions, European court and domestic culture, the influence of Polish and Austrian ceramic centres, and the changing everyday practices of different social groups. Within this context, particular attention has traditionally been paid to tableware, tea and coffee services, decorative vessels, plates, vases, and painted porcelain objects. However, several utilitarian forms related to the preparation, heating, and serving of food have remained insufficiently studied.

Among such forms is a specific group of porcelain and faience objects that may be described as pans, stewpans, crucibles, braziers, heating pans, or deep round vessels with one or more handles. These objects are typologically connected with deep bowls or low cylindrical vessels with straight or slightly rounded walls, often supplied with a side handle, a hollow socket for a wooden holder, or a lid with a sculptural finial. In the domestic context, they could be used for preparing, heating, or serving roasted dishes, stews, bigus, poultry, goose liver, soups, and

other multi-portion dishes. Despite their functional and artistic significance, these forms have not been systematised as an independent object of study in the scholarship devoted to the fine ceramics of ethnic Ukrainian lands.

The relevance of the present research is determined by several factors. First, the group of objects under consideration is extremely limited in number and is now represented mainly by isolated museum examples in Ukraine and Poland. Secondly, these objects combine utilitarian, artistic, technological, and cultural functions, which makes them valuable for the study of everyday life, table culture, and the evolution of ceramic form. Thirdly, the educational study of European fine ceramics in art institutions requires a more precise understanding of such specialised forms, especially when they belong to regional production centres that participated in broader European artistic processes. Finally, the insufficient scholarly attention given to these objects creates a gap in the typology of Ukrainian porcelain and faience.

The research problem lies in the absence of a systematic art-historical classification of pans, braziers, crucibles, and related cooking or heating forms produced by porcelain and faience enterprises in the ethnic Ukrainian territories from the late eighteenth to the early twentieth century. Although individual examples have been mentioned in museum catalogues and studies of Polish and Ukrainian ceramics, they have not been analysed as a coherent formal and functional group. Their attribution, dating, morphology, decorative schemes, and relation to European prototypes therefore require further clarification.

The scientific novelty of the article consists in identifying and analysing this group of ceramic objects as a distinct typological segment within the porcelain and faience production of Right-Bank Ukraine. The study brings together rare examples from museum collections and archival visual sources, compares their formal and decorative features, and reconstructs the evolution of these forms from the late eighteenth century to the first decades of the twentieth century. Particular attention is paid to the production of the Korets Porcelain and Faience Manufactory, the Baranivka Porcelain Factory, and the faience factory in Glynsko.

The object of the study is the porcelain and faience production of the ethnic Ukrainian lands, primarily Volhynia and Galicia, from the late eighteenth to the early twentieth century. The subject of the study is the typological evolution, functional purpose, formal structure, and decorative features of pans, crucibles, braziers, saucepan-braziers, heating pans, and related multi-portion ceramic vessels.

The study aims to reveal the evolution of round porcelain and faience forms intended for cooking, heating, and serving food in the ceramic production of Right-Bank Ukraine from the late eighteenth to the early twentieth century.

To achieve this aim, the study sets the following objectives:

- to identify known examples of this group of porcelain and faience objects preserved in museum collections and archival sources;
- to determine their attribution, dating, and connection with specific production centres;
- to analyse the formal structure of the objects, including body shape, lids, handles, supports, finials, and proportions;
- to examine the decorative systems used on these objects, including floral painting, ornamental friezes, gilding, and sculptural modelling;

- to compare Volhynian and Galician examples in terms of form, function, and stylistic features;
- to define the main typological variants within the group;
- to assess the significance of these works for the history of Ukrainian decorative and applied arts.

The theoretical significance of the study lies in clarifying the typology of Ukrainian porcelain and faience by introducing a previously under-systematised group of utilitarian and artistic ceramic forms into scholarly circulation. The research contributes to the development of terminology and classification in the field of decorative and applied arts and allows these objects to be interpreted not merely as isolated museum rarities, but as evidence of broader artistic, technological, and cultural processes.

The practical significance of the study lies in its potential application in museum attribution, catalogue preparation, restoration documentation, exhibition interpretation, and educational courses on European and Ukrainian fine ceramics. The proposed typological observations may be useful for museum curators, art historians, collectors, lecturers, and students studying the ceramic heritage of Ukraine and Eastern Europe.

Methods

The methodological basis of the study combines philosophical, historical, cultural, typological, formal-stylistic, and art-historical approaches. This interdisciplinary methodology corresponds to the nature of the research object, since the porcelain and faience forms analysed in the article are simultaneously utilitarian objects, works of decorative and applied art, products of specific manufactories, and material evidence of everyday culture.

The philosophical group of methods includes the axiological and ontological approaches. The axiological method makes it possible to interpret the objects under consideration as cultural and artistic values rather than only as household utensils. It allows the study to assess their significance within the national heritage of Ukrainian decorative and applied arts. The ontological method is applied to examine the mode of existence of these objects in everyday life, including their practical function, material form, artistic image, and role in the domestic culture of the late eighteenth and nineteenth centuries.

The historical group of methods includes the historical-genetic and comparative approaches. The historical-genetic method is used to trace the development of ceramic forms from earlier prototypes to later variants produced at the Korets, Baranivka, and Glynsko enterprises. This method helps to reveal continuity, transformation, and adaptation in the evolution of pans, braziers, heating vessels, and related forms. The comparative method is applied to compare objects from different manufactories, museum collections, and chronological stages. It also makes it possible to distinguish between Volhynian and Galician production features and to identify similarities with broader European ceramic traditions.

The cultural approach is used to interpret these objects within the context of food preparation, table culture, social habits, and domestic practices of different social groups. This method is particularly important because the objects studied were not purely decorative; they were connected with cooking, heating, serving, and the ritualised organisation of the table. Their

form and decoration therefore reflect the interaction between artistic production and everyday life.

The art-historical group of methods includes typological, formal-stylistic, and visual art analysis. The typological method is used to classify the selected objects according to their form, function, construction, lid type, handle type, supports, proportions, and decorative features. The formal-stylistic method allows the study to analyse the morphology of the vessels, including cylindrical or rounded bodies, hollow side handles, sculptural finials, three-legged supports, hemispherical or tent-shaped lids, ornamental friezes, and floral painting. The method of art-historical analysis is applied to examine the compositional, ornamental, chromatic, and figurative qualities of each object.

The source base of the study consists of published catalogues, scholarly works, museum materials, and visual documentation of preserved objects. Particular attention is paid to examples from the archive of the Institute of Art of the Polish Academy of Sciences, the National Museum of Ukrainian Folk Decorative Art, the Vinnytsia Regional Museum of Local History, the Museum of Ethnography and Artistic Crafts in Lviv, and the National Museum in Warsaw. The appendix illustrations provide important visual evidence for identifying formal and decorative features, including sculptural handles in the form of a lion cub, mushroom, or pineapple; ornamental friezes; hollow handles; floral motifs; and factory marks.

The research procedure consisted of several stages. At the first stage, the authors identified and collected information about known examples of pans, braziers, heating pans, and related ceramic vessels. At the second stage, these objects were attributed, dated, and connected with specific production centres where possible. At the third stage, their formal characteristics were described and compared. At the fourth stage, decorative systems and ornamental motifs were analysed. At the fifth stage, the objects were grouped into typological variants. At the final stage, conclusions were drawn regarding the evolution, artistic specificity, and cultural significance of this segment of Ukrainian porcelain and faience.

The study is limited by the small number of preserved objects and by the fact that several examples are known only from archival photographs or museum documentation. Nevertheless, the available material is sufficient to identify the principal formal types and to demonstrate that this group of objects deserves separate scholarly consideration.

Literature Review

The study of porcelain and faience from the territories of Right-Bank Ukraine is situated at the intersection of Ukrainian art history, Polish ceramic studies, museum attribution, and the broader history of European decorative and applied arts. The scholarly literature on this subject is valuable, but it remains uneven with regard to the specific group of objects analysed in the present article. Most previous studies have focused on the history of manufactories, the attribution of factory marks, tableware, painted porcelain, faience production, and the artistic features of services, plates, vases, and decorative objects. Pans, braziers, crucibles, saucepan-braziers, and heating vessels have usually been mentioned only incidentally.

An important contribution to the study of Polish and Eastern European porcelain was made by E. Kowecka, M. Łoś, J. Łoś, and L. Winogradow in the editions of 1975 and 1984. Their publications provided a broad overview of porcelain objects preserved in Polish museum

collections and introduced valuable material concerning the provenance, attribution, and artistic features of porcelain production associated with the Polish and neighbouring cultural regions. However, their primary attention was directed towards museum collections as a whole and towards the broader history of porcelain, rather than towards a focused typology of specialised cooking and heating forms. As a result, the objects under consideration in the present article appear only as part of a larger ceramic context.

The works of M. Starszewska and M. Jeżewska on Polish faience are also relevant for understanding the formal and technological background of the objects analysed here. Their studies help to situate faience production within the broader evolution of eighteenth- and nineteenth-century ceramic culture. Nevertheless, these publications do not provide a systematic analysis of Ukrainian or Right-Bank Ukrainian forms such as heating pans, saucepan-braziers, or multi-portion cooking vessels.

A further stage in the development of scholarship is represented by Polish researchers of the 1980s–2000s, including H. Chojnacka, B. Kostuch, and J. Sozańska. Their studies expanded attention from representative tableware to more diverse forms of porcelain and faience, including individual objects associated with the preparation and heating of food. Chojnacka's work is particularly important because it includes archival and museum material relevant to faience objects and provides visual evidence for certain rare forms, including examples connected with the Korets tradition. Kostuch and Sozańska contributed to the broader understanding of Polish and European porcelain production and museum collections, which is necessary for comparative analysis. However, these studies still do not isolate the Ukrainian group of pans, braziers, and crucibles as a separate typological problem.

The most significant contribution to the study of Ukrainian porcelain and faience was made by Faina Petriakova, who examined the production of Ukrainian manufactories from the late eighteenth to the early twentieth century. Her works on Ukrainian artistic porcelain, the Baranivka factory, the Horodnytsia manufactory, and the Korets manufactory are fundamental for the attribution and historical interpretation of this material. Petriakova was particularly attentive to the function, form, factory origin, and decorative features of domestic porcelain and faience. Her research laid the foundation for a systematic understanding of Ukrainian “white gold” as a national artistic heritage and remains indispensable for the analysis of the objects considered in this article.

At the same time, even Petriakova's studies did not fully exhaust the typological problem of pans, crucibles, and braziers. These objects were usually considered in connection with particular factories, catalogues, or museum examples rather than as an independent formal group. The present article therefore continues and develops this line of scholarship by focusing specifically on the evolution of such forms in Volhynia and Galicia and by comparing the surviving examples according to form, function, decoration, and production context.

The literature review demonstrates a clear research gap. Existing scholarship provides valuable historical, attributional, and stylistic information on porcelain and faience production in Poland, Ukraine, Volhynia, and Galicia. However, it does not offer a separate systematic classification of the group of deep round vessels used for cooking, heating, and serving food. The present study addresses this gap by identifying the known examples, distinguishing their

formal variants, and interpreting them as a unique segment of Ukrainian decorative and applied arts.

Results

In order to consolidate the analysis of fine ceramic works from the ethnic Ukrainian lands produced between the Baroque/Classicist period and the Art Nouveau era, most of which are now preserved in Polish and Ukrainian museum collections, it is necessary to bring together the known objects of this group. The majority of them date from the first third of the nineteenth century.

In particular, the archive of the Institute of Art of the Polish Academy of Sciences (*Instytut Sztuki PAN*) preserves a photograph of a Korets (?) *rynka*, or handled heating pan, dating from the late eighteenth to the early nineteenth century (*Chojnacka, 1981, p. 50*) (*Figure 1*). In its proportions, the object resembles a large basin or a shortened bucket, with a profiled side handle in the form of a short rectangular holder. The main body of the vessel stands on three plastically modelled and rather high four-toed lion paws. These supports do not hold the bowl from below; instead, they are attached to the side of the vessel, their shanks emerging from decorative trefoils that adorn the outer wall of the pan. The simple ensemble is crowned by a hemispherical lid with a plastically modelled finial in the form of a small lion cub. The animal image is treated in a highly decorative manner and resembles a small sun-like form created from the mane of a sleepy kitten. The proportions of the vessel are slender and relatively light for an object intended primarily for stewed dishes and for reheating them before serving. Judging from the photograph, the object was opaque and had no painted decoration (*Chojnacka, 1981, p. 50*).

The next type within this group is represented by the braziers of the Baranivka Porcelain Factory. Several examples of almost identical size and two decorative variants are known. These include one pan each from the collections of the National Museum of Ukrainian Folk Decorative Art, the Vinnytsia Regional Museum of Local History (*Figure 2*), and the Museum of Ethnography and Artistic Crafts in Lviv. In the first two examples, the bowl is decorated below the rim with a frieze of grapevine painted in brown. Gilded bands are applied along all edges of the vessel and along the narrowed and widened sections of its short hollow handle, which was intended to hold an additional wooden attachment and has lateral holes for fixing it (*Petrjakova, 1985*).

The form of the main body is identical to the Korets prototype; even the small chamfer before the rim is preserved. The Baranivka examples are distinguished by the absence of a lid and by the profiled base near the body of the modified handle. Judging from the mark — a triangle formed by three blue stars with a brown inscription — and from the type of ceramic body, these works may be dated to approximately 1810–1830 (*Petrjakova, 1985*). The bowl is 7.9 cm high and 21.5 cm in diameter (KS-372). An identical Korets object with overglaze painting from the 1820s is preserved in the collection of the National Museum of Ukrainian Folk Decorative Art (Fr-961; diameter: 19.5 cm). Its overglaze mark is red and consists of the “Eye of Providence” in a triangle with the inscription “Korzec” (*Petrjakova, 1989*).

The Museum of Ethnography and Artistic Crafts in Lviv preserves a porcelain object of analogous form (K/11143), decorated with floral painting in the form of a bouquet placed in the central part of the bowl. The bouquet consists of a lilac tulip, blue forget-me-nots, and

orange daisies. The object is marked with a black eagle and a red inscription “Барановка” in Russian, which corresponds to a date within the late 1820s–1830s (*Figure 3*) (*Petriakova, 1985*).

This example has a slightly different treatment of the handle: a single gilded band is placed near its outer hollow edge, and there are no holes for mounting a wooden holder. The saucepan-brazier is richly decorated with polychrome painting on a white ground. On one side of the vessel, there is a bouquet consisting of a yellow narcissus, a branch of forget-me-nots, and lilac daisies. On the other side, two tiny branches with unspecified flower buds are depicted.

Another object of this form, preserved in the collection of the National Museum in Warsaw, is dated to 1829–1830 and entered the collection as a gift from Stanisław Męczyński in 1903. From this Baranivka ensemble, a lid has survived with a finial in the form of a mushroom cap emerging from plastically modelled leaves. The edge of the mushroom cap, as well as the lid and the articulation of the handle, are decorated with green outlining. The same colour emphasises the plastic elements, including the base of a frieze composed of C-shaped segments. Small cornflower motifs are scattered across the surface of the object. The straight handle, which has no holes for a holder, is simplified in comparison with the earlier models (*Figure 4*) (*Petriakova, 1985; Sozańska, 2002*).

This object is much smaller than the later example of the form mastered at the Baranivka Porcelain Factory in 1828. The item donated by Stanisław Ursyn-Rusiecki in 1937 has a lid decoration similar to that of the saucepan-brazier with a lilac tulip from the collection of the Museum of Ethnography and Artistic Crafts in Lviv. However, in the example from the National Museum in Kraków, the decoration also includes a pansy flower. Particularly distinctive is the decoration on the side of the main body: an overloaded bouquet with dark foliage, a reddish carnation, daisies, and forget-me-nots. It is also noteworthy that, in addition to the usual central motifs, smaller clusters of daisies appear on the lid. The lid itself is hemispherical. Its high vault covers the rim of the vessel in anticipation of a heap of food, placed “over the top”, as Faina Petriakova described it, leaving the seemingly excessive edge of the lid hanging down (*Petriakova, 1989*).

The proportions of this object already show the influence of Biedermeier, with its somewhat “greedy” inclination towards larger volumes. The base of the lid finial, shaped as a plastically modelled mushroom cap, is decorated with four gilded petals twisted in one direction like a weather vane. The same motif is also applied to the upper part of this sculptural detail. The handle of the pan appears somewhat shortened in comparison with earlier models (*Figure 4*).

It is useful to compare this Volhynian object with a chronologically close Galician example from Glynsko in the Lviv region, preserved in the Museum of Ethnography and Artistic Crafts in Lviv (K/5027) (*Figure 5*). This faience object still has plastically modelled legs that are rather archaic for the period and are decoratively curved outwards. The heating pan is ornamented with a pineapple-shaped finial placed on the truncated part of a tent-shaped lid with concave sides, which also overlaps the rim as if “in excess”. It has a long handle ending in a decorative relief terminal resembling a small rounded rolling pin without additional decoration. The heating pan is decorated only with two dark outlining bands: a thicker one on the rim and a thinner one below it. A chamfer along the outer edge of the lid, which gravitates towards Austrian forms of

porcelain tableware, emphasises the refined silhouette of the ensemble, covered with a glaze of a light coffee-with-milk colour (*Starszewska & Jeżewska, 1978*).

The catalogue of Korets works published in 1989 also includes a pan from the Museum of Ethnography and Artistic Crafts in Lviv (K/11142), decorated with overglaze polychrome painting consisting of a bouquet of a yellow narcissus, blue forget-me-nots, and lilac daisies. The vessel has a rounded lower body, which resembles the Glynsko pan, although it has neither legs nor a lid. According to its mark, the object belongs to Korets production: a black triangle in the form of a pyramid, in the lower part of which a chamber is hidden—the silhouette of a semicircular sun awakening all living things at dawn, conventionally interpreted as the “All-Seeing Eye”; below the graphic motif is the number 7 with a dot. According to Faina Petriakova, this pan-ladle with a hollow handle dates from the 1810s–1820s. The bowl is 18 cm in diameter and 8.3 cm high (Figure 6) (*Petriakova, 1989*).

The only cooking pot known to the authors from a Korets porcelain set of the 1815–1820s, preserved in the collection of the National Museum in Warsaw, is also marked by experimentation with form and painting (Figure 7). The proportions of its lid are modified, as if with an “insufficient” amount of space above the rim. This unique example of replacing a soup-serving vase with an object intended specifically for preparing first courses is of particular interest as a singular and exceptional form. The lid finial, shaped as a truncated upper cap, is crowned by the umbrella of a plastically modelled mushroom with a profiled star-shaped pattern filled with gilding on the upper part of the cap (*Petriakova, 1989; Sozańska, 2002*).

On four sides of the lid, there is decoration consisting of open orange rosehip flowers. The same motif, combined with a large dark-pink blooming rose, a small rosebud, and a branch of blue forget-me-nots, decorates the central white field of the main body of the small pot. All edges of the object are outlined with gilded bands. The handles remain completely undecorated and take the form of vertically hanging ring-shaped elements suspended from a small horizontally oriented ring holder. The greenery introduced into the decoration has a muted silver-grey tone with a light greenish shade.

Discussion

The analysed material demonstrates that pans, crucibles, braziers, and related heating vessels constitute a small but highly expressive group within the porcelain and faience production of Right-Bank Ukraine. Their significance lies not in their quantity, since fewer than a dozen examples are currently known, but in their typological rarity and in the complexity of their artistic, functional, and cultural meanings. These objects stand at the boundary between utilitarian cookware, tableware, and decorative art.

The earliest known example appears to be the Volhynian Korets-type heating pan of the late eighteenth or early nineteenth century, known from a photograph preserved in the archive of the Institute of Art of the Polish Academy of Sciences. Its proportions, three sculpturally modelled lion-paw supports, side handle, hemispherical lid, and finial in the form of a small lion cub indicate an object designed not merely for practical use, but also for visual presentation. The absence of painted decoration, as suggested by the photograph, reinforces the role of form and sculptural modelling as the main artistic means.

The Baranivka examples demonstrate a further development of this type. Compared with the Korets prototype, they preserve the general idea of a deep round vessel with a side handle, but modify the proportions, lid construction, and decorative system. Some Baranivka pans are decorated with a brown vine frieze and gilded bands, while others display polychrome floral painting with tulips, forget-me-nots, narcissi, daisies, cornflowers, and related motifs. The existence of hollow handles intended for a wooden holder confirms the functional nature of these objects and suggests that they could be used for heating or serving warm dishes.

The examples from the National Museum in Warsaw reveal another important aspect of the evolution of this group: the increasing decorative complexity of the lid and finial. Mushroom-shaped sculptural handles, green outlining, scattered floral motifs, “Austrian” decorative schemes, and entomological elements show that these forms were integrated into the broader decorative vocabulary of European porcelain. At the same time, their local production context and museum provenance connect them directly with the ceramic heritage of Volhynia and Right-Bank Ukraine.

The Glynsko faience heating pan from Galicia represents a related but distinct regional variant. Its light coffee-coloured faience body, three plastically modelled legs, tent-shaped lid, pineapple-shaped finial, and restrained dark outlining differ from the more richly painted porcelain examples of Korets and Baranivka. This object appears more archaic in its sculptural construction, yet it also demonstrates the influence of Austrian forms. Its comparison with Volhynian examples confirms that similar functional types were adapted differently in different regional production environments.

A separate position is occupied by the multi-portion soup vessel or pot from the Korets Porcelain and Faience Manufactory, dated to the 1815–1820s and preserved in the National Museum in Warsaw. This object is especially important because it differs from the single-handled pan or brazier type. Its ring-shaped handles, mushroom-shaped finial, gilded borders, and floral decoration in the manner of “German flowers” indicate a more representative table function. At the same time, its form refers to cooking and serving first courses, which makes it a unique transitional object between a soup tureen and a cooking pot.

The decorative programmes of the analysed objects are also significant. The motif of “German flowers” appears repeatedly and includes narcissi, tulips, roses, daisies, forget-me-nots, and rosehip flowers. These motifs demonstrate the assimilation of European porcelain painting models into the local artistic practice of Ukrainian manufactories. Ornamental friezes, gilded bands, green outlining, scattered floral patterns, and sculptural finials create a rich vocabulary of decoration that varies depending on factory, date, material, and function.

The discussion also confirms that the evolution of these forms was influenced by changes in everyday culture. These vessels were associated with the preparation, heating, and serving of substantial dishes such as roasts, stews, bigus, poultry, goose liver, and soups. Their morphology reflects this functional orientation: deep bodies, wide openings, high lids, hollow handles, supports, and finials were not accidental features but elements connected with use. At the same time, their high artistic quality shows that the boundary between kitchen utility and table representation was flexible in elite and middle-class domestic culture.

From an art-historical perspective, the objects analysed in the article should be regarded as rare evidence of the typological diversity of Ukrainian porcelain and faience. Their study makes

it possible to expand the usual understanding of Ukrainian fine ceramics beyond tea sets, plates, vases, and decorative objects. These works show that local manufactories produced specialised forms adapted to practical domestic needs while maintaining a high level of artistic design.

The limited number of preserved examples complicates the reconstruction of a complete evolutionary line. Nevertheless, the available material allows several principal typological variants to be identified: the Korets-type heating pan with a sculptural lid finial; the Baranivka saucepan-brazier with a hollow side handle and floral or ornamental decoration; the Galician Glynsko faience heating pan with a tent-shaped lid and pineapple finial; the Korets pan-ladle with a hollow handle; and the Korets multi-portion soup pot with ring handles. Together, these forms demonstrate the richness of a small but important segment of Ukrainian ceramic heritage.

Further research should focus on expanding the corpus of objects through museum inventories, archival photographs, private collections, restoration records, and comparative analysis with Polish, Austrian, French, and German ceramic prototypes. Particular attention should be given to technological examination, provenance, factory marks, material composition, and traces of use. Such research would make it possible to clarify attribution and to reconstruct more accurately the place of these forms within European ceramic culture.

Conclusion

The study makes it possible to conclude that one of the earliest known works in the group of fine ceramic table objects intended for cooking and heating food is the Volhynian form of a Korets-type heating pan from the late 18th or early 19th century, with a handle in the form of a plastically modelled lion cub. This object is known from a photograph preserved in the archive of the Institute of Art of the Polish Academy of Sciences. Later, objects of a similar functional type appeared in the production of the Glynsko Faience Factory in Galicia, where they were made around the 1830s without painted decoration, but with linear outlining. This restraint was most likely connected with the function of the object, which implied heating over fire. In Glynsko production, the form of the light coffee-coloured faience vessel included a bowl on three plastically modelled legs and a tent-shaped lid with a sculptural pineapple-shaped finial.

Korets products dated to the 1810s–1820s represent another important stage in the evolution of this group. It was apparently in Korets porcelain that pans without lids were first produced in the form of wide ladles with hollow handles intended for a wooden holder. These objects were decorated with motifs of “German flowers”, executed in hand-painted ceramic colours, with dominant narcissus, daisy, and forget-me-not motifs. In the 1820s–1830s, a similar form of porcelain pan, without the rounded lower part and close to a deep frying pan or sauté pan, was produced at the Baranivka Porcelain Factory of the Mezer family. One such object, decorated with hand-painted floral motifs in the manner of “German flowers”, with a tulip surrounded by daisies, is now preserved in the collection of the Museum of Ethnography and Artistic Crafts in Lviv.

At the same time, Baranivka also developed a segment of saucepan-braziers decorated with hand-painted ornamental friezes of vine leaves, as represented by an example in the collection of the Vinnytsia Regional Museum of Local History. Other objects were decorated with scattered small cornflowers, “Austrian” floral arrangements, and entomological motifs. More complex decorative variants were combined with plastically modelled finials in the form of

mushrooms with profiled caps, placed on flattened or convex spherical lids, depending on the size of the vessel. Such examples are preserved in the collection of the National Museum in Warsaw.

The form of a multi-portion soup bowl in the shape of a cooking pot, dated to the mid-1810s–1820s, also belongs to this group. Judging from the currently known material, this type was produced only at the Korets Porcelain and Faience Manufactory. The object, now preserved in the collection of the National Museum in Warsaw, has a bowl-shaped lid with a mushroom-shaped finial, plastically modelled ring handles, and floral decoration in the manner of “German flowers” on the body of the vessel. The dominant motif is a rose surrounded by daisies, while the lid is decorated with small rosehip bouquets and gilded bands along the rim and lower edge.

Thus, the analysis of the formal and compositional features of heating pans, saucepans, braziers, and cooking-pot forms in the assortment of porcelain and faience manufactories of ethnic Ukraine from the late eighteenth to the 19th century, some of which continued to be reproduced until the early twentieth century, shows that this is a unique segment of national decorative and applied art. These works preserve rare examples of painting, ornamentation, and local ceramic form and are now represented mainly by individual objects in museums in Ukraine and Poland.

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Conflict of Interest

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Appendix



Figure 1. Form of a Korets (?) heating pan from the late 18th—early 19th century, with a handle in the form of a plastically modelled lion cub. Photograph from the Archive of the Institute of Art of the Polish Academy of Sciences (Instytut Sztuki PAN) (*Chojnacka, 1981, p. 50*).



Figure 2. An example of a saucepan-brazier from the Baranivka Porcelain Factory, with an ornamental frieze hand-painted in ceramic colours. 1820s. Collection of the Vinnytsia Regional Museum of Local History. Photograph by O. Shkolna.



Figure 3. Saucepan-brazier. Collection of the Museum of Ethnography and Artistic Crafts in Lviv. Baranivka Porcelain Factory. 1820s–1830s. Photograph by O. Shkolna.



Figure 4. Two saucepans with lids, plastically modelled finials, and hand-painted scattered small-flower decoration and “Austrian-style” ornamental arrangements, produced by the Baranivka Porcelain Factory in the late 1820s—early 1830s. Collection of the National Museum in Warsaw.



Figure 5. Heating pan on three plastically modelled legs, with a tent-shaped lid and a sculptural pineapple-shaped finial. Faience factory in Glynsko, within the territory of the present-day Lviv region, Galicia. Milk-coloured faience of a light coffee-with-milk shade, decorated with outlining bands. Around the 1830s.



Figure 6. Porcelain pan-ladle of the Korets Porcelain and Faience Manufactory, 1810s–1820s, with hand-painted decoration based on the “German flowers” motif. Collection of the Museum of Ethnography and Artistic Crafts in Lviv.



Figure 7. Cooking pot with a plastically modelled mushroom-shaped finial, ring-shaped handles, and hand-painted decoration based on “German flowers” motifs, produced by the Korets Porcelain and Faience Manufactory in the 1815–1820s. Collection of the National Museum in Warsaw.

Copying Classical Works as a Form of Teaching “Drawing” within Students’ Independent Work ^[3]

Abstract:

This article examines the pedagogical role of copying classical artworks in the teaching of the fundamental discipline “Drawing” within contemporary design education. The relevance of the study is determined by the need to strengthen students’ professional graphic training under conditions of reduced classroom hours and the growing importance of students’ independent work. The article argues that copying the works of old masters, academic drawings, and exemplary graphic models should not be understood as mechanical reproduction, but as an analytical and creative method that develops compositional thinking, constructive understanding of form, tonal vision, technical discipline, and artistic taste. The aim of the study is to determine the role, pedagogical value, and methodological potential of copying academic artworks as a form of students’ independent work in the teaching of drawing to future designers. The study is based on a complex methodological approach that includes structural-semantic, formal-stylistic, historical-comparative, interdisciplinary, and pedagogical analysis. The research draws on the historical experience of classical art education, the legacy of the old masters, and modern approaches to the organisation of independent learning in higher education. The article substantiates the educational, developmental, and formative functions of copying and proposes a staged methodology for its implementation: selection of an appropriate model, compositional analysis, constructive construction of the drawing, tonal modelling, and final synthesis. It is concluded that copying classical works can compensate for the limited time allocated to classroom drawing practice, deepen students’ understanding of artistic principles, and contribute to the formation of individual professional style. The proposed approach may be used by teachers of design and fine arts departments when developing curricula, methodological recommendations, and assignments for students’ independent work.

Keywords: copying, academic drawing, design education, students’ independent work, graphic training, classical artworks, art pedagogy.

Introduction

“Drawing” is one of the fundamental disciplines in the professional training of designers and representatives of other creative specialities. It provides the basis for the formation of artistic and aesthetic qualities, technical skills, visual literacy, and theoretical knowledge. Through drawing assignments, students acquire the principles of compositional organisation, constructive form-building, linear and aerial perspective, proportional relationships, tonal modelling, and the plastic representation of objects.

The relevance of this study is determined by the current transformation of higher art and design education. In many educational programmes, the number of classroom hours allocated to fundamental artistic disciplines, including drawing and painting, has been reduced, while the amount of time assigned to students’ independent work has increased. Under these conditions, the problem of organising effective independent work becomes especially important. Students must not only consolidate what they learn in the classroom, but also continue developing professional visual thinking, technical accuracy, and analytical skills outside direct teacher supervision.

One of the productive forms of such independent work is copying classical works of art, drawings by old masters, and high-quality academic examples. This method has been practised

for centuries in European art schools and academies. It allows students to analyse compositional decisions, methods of hatching, constructive form-building, tonal relationships, stylistic features, and the individual artistic language of outstanding masters. In this respect, copying is not merely a technical exercise. It has important intellectual and analytical value, since it helps students understand how an image is constructed, how artistic means are selected, and how visual form is transformed into an expressive artistic whole.

The research problem lies in the contradiction between the reduced time available for classroom drawing practice and the continuing need to provide future designers with strong academic and analytical training. At the same time, the method of copying is sometimes perceived narrowly as a mechanical reproduction of an existing model. Such an understanding does not reflect its real pedagogical potential. In contemporary design education, copying should be reconsidered as a conscious analytical method that links technical training with the development of professional thinking and creative individuality.

The scientific novelty of the study consists in interpreting the copying of classical and academic works not as an auxiliary or secondary task, but as a structured form of students' independent work within the discipline "Drawing". The article clarifies the pedagogical functions of copying in design education, identifies its methodological stages, and substantiates its value for the formation of analytical thinking, technical skills, artistic taste, and individual creative style.

The object of the study is the process of professional training of students of art and design specialities in higher education. The subject of the study is the copying of classical and academic artworks as a pedagogical method within students' independent work in the discipline "Drawing".

The study aims to determine the role of copying academic artworks as a form of learning within students' independent work in the teaching of "Drawing", and to define its pedagogical value and specific features of application in design education.

To achieve this purpose, the study addresses the following objectives:

- to analyse the historical evolution of copying as an effective method of teaching drawing;
- to determine the pedagogical functions of copying in the formation of the future designer's analytical thinking;
- to identify the relationship between copying, academic drawing, composition, perspective, anatomy, and art history;
- to define methodological principles for selecting works for copying according to students' level of preparation;
- to develop a staged algorithm for copying academic works within students' independent work;
- to determine the significance of copying for the development of professional graphic skills and creative individuality.

The theoretical basis of the research includes the pedagogical and methodological heritage of the classical school, including the principles of academic drawing and constructive analysis of form, as well as contemporary studies in art pedagogy devoted to continuity of tradition and the actualisation of classical heritage in design education. The study takes into account the

experience of drawing pedagogy associated with the old masters, classical academies, and modern educational practice.

The theoretical significance of the study lies in clarifying the pedagogical meaning of copying as a conscious analytical and interpretative process rather than as mechanical repetition. The practical significance lies in the possibility of using the proposed methodological approach in the development of curricula, independent assignments, teaching recommendations, and assessment criteria for students of design and fine arts departments.

Methods

The study applies a qualitative pedagogical and art-historical methodology aimed at analysing the role of copying classical and academic works in the teaching of drawing. The methodological framework combines structural-semantic analysis, formal-stylistic analysis, historical-comparative interpretation, interdisciplinary integration, and pedagogical modelling of students' independent work.

Copying academic works should primarily contribute to the development of analytical thinking rather than become a mechanical repetition of a selected model. Before beginning the practical task, the student should analyse the image. The artists whose works are copied have already analysed nature, selected essential elements, found artistic solutions, and, where necessary, simplified, generalised, or even stylised the represented object. The student must understand how this artistic transformation is achieved and then apply this understanding when working from nature (*Borysov, 2002*).

The method of structural-semantic analysis involves dividing an integral work of art into its components and identifying the internal relations between them. The analysis begins with the composition: whether it is static or dynamic, whether it is based on contrast or nuance, whether it has a compositional centre or appears deliberately chaotic. This approach helps students understand the logic of the author and move from mechanical copying to conscious reproduction of artistic methods (*Mabalias, 2019*). At this stage, it is necessary to consider the laws of composition previously studied in the corresponding discipline, but to interpret them through the specific requirements of drawing.

The next stage is the analysis of form construction. The formal-stylistic method makes it possible to study the specificity of form-building, the character of line, tonal modelling, and the material basis of the work. It enables students to analyse the structure of form and to understand the artistic "language" of great masters. This method supports the gradual development of the assignment: from linear-constructive analysis to deeper tonal modelling with the use of different graphic materials (*Hale, 2009; Mahalias, 2019*). The student should understand, observe, and determine how the structure of form is conveyed in the work being copied.

The selection of models for copying should follow the sequence and logic of classroom assignments. When students learn to draw geometric forms in class, their independent work should include copies based on simple geometric structures. When they study plaster heads, they should copy examples of classical head drawings. When they work with the human figure, they should copy works that contain full-figure studies. Such correspondence between classroom practice and independent work allows copying to function as an extension of the educational process rather than as an isolated exercise.

Given the limited time allocated to the teaching of drawing in design education, classroom practice often focuses mainly on linear-constructive work. More attention is given to the constructive building of form by means of line, sometimes at the expense of tonal development. In a traditional academic setting, work with light and shadow usually takes place at the final stage and requires considerable time. Students' independent work can partly compensate for this imbalance. If copying is understood as a continuation of classroom study, the execution of copies should also include analysis of how the author uses tonal relations and chiaroscuro.

When more creative tasks are assigned, a wide range of tonal drawings may be selected for copying. In such works, the line may be less dominant, while the artist concentrates on the relationships between light and shadow. Soft materials such as charcoal, sepia, and sanguine are often used in these cases. Copying such examples allows students to become familiar with the expressive potential of different graphic materials and to develop sensitivity to tone, texture, and atmospheric modelling (*Hale, 2009; Piddubna, 2012*).

Copying also supports interdisciplinary integration. It connects drawing with composition, perspective, anatomy, and art history. Work with the drawings of outstanding artists gives students a deeper, almost tactile acquaintance with the history of art. Through copying, students engage with the achievements of world and national culture, learn different styles and artistic traditions, and observe the individual features of different masters. For example, Michelangelo demonstrates the dynamism of movement and the expressive tension of the human body; Albrecht Dürer shows the precision of linear drawing; Ingres represents academic refinement; Goya reveals the force of expressive gesture; and Rembrandt van Rijn demonstrates deep tonal modelling (*Cennini, 2012; Hale, 2009*).

The study also uses pedagogical modelling to formulate a staged methodology for copying classical drawings within students' independent work. This methodology includes the following stages: selection of a work appropriate to the student's level and current classroom topic; preliminary analysis of composition; constructive construction of the drawing from the general form to details; analysis and reproduction of tonal relationships; final synthesis and harmonisation of details. This sequence transforms copying into a structured educational process and helps students develop both technical and analytical competence.

The methodological limitations of the study should also be noted. The article is theoretical and methodological in nature and does not include a quantitative assessment of students' learning outcomes. Further empirical research may test the proposed methodology in different design programmes, compare student progress before and after copying assignments, and develop assessment criteria for different levels of academic and creative performance.

Literature Review

The methodology of academic drawing, particularly the role of copying as an instrument of professional training, remains an important subject of scholarly discussion in art pedagogy. The problem is especially relevant for contemporary design education, where the reduction of classroom hours in fundamental artistic disciplines requires a reconsideration of traditional teaching methods and their transfer into the sphere of students' independent work. In this context, copying classical and academic works should not be interpreted as a mechanical

reproduction of an existing visual model, but as a complex analytical, technical, cultural, and pedagogical practice.

The historical continuity of the copying method, from antiquity through the Renaissance and Baroque periods, has been analysed in detail by Strieltsova and Zaitseva (2022). Their research demonstrates that the formation of “old master” schools was based on the transmission of artistic knowledge through direct observation, imitation, repetition, and gradual interpretation of established models. This historical perspective is important because it shows that copying functioned not merely as a technical exercise, but as a mechanism of professional succession. Through copying, students entered an artistic tradition, mastered the language of form, and gradually acquired the ability to transform inherited models into individual artistic practice.

The same logic can be observed in the creative biographies of outstanding artists. The experience of Taras Shevchenko, for example, confirms that copying and the study of classical models can become an important stage in the formation of an individual artistic language (Skliarenko, 2013; Yatsiuk, 2004). Shevchenko’s early academic works demonstrate the transition from the assimilation of classical plots and compositional schemes to the development of a national and personal artistic vision. This example is pedagogically significant because it refutes the simplified idea that copying suppresses creativity. On the contrary, when properly organised, copying may become a preparatory stage for the emergence of creative independence.

The methodological foundations of constructive form analysis, which underlie high-quality copying, are based on the classical theories of Bridgman (2012) and Hale (2009). Bridgman’s constructive approach emphasises the internal structure of the human body, the logic of volume, and the transformation of anatomical knowledge into graphic form. Hale, in turn, focuses on the study of drawings by great masters as a way to understand proportion, line, tonal modelling, plasticity, and the expressive organisation of the figure. Both authors are important for the present research because they treat drawing as an intellectual process: the artist does not merely reproduce the visible surface of the object, but analyses its construction, movement, rhythm, and internal logic.

This analytical understanding of copying is also supported by contemporary Ukrainian researchers. Mahalias (2019) examines copying and sketching as methodological tools for forming drawing skills and emphasises that the student must learn to identify the structure of the image, the logic of the line, and the system of tonal relationships. Prokhorova (2016) considers academic drawing as a foundation of creative literacy and argues that drawing develops not only technical accuracy, but also the ability to think visually. These approaches are particularly important for design education, where drawing is not an isolated artistic discipline, but a basic means of professional visual thinking.

A separate group of studies addresses the organisation of students’ independent work in higher education. Stebliuk (2024), Kvetsko (2023), and Piddubna (2012) examine the possibilities of interdisciplinary integration and the adaptation of traditional artistic disciplines to contemporary university education. Their works show that independent work becomes effective only when it is methodologically structured and meaningfully connected with classroom practice. In this regard, copying classical and academic works may become a productive continuation of classroom assignments. It allows students to deepen the skills that

cannot always be fully developed during limited classroom time, especially tonal modelling, detailed analysis of form, and work with different graphic materials.

The interdisciplinary potential of copying is also significant. Copying connects drawing with composition, perspective, anatomy, art history, material studies, and visual culture. It allows students to understand how the same artistic problem may be solved through different historical styles, techniques, and individual manners. For example, the study of Renaissance and Baroque drawings may reveal the principles of dynamic movement, anatomical construction, and expressive plasticity; the analysis of academic drawings may clarify proportion, tonal hierarchy, and compositional balance; and the copying of works by later masters may demonstrate the transformation of classical principles into more individual artistic languages. Thus, copying becomes not only a technical task, but also a form of visual research.

At the same time, the reviewed literature makes it possible to identify several unresolved issues. First, while the historical importance of copying in art education is well established, its methodological role in contemporary design education has not been sufficiently defined. Secondly, many studies emphasise the value of academic drawing, but do not always specify how copying should be organised within students' independent work. Thirdly, the criteria for assessing copying tasks remain insufficiently developed: it is not always clear whether the teacher should evaluate visual similarity, technical accuracy, analytical understanding, or the student's ability to transform the acquired experience into independent design thinking.

Borysov (2002; 2003) draws attention to the need for a balanced approach to the selection of educational material in design education. This position is important because improperly selected copying tasks may lead to formalism, superficial imitation, or passive reproduction of artistic models. The pedagogical value of copying depends on the correspondence between the selected work, the student's level of preparation, the current classroom task, and the broader objectives of professional training. For example, a first-year student may benefit more from copying works with clear constructive structure, while senior students may work with more complex examples involving dynamic composition, anatomical complexity, tonal richness, or expressive stylisation.

The analysis of the literature also shows that copying should be understood as a transitional mechanism between academic tradition and individual creative development. At the initial stage, the student learns discipline, accuracy, proportion, line, and tonal modelling. At a deeper stage, copying develops analytical thinking: the student begins to understand why the master chose a particular compositional solution, how the form is generalised, how the line organises the image, and how light and shadow reveal volume. At the final stage, the acquired knowledge may be transformed into the student's own artistic and design practice. Therefore, copying does not contradict creativity; rather, it provides a professional foundation for it.

In the context of modern digitalisation, the problem of copying receives an additional dimension. Digital technologies provide students with access to a wide range of classical works and allow them to analyse images in detail. However, the use of digital tools also raises the question of whether the tactile and material experience of traditional drawing may be weakened. This issue remains insufficiently studied in the literature and requires further pedagogical and empirical research. For the purposes of the present article, it is important to emphasise that digital access to classical works may support the copying method, but should not replace the

manual experience of drawing, through which the coordination of eye, hand, material, and analytical perception is formed.

Thus, the existing scholarship confirms the pedagogical value of copying in academic drawing, but also indicates the need to reinterpret this method within the context of contemporary design education. The reviewed studies demonstrate that copying becomes most effective when it is integrated with constructive analysis, art-historical knowledge, technical training, interdisciplinary connections, and students' independent work. However, the problem of developing a clear methodological algorithm for copying classical works within design education remains insufficiently elaborated. This research gap determines the relevance of the present study, which aims to define copying as a structured, analytical, and pedagogically meaningful form of students' independent work in the discipline "Drawing".

Results

Historical Development of the Copying Method in Art Education

Copying as a teaching method has a long history. As early as antiquity, a similar practice existed in the training of artists and sculptors. In Ancient Greece and Rome, students began their training with the elementary repetition of the works of their mentors; they then executed secondary details, filled in the background, worked from the teacher's sketches, and only afterwards began their own artistic path. However, everything started with copying. This method of teaching made it possible to transmit technical methods and professional knowledge from teacher to student, and this process of continuity led to the formation of entire schools and workshops (*Strieltsova & Zaitseva, 2022*).

This established form of teaching is especially traceable during the Renaissance, when copying became an important component of art education. Through copying, future artists studied, among other things, anatomy, linear and aerial perspective, methods of compositional solution, and, naturally, copied the works of their mentors. Considerable attention was paid to copying ancient sculpture, which was a particularly popular method.

Such outstanding artists of the Renaissance as Leonardo da Vinci, Michelangelo Buonarroti, and Raphael Santi actively practised copying and studying works from the ancient period during their training and at the beginning of their creative activity (*Cennini, 2012; Stebliuk, 2024*).

In the Middle Ages, art significantly changed its priorities and moved away from the ideals of the Renaissance, but copying became not only a teaching method, but also a principle of art-making.

With the emergence of various schools and academies in the seventeenth–nineteenth centuries, the method of copying became the foundation of classical art education. Along with drawing from plaster models and from life, students of leading European academies made copies from old engravings and copied drawings by masters. This process was divided into several stages, but continued throughout the entire period of study. Such an approach to the education system was used in many European academies, particularly in the Paris Academy of Arts, founded in 1799 (*Kvetsko, 2023*).

The outstanding genius of the Ukrainian people, Taras Hryhorovych Shevchenko, began his creative path by copying works of world art. This is evidenced by his early period of study,

in particular in the drawing classes of the Society for the Encouragement of Artists: from drawing park sculpture to the cycle of drawings executed in 1835–1837. These works were executed in the style of classicism, which was a mandatory requirement of academic education at that time (*Skliarenko, 2013; Yatsiuk, 2004*).

The Death of Lucretia (1835): a watercolour drawing, the subject of which is taken from the legend of the great Roman woman.

The Death of Virginia (1836): illustrates dramatic events from Roman history.

The Death of Socrates (1837): depicts the ancient Greek philosopher Socrates at the final moment of his life.

The work of T.H. Shevchenko shows a natural transition from purely academic ancient subjects to national historical themes.

Copying was not always recognised and valued in many movements and styles of art; this is especially true of the twentieth century, when the role of copying changed somewhat. With the emergence of new artistic ideas and the development of modernist movements, greater attention began to be paid to creative personality and the manifestation of individual identity. However, in academic art education, even in contemporary art educational institutions, copying classical works, the works of “old masters”, and works from institutional collections remains an important educational tool. Even Pablo Picasso, in the early stages of his creative work, copied the works of classical masters, which helped him develop his own artistic principles.

Thus, copying has passed from the ancient craft tradition of transmitting experience to a fundamental academic method that became an integral part of the professional training of artists. Its effectiveness, tested over centuries, proves that even under conditions of the rapid development of new visual technologies, direct contact with the classical heritage remains a key factor in forming the professional consciousness of the artist, since it allows the student, through the analysis of works by great predecessors, to comprehend the deep laws of composition, form, and style, thereby laying a solid foundation for further creative self-realisation.

Implementation of Pedagogical Functions in Copying Classical Works

The pedagogical functions of the teacher in teaching copying are certain areas of activity designed to ensure the harmonious development of the student both as an artist and as an integral personality. They must ensure the effectiveness of the educational process.

The educational function ensures the transmission of a system of theoretical knowledge, technical abilities, and skills that will help the student in further professional activity.

The formation of technical professional skills may be attributed to the educational function in copying academic works of art and drawing in particular. In the process of making copies, the student has the opportunity to study various artistic and technical features of drawing (*Kvetsko, 2023; Mahalias, 2019*).

First of all, for educational drawing, understanding the constructive construction of form is important. It is important not to simply copy the external appearance, but specifically to construct the form, whether it is the form of simple objects or the form of the human figure.

The second important point is the understanding and knowledge of proportion, especially when depicting the human body. The “old” masters had knowledge of human anatomy and

used this knowledge in their creative work. For example, proportions are very important in conveying the age and gender characteristics of a person.

At the initial stage of learning, it is useful to copy examples in which linear and aerial perspective are used. In such examples, the existing laws can be traced more clearly than from nature. What may be barely visible or hidden when observing living nature is more clearly visible in works selected for copying, since analysis has already been carried out and an appropriate solution has been found.

When analysing artistic and stylistic features, the student must understand and then use in further practice the technical methods and properties of materials. Attention should be paid, for example, to the character of the stroke, its direction, strength, activity, aggressiveness, emotionality, whether it is applied according to the form or chaotically, and its density ([Hale, 2009](#); [Pidubna, 2012](#)).

The student should analyse the tonal relationships used in the work being copied and adopt successful approaches and techniques. This will be especially useful for those students who, due to personal preferences, are inclined towards a more tonal execution of drawing.

The next function is formative. It helps to form the student's worldview and moral values and to influence the culture of behaviour and social adaptation of the personality. Copying monuments of world culture, whether directly or indirectly, influences the cultural level of the performer and accustoms the student to working according to certain algorithms.

The developmental function, in physiological terms, ensures the development of hand motor skills and visual acuity; in psychological terms, it develops emotional and mental processes, including thinking and memory, stimulates the creative potential of students, their abilities, and cognitive activity.

The development of artistic taste is also important. In addition to knowledge of art history, acquaintance with the best examples of world culture contributes to the formation of artistic taste and aesthetic thinking in future designers. Without a sense of beauty, harmony, and style, it is impossible to create things that are, first of all, functional, but at the same time aesthetic.

Adherence to such pedagogical functions in the learning process will help form a strong professional culture of drawing in future designers.

Thus, the implementation of a complex of pedagogical functions in the process of copying transforms a purely technical exercise into a powerful instrument of comprehensive professional development of the student. Through disciplined imitation of the best examples of art, the future designer not only acquires the necessary technical tools, but also cultivates inner culture, develops an analytical view of the world, and forms an aesthetic ideal, which will later allow the designer to confidently operate with the complex categories of harmony, proportion, and style when solving contemporary functional and creative tasks.

Methodology for Copying Classical Drawings

Since copying takes place within students' independent work, the student performs the task independently at home or in specially designated university workshops. The teacher gives general instructions on the organisation of the work according to a certain methodology and evaluates the result.

Selection of a work for copying. The process of copying should be a continuation of classroom assignments. In accordance with this requirement, the model for copying is selected. To achieve educational goals, it is recommended to choose works of appropriate complexity. For example, in the first year, examples that have a clear constructive structure should be selected. It is useful to use students' drawings on a given topic that were selected during previous reviews and are preserved in the department's collections. In senior years, it is already possible to turn to world classics. Modern means of information eliminate the need to visit museums for this purpose, although the latter is more beneficial.

The purpose of copying may also include such aims as becoming acquainted with different graphic techniques. In this case, examples are selected that demonstrate the artistic qualities of a particular material or instrument.

An important point in the contemporary educational process is the need to take into account the individual characteristics of the student. Therefore, examples for copying must be selected according to the student's level of preparation and individual style. Even when copying the works of others, the student must develop their own artistic manner and handwriting.

Analysis of composition. It is important to accustom the student to the correct algorithm for performing the work. Before beginning the work, the student must analyse the work of art. The student should consider compositional methods, the general character of the composition, and determine the compositional centre. When depicting the human figure, attention should be paid to proportions, the plasticity of the body, and movement.

If the goal is to study a particular artistic technique, then the character of the lines and strokes is analysed first.

Construction of the drawing. Constructive construction in copying, as in academic drawing, begins with the large, general form. Analysis is then carried out gradually: we move from the large to the small. We trace and determine the main proportions in the original and transfer them to our own work. We work through the details and move to synthesis, that is, generalisation, subordinating all elements of the composition to an integral appearance.

Work with light and shade. This is the next stage. In working with tonal relationships, the student must determine the general area of shadow and light; work begins with the treatment of the shadow. Then the student gradually moves from the darkest to the lightest areas. If this algorithm is not followed and the work begins with the light, the strength of tone in the shadow may be insufficient.

Completion of the work. Work with tone finalises the work on the copy; the details are clarified and the general tonal structure of the drawing is harmonised.

Thus, a clearly structured methodology of copying becomes an effective algorithm of professional growth, in which the student's independent work is transformed into a conscious research process. Consistent observance of the stages—from compositional analysis and construction of the general form to the subtle treatment of light and shade and the final synthesis of details—makes it possible not only to acquire the necessary technical skills, but also to develop the ability to systematise complex artistic tasks, which is an integral component of the designer's professionalism and a prerequisite for successfully mastering various graphic techniques for the realisation of their own creative ideas.

Discussion

The study demonstrates that copying classical works can become an effective pedagogical instrument in contemporary design education if it is understood not as passive imitation, but as a form of analytical reconstruction. This interpretation is especially important in the context of reduced classroom hours in the discipline “Drawing”. The central challenge is the tension between the long-term academic nature of drawing training and the current need for flexible, intensive, and individualised educational models for future designers.

The first important issue concerns the distinction between mechanical reproduction and conscious interpretation. In traditional academic practice, copying was often associated with discipline, accuracy, and technical imitation. In contemporary design education, however, its value lies primarily in the student’s ability to identify the logic of the master’s artistic thinking. The quality of the copy should therefore not be assessed only by external similarity to the original. It should also be evaluated according to the student’s understanding of composition, form construction, proportional relations, tonal structure, rhythm of line, and expressive use of material.

This point is particularly significant for students of design. Unlike students whose main professional aim is easel art, future designers must learn to analyse visual structures and transform them into new functional and communicative solutions. Copying classical works can help them acquire a disciplined visual method: to see the whole before the detail, to distinguish structure from surface effect, to understand the hierarchy of elements, and to subordinate technical means to an artistic purpose. In this sense, copying may contribute not only to drawing competence, but also to broader design thinking.

The results also confirm the pedagogical importance of integrating copying with other disciplines. When copying is linked with composition, perspective, anatomy, art history, and material studies, it becomes a multidimensional educational practice. It allows students to understand that drawing is not an isolated skill, but a synthetic visual language. This interdisciplinary function is especially valuable in design education, where professional competence depends on the ability to combine artistic, technical, historical, and conceptual knowledge.

Another important issue is the role of the teacher in the organisation of students’ independent work. Since copying is performed outside regular classroom time, there is a risk that the task may become formal or superficial. To prevent this, the teacher should provide not only the model for copying, but also clear analytical instructions, staged requirements, and assessment criteria. Feedback should address both the technical execution and the student’s analytical decisions. In this way, students’ independent work becomes a guided research process rather than a purely reproductive exercise.

The question of model selection is equally important. The copied work should correspond to the student’s level of preparation, the current classroom assignment, and the pedagogical goal. For first-year students, it is advisable to select models with clear constructive structure and relatively simple tonal relations. At later stages, students may work with more complex examples from the old masters, including figure drawings, dynamic compositions, and works executed in different graphic materials. Such progression helps avoid both excessive simplification and premature complexity.

A further discussion concerns the relationship between copying and the development of individual style. At first glance, copying may seem to contradict the idea of creative individuality. However, the historical experience of art education shows that many great artists developed their own visual language through the study and reinterpretation of earlier masters. The pedagogical purpose of copying is not to suppress individuality, but to provide students with a professional foundation from which individual solutions can later emerge. A student who understands the logic of classical form, line, proportion, and tone is better prepared to depart from tradition consciously rather than accidentally.

The role of digital tools also requires special attention. Contemporary students increasingly use digital tablets, image archives, and graphic software. These tools can expand access to visual material and support detailed analysis, scaling, and comparison. At the same time, digital copying may reduce the tactile experience associated with traditional materials such as pencil, charcoal, sepia, or sanguine. Therefore, the integration of digital tools should be balanced. Digital technologies may be useful for preliminary study and analysis, but they should not fully replace the manual experience through which eye, hand, material, and perception develop together.

The study also reveals a broader cultural dimension of copying. Through contact with classical works, students enter into dialogue with the history of world and national art. This contributes to the formation of artistic taste, cultural memory, and professional self-awareness. In the education of designers, this is particularly important because design solutions are always connected with visual culture, symbolic systems, and aesthetic values. Copying helps students perceive classical heritage not as a static museum phenomenon, but as a living source of visual methods and artistic thinking.

The proposed methodology has several practical implications. It may be used in the development of independent assignments, methodological guidelines, and assessment rubrics for the discipline “Drawing”. It may also help compensate for the reduced number of classroom hours by transferring part of the analytical and technical workload into structured independent practice. For this purpose, copying assignments should be included in curricula as a regular and systematic component rather than as an occasional supplementary task.

At the same time, the study has limitations. It is primarily theoretical and methodological and does not present quantitative data on student achievement. Future research should include empirical testing of the proposed methodology in design programmes, comparative analysis of student works before and after systematic copying tasks, and the development of criteria for assessing analytical understanding, technical quality, and creative transformation. It would also be useful to compare the effectiveness of traditional and digital copying formats.

Thus, copying classical works remains relevant in contemporary design education when it is methodologically organised and pedagogically interpreted as an analytical, developmental, and creative practice. It preserves the continuity of academic tradition while adapting it to the needs of modern visual education and the professional formation of future designers.

Conclusion

The study substantiates that, under contemporary conditions of design education, where there is a shortage of classroom hours, copying classical works of art and academic examples within students’ independent work becomes an important instrument of professional

development. To a certain extent, it helps compensate for the lack of time allocated to classroom drawing practice. The historical development of this method has shown that, from antiquity to the present day, copying has remained one of the foundations of artistic education. Many outstanding artists began their creative path through copying. The continuity of experience demonstrated by the creative biographies of artists from Leonardo da Vinci and Raphael to Taras Shevchenko and Pablo Picasso proves that copying is not a mechanical repetition, but a deep intellectual analysis of artistic form and nature.

The analysis of pedagogical functions has shown that copying ensures the comprehensive development of the student. It performs an educational function through the acquisition of technical skills, including hatching, constructive form-building, and tonal modelling. It performs a formative function by introducing students to the world's cultural heritage. It also performs a developmental function through the improvement of hand motor skills, visual accuracy, analytical thinking, knowledge of art history, and the formation of artistic taste. Over time, this knowledge may be transformed into the student's own creative style.

In the process of copying, the student does not merely reproduce an image, but analyses artistic techniques, compositional structure, and the principles of form construction. The proposed methodology, which includes staged work from compositional analysis and linear-constructive construction to final tonal modelling, allows students to systematise educational tasks and consciously approach the formation of their own creative manner.

The results of the study make it possible to state that copying classical works of art is an important method in the teaching of the discipline "Drawing". It organically combines classical academic traditions with contemporary requirements for the training of designers. The method has considerable pedagogical potential: it contributes to the formation of professional skills, develops observation, strengthens understanding of compositional structure, and supports deeper assimilation of artistic principles that later transform into the professional style of the future specialist.

Despite the rapid digitalisation of art education, copying remains relevant and necessary because it provides a basis for developing analytical thinking and intellectual preparation. Further research may focus on adapting the principles of copying to the digital environment and on developing new assessment criteria for students' independent work in contemporary art and design schools.

Therefore, copying classical works is an effective pedagogical tool that helps connect the traditions of academic art with modern approaches to artistic and design education.

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Conflict of Interest

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Lawful Use of Copyright Objects in Student Design Projects in the Context of Digitalization and Artificial Intelligence Development ^[4]

Abstract:

The article examines current issues of copyright compliance in the development and presentation of student design projects under conditions of the total digitalisation of the educational environment and the rapid expansion of artificial intelligence technologies. The relevance of the study is determined by the fact that student design projects increasingly go beyond the limits of internal academic assignments: they are published in open portfolios, submitted to professional competitions, and may become the basis for commercial start-ups. This creates legal, ethical, and reputational risks when visual content, fonts, illustrations, generative AI outputs, or other copyright-protected materials are used without proper authorisation. The article analyses the distinction between lawful conceptual inspiration and unlawful appropriation of visual content. Particular attention is paid to the challenges arising from the use of generative AI models, including Midjourney, DALL·E, and Stable Diffusion, in educational and creative practice. The study considers the legal status of AI-generated objects, licensing limitations of digital platforms, commercial risks for clients, and the need to develop legal awareness among future designers. The methodological basis of the research includes a systematic approach, logical analysis, legal and comparative analysis, and the use of the “Process book” as an evidentiary tool for documenting the stages of project development. The article proposes practical measures for ensuring academic integrity in higher art and design education: updating syllabi, regulating the permissible use of generative AI, introducing visual anti-plagiarism tools, maintaining a “Process book”, conducting patent research, and developing students’ competence in working with open licences. It is concluded that knowledge of copyright law and responsible use of artificial intelligence must become an integral component of the professional competence of contemporary designers.

Keywords: copyright, graphic design, artificial intelligence, generative AI, neural networks, academic integrity, visual content, digitalisation, Process book, patent research, visual anti-plagiarism.

Introduction

The contemporary stage of development of the creative industries is characterised by unprecedented rates of technological transformation. The digitalisation of the educational environment and the emergence of new tools for generating visual content are fundamentally changing the methodology of training future specialists in graphic design. In this context, a student design project ceases to be exclusively an internal educational exercise. It acquires the status of a full-fledged object of intellectual property, which may be published in open portfolios, participate in international competitions, and often become the basis for commercial start-ups.

At the same time, the openness of global network resources creates among students the illusion of the “general availability” of any digital content. This leads to unconscious copyright infringements that not only reduce the quality of professional training, but also create serious reputational and legal risks for the student, the higher education institution, and future employers. The problem becomes especially acute in the context of the rapid spread of generative artificial intelligence, since students increasingly use visual materials created or modified by neural networks without understanding their legal status, licensing restrictions, or limits of lawful use.

The relevance of this study lies in the need to develop a clear methodological, legal, and ethical framework for the use of copyright objects in student design projects. In contemporary design education, the future specialist must master not only visual composition, typography, branding, illustration, and digital technologies, but also the principles of lawful work with intellectual property. Legal culture is therefore becoming an essential part of professional competence in graphic design.

The research problem is determined by the contradiction between the active use of open digital resources and generative AI tools in student design practice, on the one hand, and the insufficient methodological regulation of such use in higher education institutions, on the other. Although Ukraine has an updated Law “On Copyright and Related Rights” (*On Copyright and Related Rights, 2022*), several unresolved issues remain in the pedagogical practice of art and design departments. These include the lack of a unified methodology for assessing the student’s independent creative contribution in projects created with the involvement of generative AI; the absence of effective algorithms for identifying and preventing visual plagiarism; and the insufficient standardisation of syllabi regarding the limits of AI use by students.

The object of the study is the current issues of compliance with copyright norms in the process of developing and presenting student design projects under conditions of the total digitalisation of the educational environment and the challenges arising for higher education institutions due to the massive introduction of generative artificial intelligence models into creative practice.

The subject of the study is the legal, ethical, technological, and methodological aspects of the lawful use of copyright objects, digital visual content, fonts, generative AI outputs, and other intellectual property elements in student design projects.

The aim of this article is to provide a comprehensive analysis of the legal, ethical, and technological aspects of the lawful use of copyright objects in student design projects and to develop practical recommendations and methodological tools for ensuring academic integrity under conditions of artificial intelligence expansion.

To achieve this aim, the study addresses the following objectives:

- to analyse the main copyright risks that arise in student design projects in the context of digitalisation;
- to define the distinction between conceptual inspiration, moodboarding, lawful reference use, and direct visual plagiarism;
- to examine the legal and ethical challenges connected with the use of generative AI models in design education;
- to determine the risks associated with the commercial use of AI-generated visual content;
- to justify the need to update syllabi and introduce clear rules for the use of AI in student projects;
- to consider the “Process book” as a tool for documenting authorship and the stages of project development;
- to substantiate the importance of patent research, visual anti-plagiarism systems, and open licensing literacy in the professional training of designers.

The scientific novelty of the study consists in considering the lawful use of copyright objects in student design projects not only as a legal issue, but also as a methodological and pedagogical problem of contemporary design education. The article connects copyright compliance, academic integrity, AI regulation, project documentation, and the formation of professional legal culture within one educational framework.

The theoretical significance of the study lies in clarifying the conceptual boundaries between inspiration, reference, borrowing, plagiarism, and AI-assisted generation in design education. The practical significance lies in the proposed tools that may be used by art and design departments: updated syllabi, mandatory documentation of the design process, requirements for AI labelling, visual anti-plagiarism procedures, and basic patent research. These measures may help reduce legal and reputational risks and improve the quality of professional training for future designers.

Methods

The study is based on a qualitative, interdisciplinary methodology that combines legal analysis, pedagogical analysis, design methodology, and the study of digital creative practices. The choice of methods is determined by the complex nature of the research object, since the lawful use of copyright objects in student design projects is simultaneously a legal, ethical, educational, technological, and professional issue.

The systematic approach was used as the principal general scientific method. It made it possible to consider the object of research as a complex system of interconnected elements: copyright law, academic integrity, digital visual culture, generative artificial intelligence, design education, project documentation, patent research, and professional responsibility. This approach is important because copyright violations in student design projects cannot be reduced to isolated cases of unlawful borrowing. They are connected with the broader structure of educational practice, the availability of digital content, the lack of legal literacy, and insufficient regulation of AI tools in curricula.

The logical method was applied to study the object of research in its internal sequence. It allowed the analysis to move from the general legal principles of copyright protection to specific problems of student design practice. The logical structure of the study includes the following stages: identification of protected copyright objects; differentiation between ideas and forms of expression; analysis of lawful and unlawful use of visual content; examination of AI-generated objects; identification of commercial and reputational risks; and development of practical methodological recommendations.

The legal analysis method was used to interpret the main provisions of Ukrainian copyright legislation and to determine their relevance for student design projects. Particular attention was paid to the principle according to which copyright protection applies to the form of expression of a work, but not to ideas, processes, methods, concepts, or stylistic directions as such (*On Copyright and Related Rights*, 2022). This method made it possible to clarify the boundary between lawful inspiration and unlawful appropriation of protected visual form.

The comparative method was applied to examine the differences between traditional copyright objects created by human authors and objects generated by artificial intelligence systems. It was also used to compare the legal status of AI-generated outputs, licensing

restrictions of digital platforms, and the practical needs of design education. The comparative perspective is necessary because the legal status of AI-generated content is still developing and is not interpreted uniformly across different jurisdictions (*Shtefan, 2023; Tarasenko, 2024; Yavorska, 2017; Yushyna, 2023*).

The method of content analysis was used to examine educational and professional materials related to the use of digital content in design projects. This included the analysis of project documentation practices, syllabus requirements, licensing conditions, visual references, moodboards, and process-based evidence of authorship. This method helped identify the practical points at which copyright risks most often arise: image selection, use of fonts, use of third-party illustrations, generation of visual content by AI, and presentation of final projects.

The methodological tool of the “Process book” was considered as a specialised method for documenting the development of a design project. The “Process book” makes it possible to obtain a general understanding of the project under development and to record all stages of the design process: preliminary research, references, sketches, drafts, intermediate iterations, compositional solutions, AI prompts if used, and final layout decisions (*Endo, n.d.*). In the context of this study, the “Process book” is interpreted not only as a design education tool, but also as an evidentiary base for confirming the student’s authorship and independent creative contribution.

The method of patent research was included as a practical research procedure relevant to the training of future designers. Patent research allows students to check whether a proposed visual solution, sign, logo, industrial design, or other element of a project is novel and does not infringe existing rights. The methodological basis for this component is provided by the State Standard of Ukraine on patent research, which defines the general provisions, procedure, and reporting form for such studies (*National Academy of Sciences of Ukraine, n.d.*).

The study also used a pedagogical modelling method. It made it possible to formulate recommendations for improving educational practice in design departments. These recommendations include updating syllabi, introducing mandatory rules for AI use and labelling, requiring students to document the design process, integrating visual anti-plagiarism systems, and developing students’ competence in open licences and font licensing.

The limitation of the study is that it is theoretical and methodological in nature. It does not include empirical measurement of the effectiveness of the proposed tools in specific educational programmes. Further research may include the testing of updated syllabi, “Process book” requirements, AI-use declarations, and visual anti-plagiarism procedures in real design education contexts.

Literature Review

Issues of legal regulation of intellectual property in the digital age are at the centre of attention of many Ukrainian and international researchers. The fundamental principles of copyright protection in Ukraine are presented in the works of Androshchuk (*2023*), Kharytonova (*2023*), and Popova et al. (*2021*). Androshchuk (*2023*) examines the legal aspects of regulating artificial intelligence technologies, their influence on scientific and inventive activity, and the role of intellectual property protection, including patent and copyright law, in

ensuring a balance between competing interests. The author also identifies a number of current legal problems connected with the development and application of AI technologies.

Kharytonova (2023) analyses the concept, essence, and role of legal prohibition in intellectual property. This approach is important for the present study because student design practice requires not only knowledge of permitted forms of use, but also clear understanding of prohibited actions, including unlawful copying, appropriation, modification of protected works without authorisation, and commercial use of materials obtained from unreliable sources. Popova et al. (2021) reveal the role and importance of developing intellectual creative activity and commercialising its results for the effective functioning and development of business entities and the state as a whole. Their work makes it possible to consider student design projects not only as academic tasks, but also as potential economic and commercial products.

The specific protection of copyright directly in graphic design and visual communications, as well as under the conditions of the information society, has been studied by Leheza (2024) and Soroka (2019). Leheza (2024) focuses on copyright protection in graphic design under conditions of digitalisation and emphasises the legal vulnerability of visual works that circulate in digital environments. Soroka (2019) analyses copyright and related rights in the information society and draws attention to the European experience of regulating digital content. These studies are relevant because contemporary student design projects often exist simultaneously as academic works, digital portfolio items, competition submissions, and potential commercial products.

International experience, case law, and the legal status of generated objects, including issues of IT law and *sui generis* rights, have been studied by Shtefan (2023), Tarasenko (2024), Yavorska (2017), and Yushyna (2023). These researchers note that modern law is still in the process of forming unified approaches to assessing the results of machine creativity. Shtefan (2023) examines the first global experiences of legal protection for objects generated by computer programmes or artificial intelligence without direct human participation. Tarasenko (2024) analyses the main trends and changes in copyright in the digital age. Yavorska (2017) considers the broader field of IT law, while Yushyna (2023) focuses on the question of who owns copyright and property rights in the context of artificial intelligence and *sui generis* regulation. These works are especially important for understanding why AI-generated visual objects cannot be automatically treated as ordinary copyright works created by a human author.

The methodological aspect of the design process is represented by the work of Endo (*n.d.*), who examines the possibilities of improving a designer's creative abilities through the step-by-step implementation of the design process. The key stages of design creation help define the problem, divide it into manageable parts, develop practical solutions, and achieve the best possible results. In the context of the present article, this approach is connected with the concept of the "Process book", which may serve not only as a creative and methodological instrument, but also as evidence of the student's independent contribution and authorship.

The State Standard of Ukraine "Patent Research" establishes the basic provisions, procedure, and report form for conducting patent research (*National Academy of Sciences of Ukraine, n.d.*). This source is significant because student design projects may include logos, visual identity systems, packaging, printed products, industrial design elements, and other objects that

require preliminary verification for novelty and possible legal conflicts. Therefore, patent research should be considered part of the professional training of future designers.

The analysed literature shows that the problem of lawful use of copyright objects in student design projects is interdisciplinary. It combines copyright law, AI regulation, design methodology, digital ethics, academic integrity, visual communication, and professional responsibility. However, the reviewed sources also reveal a research gap: while legal aspects of copyright and AI-generated objects are widely discussed, there is still an insufficiently developed pedagogical methodology for applying these principles directly in higher design education. This determines the relevance of the present study, which focuses on practical instruments for preventing visual plagiarism and ensuring lawful design practice among students.

Results

Understanding the boundaries of the lawful use of another person's content begins with a basic awareness of what exactly is protected by law. In the student environment, the so-called "Pinterest syndrome" is widespread: the false idea that any image found through search engines or on aggregator platforms has no author and may be freely used in one's own layouts.

According to the Law of Ukraine "On Copyright and Related Rights", legal protection applies exclusively to the form of expression of a work (*On Copyright and Related Rights, 2022*). The law directly states that copyright does not extend to ideas, processes, methods of activity, mathematical concepts, or stylistic directions as such. For a student designer, this means the need to clearly distinguish between the concepts of "conceptual inspiration" or moodboarding and "direct borrowing" or plagiarism. For example, the use of the aesthetics of Swiss minimalism of the 1950s or the idea of dividing a poster into modular grids is lawful inspiration. By contrast, vectorising another person's illustration, using a unique authorial pattern, or redrawing a logo with minimal changes constitutes a direct infringement of the property rights of the author of the original work.

A separate and extremely complex challenge for the educational process has been the mass availability of generative artificial intelligence models, such as Midjourney, DALL·E, and Stable Diffusion. The speed with which high-quality images can be generated creates a temptation for students to replace their own creative work with an automated result, namely prompt engineering.

From a legal point of view, the use of artificial intelligence creates a deep legal vacuum. Contemporary global legal practice tends towards the position that objects generated by artificial intelligence without substantial human creative contribution are not subject to registration as copyright objects. A representative precedent is the widely discussed case concerning the graphic novel *Zarya of the Dawn*. The United States Copyright Office cancelled the previously issued copyright registration certificate for images generated by the artist Kris Kashtanova with the help of Midjourney, arguing that prompt engineering, that is, writing textual prompts, does not constitute sufficient human creative contribution for recognition of authorship. In Ukraine, legislation introduces the concept of a special type of right, or *sui generis* right, for non-original objects generated by a computer programme; however, such a result is not recognised as a fully-fledged authorial work (*On Copyright and Related Rights, 2022; Shtefan, 2023; Yushyna, 2023*).

This creates serious commercial risks in the development of real projects, which is a common practice for diploma works. If a student generates a logo, corporate identity, or key visual for a client entirely with the help of a neural network, the client may later be unable to register this visual image as a trademark, or a sign for goods and services. Thus, ignoring the legal status of generated objects directly places the client's business at risk.

In addition, students often ignore the terms of licensing agreements, or Terms of Service, of the platforms themselves. For example, the rules for using the free versions of many generators directly prohibit the use of the resulting images for commercial purposes. The lawful way to use artificial intelligence in the educational process is to position it exclusively as an auxiliary tool: at the stage of searching for concepts, generating complex background textures, or creating draft sketches. At the same time, the generated material must undergo mandatory and substantial creative reworking. Concealing the fact that artificial intelligence has been used and presenting a "raw" generated image as one's own authorial illustration constitutes intellectual fraud.

To solve these problems, higher education institutions need to implement new approaches to project assessment. Taking the above into account, there is an urgent need at the level of design departments to update the working programmes of academic disciplines, or syllabi. These documents should clearly regulate the rules for using generative artificial intelligence: the permissible percentage of automated content, the rules for its mandatory labelling when submitting course or diploma projects, and the sanctions for concealing the fact of generation.

The most effective methodology for confirming authorship that should be introduced in departments is the mandatory maintenance of a "Process book", or development journal. This is a documented history of the creation of a design product, which includes initial hand sketches, moodboards, a description of the prompts used if artificial intelligence was applied, intermediate iterations of the project, and screenshots of the working process with open Layers panels in graphic editors. The presence of such a journal makes it impossible to pass off generated work as one's own and serves as irrefutable evidence of authorship (*Endo, n.d.*).

At the level of technical support in higher education institutions, the need to introduce visual anti-plagiarism systems is becoming increasingly relevant. These algorithms are based on computer vision methods and are capable of analysing colour histograms, compositional descriptors, digital fingerprints of images, and identifying specific digital noise, or artefacts, characteristic of diffusion models of artificial intelligence.

An important element in developing the legal awareness of future designers is teaching them to work with open licences, including Creative Commons, and font licences, including the SIL Open Font License. The use of commercial typefaces downloaded from pirated resources forms an extremely harmful professional habit that must be eradicated at the stage of university training.

Discussion

The digitalisation of the educational environment has fundamentally changed the methodology of training future specialists in graphic design. Students now work with open visual databases, stock platforms, social networks, AI image generators, font libraries, online portfolios, and digital design tools. This creates a new educational situation in which the ability

to use visual materials lawfully becomes as important as the ability to create an aesthetically convincing composition. Therefore, copyright literacy should not be treated as a secondary legal topic, but as an essential component of professional design competence.

The first major issue concerns the boundary between inspiration and infringement. In design education, students often use moodboards, references, stylistic analogues, and examples of existing visual solutions. Such practices are normal and even necessary in the early stages of design research. However, they become problematic when the student moves from conceptual inspiration to direct borrowing of protected visual form. For this reason, teachers should help students understand that copyright does not protect an abstract idea or stylistic direction, but it does protect the concrete form of expression. The use of Swiss minimalism, modular grids, or general visual principles may be lawful, while copying a specific illustration, pattern, logo, or typographic composition without permission may constitute infringement.

The so-called “Pinterest syndrome” is one of the most visible manifestations of this problem. Many students perceive images found online as anonymous, ownerless, and freely available for reuse. This misconception is intensified by the visual logic of digital platforms, where authorship, licences, and source information are often hidden or ignored. As a result, students may unintentionally reproduce protected visual content in course projects, diploma works, portfolios, or commercial proposals. The educational response to this problem should include systematic work with source attribution, licence verification, and the distinction between reference, adaptation, transformation, and plagiarism.

The second major issue is connected with generative artificial intelligence. AI systems such as Midjourney, DALL·E, and Stable Diffusion radically accelerate the production of visual content and create the illusion that a complete design solution can be obtained through prompt engineering. This situation challenges traditional concepts of authorship, originality, and creative labour. If a student presents a raw AI-generated image as their own original illustration, the problem is not only legal, but also ethical and pedagogical. Such practice undermines academic integrity because it conceals the actual mechanism of production and misrepresents the student’s creative contribution.

At the same time, the use of AI should not be prohibited entirely. Generative AI may be useful at the stage of searching for concepts, generating background textures, testing visual directions, or creating rough drafts. The key condition is transparency and substantial human creative processing. The student must be able to show how the AI-generated material was transformed, reinterpreted, edited, combined with original sketches, and integrated into the final design. In this regard, AI should be positioned as an auxiliary tool, not as a substitute for authorship.

The third issue concerns the commercial risks of AI-generated visual content. A student design project may later become part of a real business identity, advertising campaign, packaging system, start-up presentation, or brand strategy. If the core visual element of such a project is fully generated by a neural network and lacks sufficient human creative contribution, the client may face difficulties in registering it as a trademark or protecting it as an object of intellectual property. This means that an insufficiently regulated educational practice may later create real economic risks for businesses. Design departments must therefore teach students to consider not only the visual quality of a project, but also its legal usability and commercial safety.

The fourth issue is the documentation of authorship. In the context of digitalisation and AI, the final image alone is no longer sufficient to evaluate the originality of a student's work. It is necessary to see the process: preliminary research, sketches, unsuccessful attempts, revisions, compositional searches, prompts, image edits, layer structures, and final decisions. The "Process book" is therefore one of the most effective instruments for confirming authorship and independent contribution. It changes the logic of assessment: the teacher evaluates not only the finished project, but also the student's path towards the result.

The "Process book" also has pedagogical value. It disciplines the student, develops reflective thinking, and teaches the logic of project documentation. In professional design practice, the ability to explain and justify one's decisions is as important as the ability to create a visually attractive product. Therefore, the introduction of mandatory process documentation may strengthen both academic integrity and professional readiness.

The fifth issue concerns institutional regulation. Syllabi must clearly define what forms of AI use are permitted, what must be declared, what percentage or type of automated content is acceptable, and what sanctions apply in cases of concealment or misrepresentation. Without such regulation, each teacher may interpret the use of AI differently, which creates uncertainty for students and weakens academic standards. Unified departmental rules would make assessment more transparent and reduce conflicts between students and teachers.

Visual anti-plagiarism systems may also become an important part of institutional practice. Traditional text-based plagiarism detection tools are not sufficient for design education because visual plagiarism has a different structure. It may involve copying composition, colour schemes, vector forms, illustration fragments, type arrangements, patterns, or image structure. Computer vision tools can help detect visual similarity, image reuse, digital artefacts, and possible AI-generation traces. However, such tools should support expert assessment, not replace it. The final decision must remain with the teacher or academic commission, since visual similarity may sometimes be caused by shared style, genre conventions, or legitimate reference use.

Another important component is work with open licences and font licences. Students often underestimate the legal significance of typography and downloaded assets. The use of pirated commercial fonts, unlicensed illustrations, or unclear stock images forms a harmful professional habit that may later lead to legal claims in real practice. Training students to work with Creative Commons licences, SIL Open Font License, stock licences, and platform Terms of Service should therefore become a regular part of design education.

The discussion shows that lawful use of copyright objects in student design projects requires a comprehensive educational strategy. It is not enough to warn students that plagiarism is prohibited. They must be taught how to work lawfully: how to search for licensed materials, how to document sources, how to transform references, how to declare AI use, how to maintain a "Process book", how to conduct preliminary patent searches, and how to assess the commercial safety of a visual solution. Only such an integrated approach can form the legal culture of future designers.

The limitation of the present study is that it proposes a theoretical and methodological framework without empirical testing in a specific educational programme. Further research should evaluate the effectiveness of updated syllabi, "Process book" requirements, AI-use

declarations, and visual anti-plagiarism systems in real design education. It would also be useful to compare students' legal awareness before and after the implementation of these tools.

Thus, the development of copyright literacy in design education should be understood as part of the broader transformation of professional training under conditions of digitalisation and artificial intelligence. The future designer must be not only creative and technologically competent, but also legally responsible.

Conclusion

Under the conditions of the information society and the rapid development of artificial intelligence technologies, knowledge of copyright law is no longer an optional skill. It is becoming a critically important component of the professional competence of the contemporary designer. A competitive specialist must understand the legal nature of every element of their project and be aware of responsibility to future clients, employers, educational institutions, and the professional community.

Artificial intelligence opens enormous opportunities for expanding the creative horizon, accelerating the search for visual concepts, and experimenting with form, texture, style, and composition. However, it cannot replace the human being as the subject of copyright. AI-generated materials may be useful in the educational process only when their use is transparent, properly documented, and accompanied by substantial human creative contribution. Concealing the use of AI or presenting raw generated content as one's own original work should be regarded as a violation of academic integrity.

The study shows that higher education institutions training designers need to update their methodological and regulatory framework. Syllabi should clearly define the permissible limits of using generative AI, the requirements for declaring automated content, and the sanctions for concealing such use. The "Process book" methodology should be introduced as an obligatory tool for documenting the stages of project development and confirming the student's independent contribution. Patent research and visual anti-plagiarism tools should become part of the educational process, especially in projects connected with branding, logos, packaging, printed products, and commercial visual communication.

The formation of legal culture among future designers must also include systematic work with open licences, font licences, stock resources, and platform Terms of Service. Students should understand that visual quality alone is not sufficient for professional design practice. A design project must also be lawful, ethically created, properly documented, and commercially safe.

Thus, only the synergy of free creative search and a deep understanding of ethical and legal norms will allow future specialists to create high-quality, lawful, and commercially reliable visual content. The lawful use of copyright objects should therefore be regarded as an integral part of academic integrity, design methodology, and the professional identity of the contemporary graphic designer.

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Conflict of Interest

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Compliance 4.0: Transformation of Enterprise Financial Management towards Transparency, Integrity and Fraud Protection ^[5]

Abstract:

Ensuring transparency, integrity and protection against financial fraud is one of the key challenges for enterprises under the conditions of digital transformation and increasing financial risks. The effectiveness of financial management directly depends on the ability of enterprises to identify threats, prevent fraudulent activities and develop reliable compliance systems. Although traditional compliance mechanisms are widely used in enterprises, modern economic conditions require their transformation towards Compliance 4.0, which combines digital technologies, risk management, automated monitoring and principles of corporate integrity. The subject of the study is the transformation of enterprise financial management through the implementation of Compliance 4.0 tools aimed at increasing transparency, strengthening integrity and preventing financial fraud. The object of the study is the enterprise financial management system under the conditions of digitalisation, growing compliance risks and the need for effective protection against internal and external threats. The study aims to develop theoretical foundations and practical recommendations for implementing Compliance 4.0 as a modern approach to transforming enterprise financial management towards transparency, integrity and fraud protection. The article proposes an integrated approach to the development of Compliance 4.0 systems in enterprises. The importance of transforming traditional control mechanisms into proactive digital compliance models is substantiated. The study analyses the main types of financial fraud, systematises compliance risks and identifies key instruments for improving the transparency of financial flows. The proposed approach is based on the integration of digital monitoring technologies, automated risk analysis, internal control mechanisms, ESG principles and ethical standards into enterprise financial management. Particular attention is paid to the role of compliance in preventing fraud, strengthening stakeholder trust and improving financial security. The stakeholder-oriented approach is considered as an important element of Compliance 4.0 aimed at developing responsible interaction between enterprises, employees, partners, investors and regulatory authorities. The paper presents the classification of enterprise financial fraud, compares Compliance 4.0 with internal and management control systems, and develops an organisational model for implementing compliance mechanisms. The results confirm that Compliance 4.0 allows enterprises to move from reactive control methods to preventive risk management systems focused on early identification of threats and protection of financial resources. The implementation of Compliance 4.0 is especially important for enterprises operating under conditions of economic instability, digital risks and integration into the European business environment. Consequently, the proposed approach is recommended as a strategic tool for increasing financial transparency, developing a culture of integrity, reducing fraud risks and ensuring sustainable enterprise development.

Keywords: Compliance 4.0, financial management, transparency, integrity, fraud protection, risk management, digital technologies, financial security.

Abbreviations:

ACFE is Association of Certified Fraud Examiners

AI is artificial intelligence

COSO is Committee of Sponsoring Organizations of the Treadway Commission

ESG is environmental, social and governance

ISA is International Standard on Auditing

INTOSAI is International Organization of Supreme Audit Institutions

USA is United States of America

Introduction

Ensuring transparency, integrity and financial stability of enterprises is one of the main challenges in the modern digital economy. The rapid development of digital technologies, the growth of financial transactions and global business changes require new approaches to financial management and control. Although traditional compliance systems are widely used in enterprises, modern conditions require their transformation towards Compliance 4.0, which combines digital technologies, analytical tools and proactive methods for preventing fraud.

Recent studies show that financial fraud, corruption risks and violations of corporate rules remain serious problems for enterprises. These problems lead to financial losses, reduce business reputation and negatively influence stakeholder trust (*Association of Certified Fraud Examiners, 2024; PricewaterhouseCoopers, 2024*). Even with the development of internal control systems and regulatory standards, many enterprises still use compliance mainly as a tool for detecting violations. However, modern business conditions require compliance systems that can identify risks at an early stage and prevent possible financial threats.

The development of Compliance 4.0 changes the role of compliance in enterprise management. It is no longer only a control function but becomes an important part of strategic financial management. Modern compliance systems help enterprises increase transparency, improve financial security and support responsible decision-making (*Orieckhova, 2017; Azarenkova et al., 2020*). The use of digital platforms, artificial intelligence and automated monitoring allows enterprises to create more effective systems for fraud protection and risk management.

The subject of the study is the transformation of enterprise financial management through the implementation of Compliance 4.0 tools aimed at increasing transparency, strengthening corporate integrity and protecting enterprises from financial fraud.

The object of the study is the enterprise financial management system under the conditions of digitalisation, increasing financial risks and the growing need for transparency and responsible business behaviour.

The study aims to develop theoretical foundations and practical recommendations for using Compliance 4.0 as a modern approach to transforming enterprise financial management towards transparency, integrity and effective fraud protection.

To achieve the stated purpose, the following study objectives were formulated:

- to analyse modern approaches to compliance development and their role in enterprise financial management;
- to identify the main financial risks and fraud threats affecting enterprise activity;
- to study the influence of digital technologies and artificial intelligence on the development of Compliance 4.0;
- to determine the relationship between compliance, financial security and sustainable enterprise development;
- to systematise the main Compliance 4.0 tools used for increasing transparency and preventing fraud;

- to develop recommendations for integrating compliance mechanisms into enterprise financial management;
- evaluate the role of Compliance 4.0 in improving corporate integrity and stakeholder trust.

Thus, the development of Compliance 4.0 as a tool for transforming enterprise financial management is a relevant scientific and practical task. Its implementation allows enterprises to move from traditional control mechanisms to digital, risk-based and proactive systems aimed at improving transparency, strengthening integrity and preventing financial fraud.

Methods

The research uses a set of general scientific methods commonly applied in financial management, compliance analysis and enterprise security studies. Analytical methods were used to study existing approaches to compliance management and define the role of Compliance 4.0 in improving transparency, integrity and protection against financial fraud. Theoretical generalisation was applied to systematise modern concepts of compliance, financial security and digital transformation of enterprise management.

System analysis was used as the main method for studying compliance as an important part of enterprise financial management. This approach made it possible to identify the relationship between compliance procedures, internal control systems, financial risks and stakeholder interests. The structural approach was applied to define the main elements of the Compliance 4.0 system, including digital monitoring tools, risk assessment mechanisms and fraud prevention instruments.

Comparative analysis was used to study traditional compliance models and modern digital compliance approaches. This helped to identify the main differences between reactive systems focused on detecting violations and proactive Compliance 4.0 systems aimed at preventing financial risks. The comparison was based on criteria such as transparency, level of automation, effectiveness of fraud prevention and influence on enterprise financial security.

Among the specialised methods, risk-oriented analysis was used to identify the main sources of financial fraud, compliance risks and threats affecting enterprise activity. This method helped to assess the influence of internal and external risk factors on financial management processes and develop measures to reduce their negative impact.

Digital analysis methods were applied to study the role of modern technologies in compliance transformation. In particular, the research considered the use of artificial intelligence, automated monitoring systems and data analysis tools for improving financial control and preventing fraud.

Expert evaluation methods were used to develop practical recommendations for applying Compliance 4.0 tools in enterprise financial management. This made it possible to identify effective compliance instruments for increasing transparency, strengthening integrity and supporting responsible financial decisions.

Finally, evaluation methods were applied to assess the expected results of Compliance 4.0 application in enterprises. The analysis included improvements in financial security, reduction of fraud risks, development of stakeholder trust and creation of a sustainable compliance culture.

Literature Review

The development of Compliance 4.0 is based on the transformation of traditional compliance systems into modern digital models focused on transparency, integrity and fraud prevention. Existing studies consider compliance from different aspects, including legal regulation, financial security, risk management and sustainable enterprise development.

A number of researchers analyse the theoretical foundations of compliance and its role in business activities. Korshun (2021) studies the introduction of the concept of “compliance” into the business environment and highlights the importance of following legal and ethical standards. Ovsienko and Svitlychnyi (2021) consider compliance consulting as a tool for improving enterprise management and adapting business processes to modern requirements. However, these approaches mainly focus on organisational and legal aspects and pay less attention to the digital development of compliance mechanisms.

Another research direction is related to the creation of internal compliance control systems. Tiutchenko (2021) proposes a model for organising compliance control as an instrument for increasing enterprise security. Karpushenko and Karpushenko (2023) study theoretical and methodological aspects of developing compliance systems, while Bortnikova et al. (2023) focus on practical compliance tools used by enterprises. These studies confirm the importance of compliance control, but the use of digital technologies and automated fraud prevention tools requires further research.

Financial security is also an important part of modern compliance systems. Beleviat and Spasenko (2013), Nikolaienko (2017), Oriekhova (2017), and Azarenkova et al. (2020) analyse financial security as a complex system aimed at protecting enterprise resources, ensuring stability and reducing financial threats. Their studies create a theoretical basis for considering compliance not only as a control function but also as a strategic element of financial management.

The importance of information technologies and financial processes in enterprise management was also highlighted by Fedorenko and Fedorenko (2012). The authors emphasise the role of information support and financial management tools in improving the efficiency of enterprise activities, which creates prerequisites for the development of modern digital compliance systems.

In the conditions of digitalisation, financial transactions and cash flows require new approaches to monitoring and control. Brown (2020) investigates financial compliance in the digital environment and shows the need for modern control mechanisms. Wilson (2021) studies the development of compliance in cash flow strategies. Ahmed and Singh (2022) and Nguyen (2023) analyse compliance challenges in sectors with intensive financial operations. These studies demonstrate that traditional compliance tools are not enough for preventing modern financial risks.

Special attention in scientific and practical studies is given to fraud identification and prevention. According to International Standard on Auditing 240, fraud is defined as an intentional action involving deception in order to obtain an illegal advantage. The Association of Certified Fraud Examiners (2022; 2024), Ernst & Young (2022), and PricewaterhouseCoopers (2020; 2024) show that financial fraud remains a serious global problem that causes financial losses, reputational damage and a decrease in stakeholder

confidence. These results confirm the need to move from reactive control systems to proactive compliance models.

The development of sustainable business practices has also changed the role of compliance. Poiedynok (2023) considers corporate sustainability as a new direction for compliance development. This approach expands the role of compliance from simple regulatory control to the formation of responsible corporate behaviour, ethical decision-making and long-term stakeholder trust.

At the same time, modern enterprises face new challenges caused by digital transformation, including cyber risks, data manipulation and the increasing complexity of financial operations. Therefore, existing approaches require further improvement through the use of Compliance 4.0 principles based on automation, digital monitoring, analytical technologies and risk-oriented management.

However, despite significant scientific contributions, the integration of digital technologies, compliance instruments and fraud prevention mechanisms into a unified Compliance 4.0 model of enterprise financial management remains insufficiently studied. This determines the need for further research aimed at developing practical approaches to ensuring transparency, integrity and financial security of enterprises.

Results

The analysis of scientific literature and international regulatory documents shows that the concept of “fraud” is generally understood in a similar way in international and national approaches. It is considered as obtaining illegal benefits through deception, abuse of trust or manipulation of information. Such activities create serious threats to the transparency of financial flows, enterprise stability and stakeholder confidence (*International Federation of Accountants, 2009; Criminal Code of Ukraine, 2001*). In the context of digital transformation and the development of Compliance 4.0, the identification and classification of fraud risks become especially important. The modern compliance approach focuses not only on detecting violations but also on their early prevention through digital technologies, automated monitoring and risk-based control mechanisms.

Based on the analysis of scientific studies on financial security, compliance management and fraud prevention (*Beleviat & Spasenko, 2013; Oriekhova, 2017; Tiutchenko, 2021; Skachkova, 2021; Bortnikova et al., 2023; Karpushenko & Karpushenko, 2023*), it has been established that financial fraud in enterprises can be classified according to several key criteria. These include the object and subject of fraudulent activities, methods of committing fraud, the nature of financial transactions and the tools used for fraudulent actions.

The proposed classification creates a basis for developing a comprehensive Compliance 4.0 system aimed at increasing transparency, strengthening corporate integrity and improving enterprise financial security (*Table 1*).

An important contribution to the study of financial fraud, compliance risks and mechanisms for strengthening corporate integrity has been made by the Association of Certified Fraud Examiners (ACFE) through its regular analytical reports “Report to the Nations” (*Association of Certified Fraud Examiners, 2022; Association of Certified Fraud Examiners, 2024*).

In the context of Compliance 4.0 development, special attention should be given not only to identifying fraudulent activities but also to creating an integrated system for their early detection, prevention and reduction of their impact on enterprise financial security. Such an approach requires the combination of traditional compliance mechanisms with digital technologies, automated monitoring systems and risk-oriented financial control.

According to the report “Occupational Fraud 2024: A Report to the Nations” prepared by ACFE, the main types of occupational fraud affecting enterprises include asset misappropriation, corruption and financial statement fraud (*Association of Certified Fraud Examiners, 2024*). These types of fraud differ in their mechanisms and consequences but all require the use of modern Compliance 4.0 tools aimed at improving transparency, strengthening internal control and protecting financial resources (*Figure 1*).

In addition to the ACFE research, important results in the field of financial fraud analysis and compliance risk assessment are presented in the “Global Economic Crime and Fraud Survey 2024” conducted by PricewaterhouseCoopers (*PwC, 2024*). This study provides practical evidence of the growing importance of transforming traditional financial control systems into modern Compliance 4.0 models.

In the context of Compliance 4.0 development, the results of the survey confirm the need to introduce digital monitoring tools, improve the transparency of financial flows and strengthen a culture of corporate integrity. The transition from traditional control mechanisms to risk-oriented compliance systems allows enterprises to identify threats earlier and reduce the negative impact of fraudulent activities.

According to the survey results, about half of Ukrainian enterprises (51%) analysed during the period 2020–2024 faced different forms of economic crime and fraud. Moreover, this indicator increased by 4% in 2024 compared with 2022, which demonstrates the growing importance of developing comprehensive compliance systems as an instrument for protecting enterprises from financial threats (*Figure 2*).

The analysis of the main types of fraud affecting Ukrainian enterprises shows that the most common threats include asset misappropriation (47%), bribery and corruption (43%), cybercrime (38%), and procurement fraud (35%) (*PricewaterhouseCoopers, 2024*). These areas require the use of modern Compliance 4.0 instruments focused on preventing violations, improving financial transparency and strengthening enterprise security.

The spread of these risks confirms the need to transform traditional financial management approaches through the implementation of digital compliance tools. Such tools are aimed at ensuring the transparency of financial flows, developing a culture of corporate integrity and identifying possible fraud risks at an early stage.

Since many fraudulent schemes have similar characteristics in different countries, comparative analysis is an important method for studying international experience in the development of compliance systems. This approach helps to identify common elements of fraud schemes, understand the reasons for their occurrence and develop effective preventive mechanisms based on the principles of Compliance 4.0.

Modern measures for preventing corporate fraud in different countries, including Ukraine, are gradually changing from traditional control procedures into integrated compliance risk

management systems. Enterprises increasingly combine internal control, auditing procedures, digital monitoring technologies and ethical standards of corporate behaviour.

Management reviews, external audits of enterprise activities and digital instruments for analysing financial operations are widely used to reduce fraud risks. However, depending on the economic sector, the methods of committing fraud and the required compliance measures may differ.

According to the international audit company Ernst & Young (2022), internal audit remains one of the key tools for reducing fraud risks, especially for enterprises with significant financial and material flows. At the same time, under the conditions of digital transformation, internal audit should be supported by Compliance 4.0 instruments, including automated transaction monitoring, risk-oriented control, data analytics, counterparty verification and the development of a culture of corporate integrity.

The most common tools for reducing fraud risks in Ukraine and worldwide are presented in the Appendix (Table 2). The results show that internal audit and internal control remain the most widely used instruments and create the basis for developing modern compliance systems.

Ukrainian researchers highlight that internal audit plays an important role as one of the main mechanisms for preventing and identifying fraud in enterprises. In the context of Compliance 4.0 development, its role is expanding from traditional verification of financial operations to an integrated instrument for risk monitoring, improving the transparency of financial flows and strengthening a culture of corporate integrity (Tiutchenko, 2021; Karpushenko & Karpushenko, 2023; Bortnikova et al., 2023).

This situation can be explained by the fact that external audit in Ukraine is mainly focused on confirming the reliability of financial statements for previous periods. As a result, enterprises require additional internal mechanisms that allow continuous monitoring of financial processes and early identification of possible risks.

At the same time, international experience in combating financial fraud demonstrates a wider approach. Significant attention is paid to the combination of external audit, compliance control, automated monitoring systems and digital tools for risk analysis (Ernst & Young, 2022; PricewaterhouseCoopers, 2024).

This approach reflects the principles of Compliance 4.0, where control systems are focused not only on detecting fraud and economic crimes but also on preventing them through digital technologies, data analysis, risk-oriented management and the development of ethical corporate behaviour.

The main tools for combating fraud at the international level as elements of the transformation of enterprise financial management towards transparency and integrity are presented in the Appendix (Figure 3).

The presented data (Figure 4) show that external audit of financial statements remains one of the most widely used tools for reducing fraud risks in enterprises worldwide (83%). However, under the conditions of digital transformation, traditional audit procedures should be combined with compliance control, digital monitoring systems and risk-oriented technologies to improve the effectiveness of fraud prevention.

At the same time, the results presented in Figure 4 demonstrate that the practical ability of external audit to identify fraudulent activities is limited. According to ACFE reports, only 5%

of fraud cases are detected through external audits of financial statements. This indicates that traditional control mechanisms mainly focus on checking previous financial information and are not always effective for early identification of risks.

As shown in Figure 4, more than 38% of fraud cases remain undetected by traditional control instruments. This confirms the need to move from reactive approaches focused on detecting existing problems to preventive risk management models based on the principles of Compliance 4.0.

Compliance control is becoming one of the key instruments for identifying and preventing fraudulent activities. In modern conditions, it is transforming into an integrated system for managing the transparency of financial flows. This system combines digital monitoring, data analytics, compliance risk assessment, automated control procedures and the development of a culture of corporate integrity.

Other important instruments for reducing fraud risks include internal audit (78%) and management reviews of financial processes (75%). These tools support continuous monitoring, improve the quality of management decisions and strengthen the overall system of enterprise financial security.

The obtained results confirm the importance of integrating internal control mechanisms, digital technologies and compliance instruments within the Compliance 4.0 system. Such integration allows enterprises to prevent fraud more effectively, ensure financial transparency and increase their resilience in a changing economic environment.

The comparative analysis of fraud sources shows that the role of external participants in fraudulent activities is increasing. In Ukraine, the share of fraud cases committed by third parties increased from 41% in 2020 to 45% in 2024. At the same time, the global indicator remained almost unchanged and decreased slightly from 39% in 2020 to 38% in 2024 (*Figure 5*).

This trend demonstrates the growing influence of external compliance risks on enterprise activities and confirms the need to transform traditional financial management approaches through the development of Compliance 4.0 systems. This approach is based on digital monitoring, risk-oriented control, comprehensive counterparty verification (due diligence) and ensuring the transparency of financial flows.

Digital counterparty verification systems, including analytical platforms such as YouControl (2026), support compliance procedures by improving transparency and reducing external risks.

Considering that the level of financial fraud committed by third parties is significant, enterprises should pay more attention not only to internal risks but also to risks related to suppliers, contractors, partners and other external stakeholders. This requires the development of new mechanisms for controlling business relationships and preventing possible violations.

Therefore, the modern concept of Compliance 4.0 provides a transition from formal control procedures to a proactive system for managing corporate integrity and financial security. Such a system includes counterparty verification procedures, reputation risk assessment, automated analysis of financial transactions and the development of a culture of responsible corporate behaviour.

The experience of European companies shows that compliance has become an essential element of corporate governance and financial management. Therefore, the integration of

Ukrainian enterprises into the European economic and business environment requires the implementation of modern compliance systems based on European standards of transparency, integrity, fraud prevention and sustainable development.

The development of effective compliance systems requires the use of international standards and best practices in the field of internal control, audit and risk management. The INTOSAI has developed a number of standards aimed at improving internal audit systems, strengthening control mechanisms and ensuring the transparency of financial processes (*INTOSAI, 2026*).

An important feature of these standards is their systematic approach to creating effective risk management mechanisms. At the same time, in the field of internal control, INTOSAI approaches are closely connected with the principles of the COSO framework developed by the COSO. These principles form the basis for organising internal control, identifying risks and improving management processes.

Under the conditions of digitalisation and transformation of financial management, these approaches create a foundation for the development of the Compliance 4.0 concept. This concept combines internal control, risk management, digital monitoring technologies and the principles of corporate integrity.

Compliance can be considered as a strategic tool that ensures the correspondence of enterprise activities with legal requirements, professional standards and ethical principles. Within Compliance 4.0, traditional compliance mechanisms are complemented by digital control technologies, automated risk analysis and instruments for ensuring the transparency of financial flows.

The main purpose of compliance is to reduce risks connected with possible administrative, legal, financial and reputational losses caused by interactions with regulators, customers, business partners and other stakeholders. Compliance includes following internal regulations, international standards, corporate procedures and principles of responsible business behaviour.

Although compliance is often associated with audit and internal control, it has a wider role in the enterprise management system. Unlike traditional internal audit, which mainly evaluates specific operations and financial activities, compliance provides continuous monitoring of the effectiveness of control systems and supports the prevention of possible violations.

Within the Compliance 4.0 concept, compliance is transforming from a separate control function into an integrated system of preventive financial risk management. This system is focused on preventing fraud, improving the transparency of financial operations and developing a culture of responsibility and integrity.

The effectiveness of Compliance 4.0 depends on its ability to adapt to changes in the external environment. These changes include new regulatory requirements, technological development, digital risks, cyber threats and new forms of financial fraud. Therefore, modern enterprises need flexible compliance systems that can quickly respond to challenges and support sustainable financial development.

To determine the role of compliance in the enterprise financial management system, it is important to compare it with other control mechanisms, including internal control and management control (*Table 3*).

This comparison helps to identify the specific features of compliance development and explain its transformation from a traditional control function into an integrated Compliance 4.0 system. This system combines financial control, risk management, digital monitoring and the principles of corporate integrity.

The analysis shows that compliance, management control and internal control have a common purpose: to help enterprises prevent financial losses, reduce fraud risks and support stable development. However, each of these systems uses different methods and instruments to achieve these objectives.

Under the conditions of digital transformation of financial management, compliance is becoming a strategic element of enterprise governance. It supports transparency of business processes, protection against internal and external threats and the development of stakeholder trust.

In a broad sense, compliance can be considered as a part of the internal control system used by enterprises. In a narrow sense, compliance is a separate system focused on following legal requirements, professional standards and ethical principles in all areas of enterprise activity. Special attention is given not only to financial control but also to non-financial aspects, including reputation risks, corporate responsibility and ethical behaviour.

Within the Compliance 4.0 concept, compliance is transforming into a digitally oriented risk management system. It ensures transparency of financial processes, supports a culture of integrity and provides preventive protection against fraud through the use of digital technologies, automated monitoring and analytical tools.

Compliance helps enterprises avoid the uncontrolled acceptance of risks, ensures that business activities follow legal requirements, professional standards and ethical principles, and reduces the possibility of financial, administrative and reputational losses. It also allows enterprises to respond more effectively to changes in the external environment.

In the context of Compliance 4.0 development, the role of compliance is expanding through the use of digital technologies, automated monitoring systems, risk analytics and tools aimed at preventing financial fraud. As a result, compliance is becoming not only a control mechanism but also an important element of strategic financial management.

The main purpose of compliance, management control and internal control is to support enterprises in reducing financial losses, managing risks and ensuring sustainable development through specific methods and instruments. However, under the conditions of digital transformation, compliance plays a wider role because it ensures the transparency of financial flows, strengthens corporate integrity and protects enterprises against internal and external threats.

In a broad sense, compliance can be considered as an element of the internal control system. In a narrow sense, compliance is a separate management system focused on following legal requirements, professional standards and ethical principles in all areas of enterprise activity. Special attention is paid to non-financial aspects, including reputation, stakeholder relations and responsible business behaviour.

Within the Compliance 4.0 concept, compliance is transforming from a traditional verification mechanism into an integrated risk management model. This model combines digital

control, compliance risk assessment, fraud prevention mechanisms and the development of a culture of responsible business conduct.

Compliance 4.0 can be defined as a system of rules, standards and values integrated with modern digital technologies aimed at ensuring transparency, integrity and efficiency of enterprise activities. It regulates corporate relationships between employees and establishes standards of behaviour in cooperation with external stakeholders, including suppliers, customers, contractors, public authorities, local communities, partners and other participants in business processes.

In addition, modern compliance includes the principles of corporate social responsibility, ESG approaches and mechanisms for building long-term trust between enterprises and stakeholders. This expands the role of compliance from regulatory control to a strategic instrument for sustainable business development.

Compliance 4.0 forms the basis for ensuring the transparency of enterprise financial flows because it establishes rules, procedures and standards that support legal, ethical and controlled financial operations through the use of digital tools. At the same time, the transparency of financial flows is an indicator of the effectiveness of compliance programmes, as it provides clear and reliable information about the movement of financial resources for internal and external stakeholders.

Thus, compliance acts as a strategic tool for transforming enterprise financial management by creating an integrated system that combines internal control, risk management, digital technologies and fraud prevention.

Scientific studies confirm that the transparency of financial flows is an important element of enterprise financial security. It contributes to increasing customer trust, strengthening business reputation, attracting reliable partners and qualified employees, and maintaining competitive advantages (*Beleviat & Spasenko, 2013; Oriekbova, 2017; Azarenkova et al., 2020; Bortnikova et al., 2023; Karpushenko & Karpushenko, 2023*).

International rating approaches also confirm that transparency, risk management and effective corporate governance influence enterprise reliability and stakeholder confidence (*Standard & Poor's Global Ratings, 2026*).

In the modern business environment, transparency of financial processes is becoming a necessary condition for effective enterprise development and an important component of the Compliance 4.0 concept. It supports financial stability, responsible decision-making and effective cooperation with stakeholders, including investors, creditors and regulatory authorities.

In the context of Compliance 4.0, the transparency of financial flows is the result of combining digital technologies, ethical standards, risk-oriented management and preventive mechanisms for protecting enterprises against fraud.

At the same time, the implementation of compliance at all levels of the organisational structure requires a systematic approach, appropriate resources, digital transformation of processes, the development of a culture of integrity, and the gradual implementation of a set of management measures (*Figure 6*).

The implementation of Compliance 4.0 in enterprise financial management is becoming especially important under the conditions of economic instability, digital transformation and increasing fraud risks. This concept is aimed at improving the transparency of financial flows,

developing a culture of integrity and creating a preventive system for protecting enterprises against financial threats.

The development of Compliance 4.0 is supported by both enterprises and state regulatory authorities. This interaction creates opportunities for improving compliance mechanisms, developing digital control systems and strengthening trust between business, government institutions and society.

From the enterprise perspective, the main factors motivating the implementation of Compliance 4.0 include the need to increase the trust of investors, creditors, partners and other stakeholders through open and reliable financial information. Enterprises also focus on meeting regulatory requirements and international standards related to ESG principles, financial compliance, auditing and corporate governance.

Another important factor is the need to reduce internal and external risks connected with fraud, corruption, conflicts of interest, unauthorised expenses and violations of financial discipline. The use of digital compliance tools allows enterprises to improve the quality of management decisions through access to reliable financial information, risk analytics and automated monitoring systems.

From the perspective of state regulatory authorities, Compliance 4.0 is considered as an important instrument for reducing the shadow economy, preventing corruption and improving financial discipline. Digital compliance mechanisms support effective monitoring, supervisory control and the fulfilment of international requirements in the areas of financial transparency, ESG transformation, European integration and digital governance.

Thus, improving the transparency of financial flows is not only a part of an enterprise's internal management strategy but also an important direction in the transformation of financial management based on Compliance 4.0 principles. This transformation requires the use of digital monitoring platforms, automated risk analysis systems, internal control instruments and effective cooperation with regulatory authorities.

At the enterprise level, the successful implementation of Compliance 4.0 depends on the development of a corporate culture based on honesty, openness, responsibility and ethical decision-making. Management plays an important role in forming these values and strengthening trust among employees, investors, partners and other stakeholders.

The first stage of introducing Compliance 4.0 into financial processes is the involvement of employees in supporting corporate values and understanding compliance risks. This can be achieved through training programmes, management support and the development of a culture of integrity.

Effective communication is also an important element of Compliance 4.0. Enterprises should create transparent information exchange systems using digital platforms for reporting, financial monitoring and compliance risk management. These tools provide quick access to information, improve cooperation between departments and help identify possible violations at an early stage.

Managers play a key role in ensuring the transparency of financial processes because they connect strategic goals with everyday enterprise activities. They organise staff training, support compliance with internal standards and promote a common understanding of transparency, integrity and responsible management of financial resources.

An important element of compliance culture is an open communication policy that allows employees to report problems, discuss financial risks and receive support from management. Such an approach helps prevent fraud, increases trust in decision-making and creates a corporate environment where ethical behaviour and integrity become basic principles.

Regular meetings and discussions of financial indicators, compliance requirements and possible risks are also important tools within Compliance 4.0. They help increase employee involvement, improve cooperation between departments and support the continuous improvement of financial management processes.

Therefore, Compliance 4.0 creates an integrated model of enterprise financial management that combines digital technologies, internal control, risk management and corporate culture. This approach improves the transparency of financial flows, reduces fraud risks and strengthens the long-term financial security of enterprises.

The absence of effective communication on financial issues may lead to employee dissatisfaction, internal conflicts, higher operational risks and lower management efficiency. At the same time, open discussion of performance results, possible improvements and compliance with established standards helps prevent conflicts, reduce fraud risks and increase employee responsibility.

The implementation of Compliance 4.0 principles and the improvement of financial process transparency provide several advantages for Ukrainian enterprises. Firstly, this approach demonstrates responsibility towards employees, customers, partners and other stakeholders because it ensures a clear understanding of financial operations, possible risks and expected results. It helps strengthen stakeholder trust, improve business reputation and support responsible business development in accordance with European corporate governance standards.

Secondly, transparency of financial flows within the Compliance 4.0 concept allows enterprises to respond more effectively to crisis situations and reduce the influence of internal and external risks. Under the conditions of economic instability, enterprises can use digital reporting systems, monitoring tools and communication channels with stakeholders to provide timely information about their financial position, possible risks and strategic decisions.

Such an approach strengthens confidence in enterprises, increases their reputational stability and improves their ability to manage financial challenges. The implementation of modern compliance recommendations, including reporting automation, digital monitoring instruments, risk-based data analysis and anti-corruption mechanisms, allows enterprises to respond effectively to modern threats and ensure sustainable development based on transparency, responsibility and corporate integrity.

Taking into account the conditions of martial law, reducing the shadow economy and implementing Compliance 4.0 principles are becoming especially important. These measures support the more effective use of financial resources, contribute to economic recovery and strengthen the financial stability of enterprises and the national economy.

The development of transparent mechanisms for managing financial flows, strengthening control over fraud risks and creating a culture of corporate integrity provide the basis for improving the efficiency of resource use at both enterprise and state levels.

Transparent financial flows ensured through digital compliance tools, automated monitoring systems and risk-oriented management create the foundation for stable enterprise operation, strengthening financial security, attracting investment and developing long-term cooperation with international partners.

Thus, Compliance 4.0 acts as a strategic direction for transforming enterprise financial management. It combines digital technologies, transparency, responsibility and stakeholder trust in accordance with modern European standards of doing business.

Discussion

The results of the study confirm that Compliance 4.0 should be understood not as a technical continuation of traditional compliance control, but as a qualitative transformation of enterprise financial management. Its significance lies in the transition from fragmented, retrospective and mainly formal control procedures to an integrated, preventive and digitally supported system aimed at ensuring transparency, integrity and protection against financial fraud. This transformation is especially important under conditions of economic instability, digitalisation of financial operations, increased interaction with external stakeholders and the growing complexity of fraud schemes.

The proposed classification of enterprise financial fraud demonstrates that fraudulent activities may differ by object, subject, method, transaction type and instruments used. This multidimensional nature of fraud means that enterprises cannot rely on a single control procedure or isolated audit mechanism. Fraud may be committed by employees, managers, top management, contractors, suppliers, customers, investors, financial institutions or several participants acting together. It may involve cash transactions, bank operations, barter schemes, manipulation of financial instruments, falsification of documents, corruption, price manipulation, tax evasion, misuse of assets or insider information. Therefore, the response must also be multidimensional. Compliance 4.0 provides such a response because it combines digital monitoring, automated risk assessment, due diligence, anti-corruption procedures, reporting channels, internal control and ethical standards into one coherent management system.

The comparison between Compliance 4.0, management control and internal control shows that these systems share a common strategic purpose: reducing risks, preventing losses and supporting sustainable enterprise development. However, their operational logic differs. Management control is mainly focused on achieving planned financial and strategic indicators. Internal control is oriented towards operational efficiency, asset protection, accuracy of reporting and compliance with established procedures. Compliance 4.0, by contrast, expands the control field to include legal requirements, ethical standards, transparency of financial flows, stakeholder relations, reputation risks, corruption prevention and fraud protection. This broader scope explains why Compliance 4.0 should be considered a strategic element of financial management rather than merely an administrative control function.

The empirical evidence used in the article supports the need for such transformation. Reports by the Association of Certified Fraud Examiners and PricewaterhouseCoopers show that financial fraud remains a serious and persistent threat to enterprises. The data on Ukrainian enterprises are particularly important because they demonstrate that economic crime and fraud are not abstract global risks, but direct challenges for companies operating in Ukraine. The fact

that a significant share of enterprises experienced economic crime and fraud during the analysed period confirms the insufficiency of purely traditional control mechanisms. At the same time, the structure of fraud risks—including asset misappropriation, corruption, financial statement fraud, cybercrime, tax evasion and other forms of economic crime—indicates that modern fraud is increasingly complex and requires integrated digital and organisational countermeasures.

One of the most important discussion points concerns the limited effectiveness of external audit as an anti-fraud instrument. External audit remains widely used and necessary for confirming the reliability of financial statements, but the study shows that it is not sufficient for early fraud detection. This limitation is structural rather than accidental. External audit usually assesses financial information for a previous reporting period and is not designed to provide continuous monitoring of business processes in real time. Therefore, enterprises that rely mainly on external audit may detect fraud only after significant losses have already occurred. Compliance 4.0 addresses this weakness by shifting attention from retrospective confirmation to preventive monitoring, early warning, continuous risk assessment and rapid response to suspicious transactions.

Internal audit and internal control remain crucial elements of the enterprise security system, but their role must also change. Under Compliance 4.0, internal audit should not be limited to periodic verification of documentation and procedural compliance. It should become part of a wider digital risk-management architecture that includes automated analysis of transactions, monitoring of financial flows, verification of counterparties, assessment of corruption risks, identification of conflicts of interest and evaluation of compliance culture. In this sense, internal audit becomes not only a diagnostic tool but also an instrument of preventive financial security.

A separate issue concerns the increasing role of third parties in fraudulent schemes. The article shows that the share of fraud committed by external participants is significant and, in the Ukrainian context, tends to increase. This finding has important implications for enterprise governance. It means that financial security cannot be ensured only by controlling internal employees and internal processes. Enterprises must also manage external compliance risks connected with suppliers, contractors, partners, customers, intermediaries, consultants, investors and public authorities. Due diligence procedures, counterparty verification, reputation screening, sanctions checks, conflict-of-interest analysis and monitoring of contractual behaviour should therefore become mandatory components of Compliance 4.0.

This external dimension of compliance is especially important for Ukrainian enterprises seeking integration into the European business environment. European corporate governance standards place strong emphasis on transparency, anti-corruption mechanisms, responsible business conduct, ESG principles and stakeholder accountability. Enterprises that cannot demonstrate transparent financial flows, reliable compliance procedures and an integrity-oriented corporate culture may face difficulties in attracting investment, entering international supply chains, cooperating with foreign partners or receiving financing. Therefore, Compliance 4.0 has not only a protective function but also an integration function: it helps enterprises become compatible with international expectations of responsible and transparent business.

The role of digital technologies is another key aspect of the discussion. Compliance 4.0 is impossible without the use of digital monitoring platforms, automated risk analysis, data analytics, artificial intelligence tools and digital reporting systems. These instruments allow

enterprises to process large volumes of financial and operational data, identify unusual patterns, detect suspicious transactions and assess risks more quickly than traditional manual procedures. However, digitalisation should not be interpreted as a purely technological solution. The effectiveness of digital compliance depends on the quality of data, the adequacy of algorithms, staff competence, management support and the ethical culture of the organisation. Digital tools may strengthen compliance, but they cannot replace responsible governance.

Artificial intelligence and automated analytics create new opportunities for fraud prevention, but they also generate new risks. Automated systems may detect anomalies in transactions, compare counterparties, analyse behavioural patterns and support early-warning mechanisms. At the same time, excessive reliance on algorithms may create false confidence if models are poorly calibrated, data are incomplete or management ignores non-quantifiable risks. Compliance 4.0 should therefore combine technological instruments with human expertise, ethical judgement and managerial responsibility. The most effective model is not full automation, but hybrid governance in which digital systems support decision-making while compliance officers and managers retain responsibility for interpretation and action.

The study also highlights the importance of corporate culture. Fraud prevention cannot be reduced to formal rules, software or reporting procedures. Many violations occur not because enterprises lack regulations, but because employees do not believe in the fairness of rules, do not trust reporting channels or observe unethical behaviour tolerated by management. Therefore, Compliance 4.0 must include the development of an integrity culture based on honesty, openness, responsibility, ethical decision-making and protection of whistleblowers. Training programmes, communication policies, regular discussions of compliance risks and management commitment are essential for transforming compliance from a formal requirement into an everyday organisational practice.

The stakeholder-oriented approach is particularly important. Transparent financial flows are valuable not only for owners and managers, but also for employees, investors, creditors, partners, customers, regulators and society. Stakeholders require reliable information about how enterprise resources are formed, distributed and controlled. When financial processes are opaque, trust decreases and reputational risks increase. When financial flows are transparent and compliance procedures are effective, enterprises improve their credibility and resilience. Therefore, Compliance 4.0 contributes to strengthening stakeholder trust, which is an important intangible asset in the modern business environment.

The article also demonstrates that transparency of financial flows should be interpreted as both a result and an indicator of compliance effectiveness. On the one hand, compliance procedures, digital monitoring and internal control mechanisms create conditions for transparent financial operations. On the other hand, the level of transparency allows enterprises and external stakeholders to assess whether compliance programmes are actually functioning. If financial flows remain unclear, fragmented or difficult to verify, then compliance exists only formally. If financial information is accurate, timely, traceable and accessible to authorised stakeholders, then compliance becomes a real mechanism of financial security.

In the Ukrainian context, the importance of Compliance 4.0 is strengthened by martial law, economic instability, reconstruction needs and the necessity to reduce the shadow economy. Under such conditions, the transparency of financial flows becomes not only an enterprise-level

issue but also a matter of national economic resilience. Transparent resource management supports more effective use of financial resources, prevents corruption losses, increases investor confidence and strengthens the ability of enterprises to cooperate with international partners. Thus, Compliance 4.0 may contribute to both microeconomic stability and broader economic recovery.

The integration of ESG principles into Compliance 4.0 also deserves attention. ESG-oriented business requires transparency, ethical conduct, responsible governance and accountability to stakeholders. Compliance systems that include ESG principles help enterprises move beyond narrow legal compliance towards sustainable corporate behaviour. This is particularly relevant because investors and international partners increasingly evaluate companies not only by financial results, but also by governance quality, corruption risks, social responsibility and transparency. Consequently, Compliance 4.0 can become a bridge between financial management, corporate sustainability and stakeholder trust.

At the same time, the implementation of Compliance 4.0 may face several obstacles. First, enterprises may lack financial and technological resources for introducing automated monitoring systems and digital compliance platforms. Secondly, staff may resist new procedures if they perceive compliance as excessive bureaucracy or surveillance. Thirdly, small and medium-sized enterprises may have difficulty creating separate compliance departments or appointing specialised compliance officers. Fourthly, digital tools require high-quality data and cybersecurity protection. These limitations mean that Compliance 4.0 should be implemented gradually and proportionally, taking into account the size, sector, risk profile and organisational maturity of the enterprise.

The role of the compliance officer becomes central in this transformation. In a traditional model, compliance officers may be responsible mainly for monitoring adherence to rules and preparing reports. In the Compliance 4.0 model, their role is broader: they coordinate risk management, communicate with management and employees, support ethical standards, organise due diligence, analyse compliance data, interact with regulators and contribute to strategic decision-making. Therefore, enterprises need to invest not only in technologies but also in professional competence, independence and authority of compliance specialists.

The findings also indicate that the development of Compliance 4.0 requires coordination between enterprises and state regulatory authorities. Enterprises need clear regulatory requirements, predictable supervisory practices and access to digital public infrastructure. Regulators, in turn, need reliable reporting, transparent business behaviour and effective cooperation from enterprises. This interaction is especially important for reducing the shadow economy, preventing corruption and supporting Ukraine's European integration. Compliance 4.0 can therefore be seen as an institutional mechanism linking enterprise-level governance with national-level financial transparency.

From a theoretical perspective, the study contributes to the understanding of compliance as an evolutionary concept. Traditional compliance was primarily associated with following rules and avoiding penalties. Compliance 4.0 expands this understanding by integrating digitalisation, proactive risk management, financial transparency, corporate integrity, ESG principles and stakeholder orientation. This means that compliance becomes not only a protective mechanism,

but also a value-creating element of enterprise financial management. It protects resources, improves decision-making, supports reputation and contributes to sustainable development.

From a practical perspective, the study suggests that enterprises should not introduce Compliance 4.0 as a separate project disconnected from financial management. It should be embedded into budgeting, cash flow management, procurement, investment decisions, counterparty relations, reporting, internal audit and strategic planning. Only in this case can compliance influence real financial behaviour rather than remain a formal declaration. The integration of compliance into everyday financial processes is the main condition for moving from reactive control to preventive risk management.

The discussion also confirms that Compliance 4.0 should be assessed by measurable outcomes. These may include reduction in fraud losses, faster identification of suspicious transactions, improved quality of financial reporting, increased number of detected conflicts of interest, improved counterparty verification, higher employee awareness, greater stakeholder trust and stronger investment attractiveness. Without such indicators, compliance effectiveness may remain difficult to evaluate. Future research should therefore develop methodological tools for measuring the efficiency and economic impact of Compliance 4.0 implementation.

The limitations of the present study are connected with its conceptual and analytical focus. The article systematises fraud risks, compliance instruments and organisational approaches, but further empirical research is needed to evaluate the practical effectiveness of Compliance 4.0 in different sectors and enterprise sizes. Future studies should compare enterprises with different levels of compliance digitalisation, analyse the cost-benefit ratio of digital monitoring systems, study the role of artificial intelligence in fraud detection and evaluate the influence of compliance culture on financial security.

Thus, the results of the study confirm that Compliance 4.0 represents a strategic direction for transforming enterprise financial management. It allows enterprises to move beyond formal control and create a proactive system based on transparency, integrity, digital monitoring, risk-oriented management and stakeholder trust. Under conditions of economic instability, digital risks and European integration, this transformation becomes not only desirable but necessary for ensuring financial security and sustainable enterprise development.

Conclusion

The research confirms that the implementation of the Compliance 4.0 concept is an important direction in the transformation of enterprise financial management under the conditions of digitalisation, growing fraud risks and the need to ensure financial transparency. Compliance 4.0 is considered not only as a control instrument but also as an integrated system that combines digital technologies, risk management, ethical standards and mechanisms for preventing financial fraud.

It has been established that an effective Compliance 4.0 system is based on the interaction of preventive, diagnostic and corrective functions. Together with digital monitoring technologies, automated data analysis, risk assessment procedures and counterparty verification, these functions form a mechanism for identifying, evaluating and reducing compliance risks.

The study demonstrates that Compliance 4.0 changes the traditional approach to internal control by expanding its role towards the digital analysis of financial operations, early

identification of risks, fraud prevention, improvement of management transparency and development of an ethical corporate culture. The proposed classification of financial fraud and systematisation of compliance instruments provide a basis for strengthening the financial security of enterprises.

The research substantiates the need to develop an organisational model of compliance management that takes into account the size, structure and specific characteristics of enterprise activities. Within this system, the compliance officer plays an important role in coordinating risk management processes, supporting corporate integrity and ensuring effective communication between management, employees, partners and regulatory authorities.

The implementation of Compliance 4.0 is especially relevant for Ukrainian enterprises under the conditions of economic instability, martial law and integration into the European business environment. The use of digital compliance platforms, automated financial monitoring systems, ESG principles and transparent communication mechanisms contributes to preventing financial violations, increasing investment attractiveness and developing long-term cooperation with international partners.

Thus, Compliance 4.0 represents a modern approach to enterprise financial management based on transparency, integrity and proactive risk management. Its development allows enterprises to improve financial stability, increase stakeholder trust and create conditions for sustainable growth in a changing economic environment.

Future research should focus on developing practical approaches for evaluating the effectiveness of Compliance 4.0 implementation in enterprises. Special attention should be given to the role of artificial intelligence, advanced analytics and digital technologies in fraud prevention, compliance risk management and improvement of enterprise financial security.

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Conflict of Interest

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Appendix

Table 1. Classification of Enterprise Financial Fraud in the Context of Developing a Compliance 4.0 System

Classification criterion	Types of fraud	Response measures within Compliance 4.0
By the object of fraudulent activities	Fraud involving resources of private enterprises, individuals, state institutions, local authorities or several entities at the same time	Development of transparent financial flow management; digital monitoring of resources; automated risk assessment and control mechanisms
By the subject of fraudulent activities	Fraud committed by top management, managers, employees, investors, suppliers, contractors, customers, financial institutions, public authorities or several participants together	Development of a compliance culture; due diligence procedures; management of conflicts of interest; introduction of ethical standards and responsibility mechanisms
By methods of committing fraudulent activities	Providing false information, abuse of trust, misuse of official position, influence or creation of incorrect understanding of enterprise activities	Use of risk-oriented compliance monitoring; development of reporting channels; application of digital tools for identifying suspicious activities
By the nature of transactions related to fraud	Fraud in cash transactions, bank operations, barter transactions, financial instruments and combined schemes	Increasing transparency of financial operations; automation of financial control; application of digital analytics for transaction monitoring
By the tools used to commit fraud	Manipulation of accounting documents, illegal use of assets, corruption, tax evasion, misuse of funds, price manipulation, falsification of reports, illegal use of insider information and unfair competition	Integration of Compliance 4.0 tools, including digital auditing, anti-corruption procedures, automated financial monitoring and development of corporate integrity

Source: compiled by the authors based on scientific studies on compliance, financial security and fraud prevention (Beleviat & Spasenko, 2013; Oriekhova, 2017; Tintchenko, 2021; Skachkova, 2021; Karpushenko & Karpushenko, 2023; Bortnikova et al., 2023).

Table 2. Tools for Reducing Fraud Risks as Components of Developing the Compliance 4.0 System in Ukraine and Worldwide

Tool	Worldwide, %	Ukraine, %	Role in the Compliance 4.0 system
Internal audit	78	68	Identification of risks, evaluation of control effectiveness and continuous monitoring of financial processes
Internal control	70	66	Ensuring transparency of operations, compliance with internal procedures and prevention of possible violations
Management reviews	58	59	Strengthening management responsibility, improving decision-making and controlling compliance risks
External audit	48	42	Independent assessment of financial reporting reliability and identification of high-risk operations
Anti-fraud training and communication	55	38	Development of compliance culture, ethical behaviour and employee awareness of fraud risks

Support and protection of whistleblowers	45	28	Creation of secure reporting channels, early detection of violations and strengthening corporate integrity
Regular staff rotation	35	12	Prevention of conflicts of interest, reduction of operational risks and improvement of internal control

Source: improved by the author based on analytical reports (*Association of Certified Fraud Examiners, 2022; Ernst & Young, 2022; PricewaterhouseCoopers, 2020; PricewaterhouseCoopers, 2024; Association of Certified Fraud Examiners, 2024*), considering the Compliance 4.0 concept.

Table 3. Comparative Analysis of Compliance 4.0, Management Control and Internal Control in the Enterprise Financial Management System

Comparison criterion	Compliance 4.0	Management Control	Internal Control
Definition	A digitally oriented system for ensuring that enterprise activities comply with legal requirements, ethical standards, and the principles of transparency and integrity through the use of modern risk monitoring technologies	A process that ensures the fulfilment of management tasks by achieving the planned financial and strategic goals of an enterprise	A system of measures aimed at ensuring operational efficiency, protection of assets, accuracy of financial reporting, and compliance with legislation
Object of control	Enterprise activities in terms of compliance with external and internal regulations, transparency of financial flows, and interaction with stakeholders	Economic results of an enterprise and its responsibility centres	All business processes, operations, assets, and liabilities of an enterprise
Subject of control	Compliance risks, fraud risks, corruption, violations of ethical standards, lack of transparency in financial operations, and non-compliance with standards	Achievement of financial and strategic performance indicators of an enterprise	Efficient use of resources, reliability of financial reporting, risks, and mechanisms for their minimisation
Control indicators	Financial and non-financial compliance indicators, level of transparency and integrity, risk indicators, and indicators of compliance culture	Financial results, such as income, costs, profit, profitability, and operational efficiency	Financial and non-financial indicators, such as economic efficiency, compliance with regulations, and effectiveness of procedures
Control authority	Compliance officer, compliance control committee, digital monitoring and risk management systems	Management staff, controllers, and financial managers of an enterprise	Internal control department or internal audit service
Purpose of control	Ensuring the transparency of financial flows, reducing compliance risks, preventing fraud, and developing a culture of integrity and stakeholder trust	Achieving the strategic and financial goals of an enterprise through the efficient use of resources	Ensuring the accuracy and timeliness of reporting, protection of assets, and compliance of operations with established standards
Methods of control	Digital monitoring of operations, automated risk analysis, counterparty verification, reporting channels	Planning and analysis of financial indicators, management decisions, and assessment of	Physical control, verification of documentation, computerised systems,

	for violations, and control of business process integrity	information for process optimisation	and separation of responsibilities

Source: compiled based on the generalisation of scientific studies (*Criminal Code of Ukraine, 2001; Ahmed & Singh, 2022; Ernst & Young, 2022; Nguyen, 2023; Wilson, 2021*).

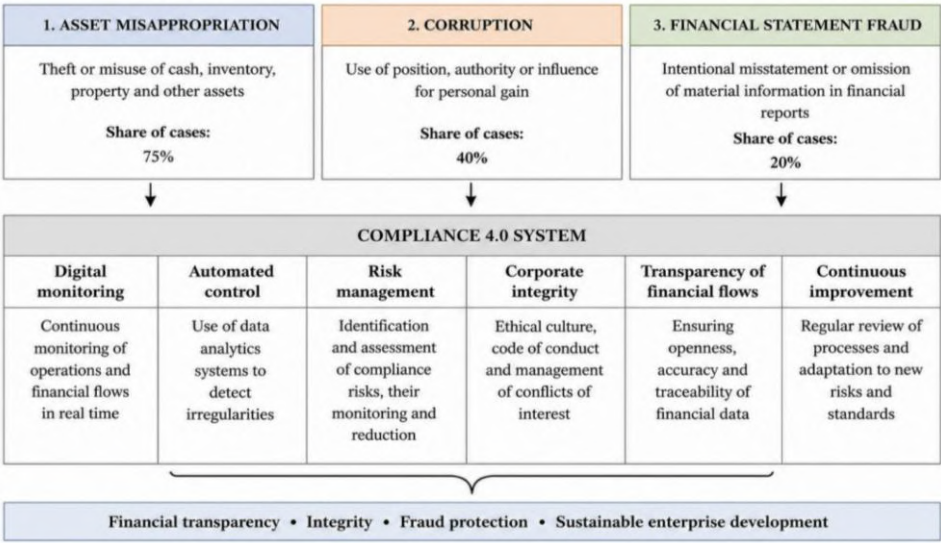


Figure 1. Main Types of Financial Fraud as Objects Influenced by the Compliance 4.0 System (Source: compiled based on ACFE Report to the Nations (2024))

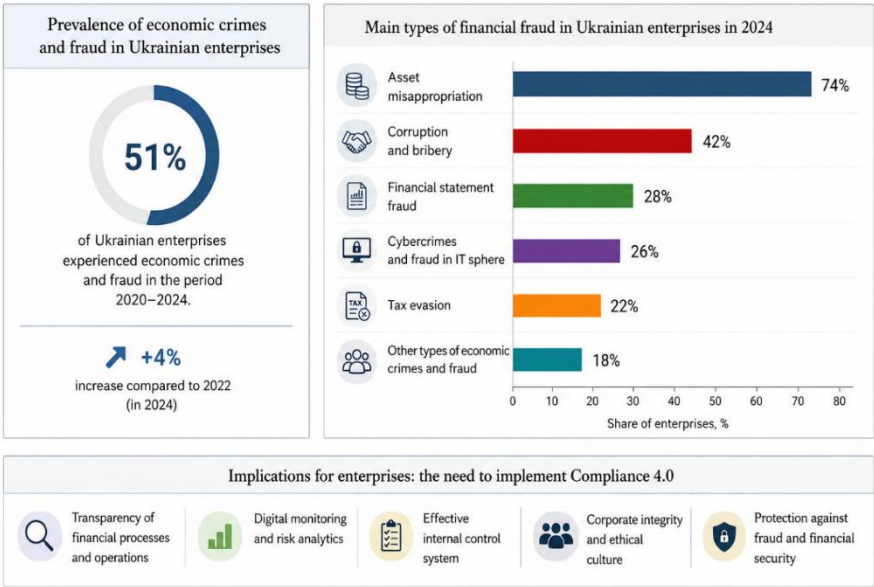


Figure 2. Main Types of Financial Fraud in Ukrainian Enterprises as a Basis for Developing the Compliance 4.0 System (Source: developed by the author based on PricewaterhouseCoopers (2024))

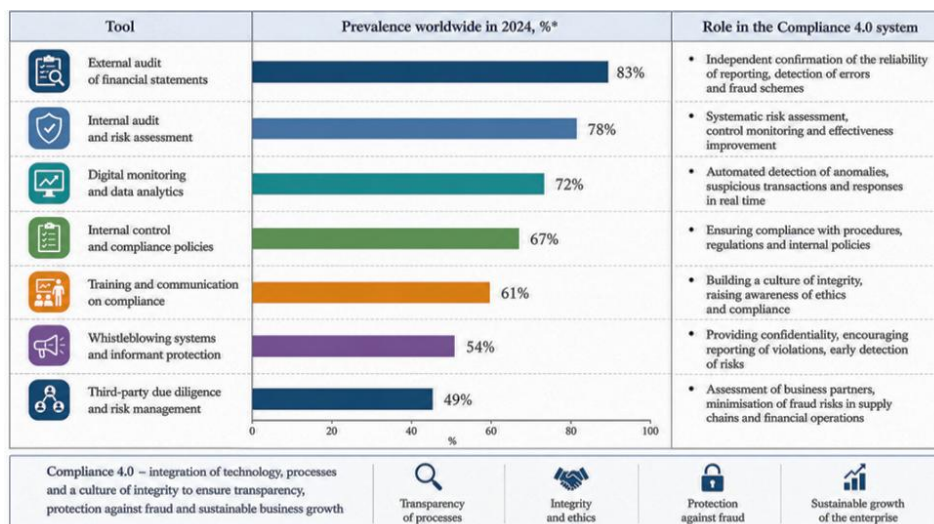


Figure 3. Tools for Ensuring Transparency, Integrity and Protection Against Fraud in the Compliance 4.0 System (Source: compiled by the author based on data from ACFE reports (2022; 2024), PricewaterhouseCoopers (2020; 2024), Ernst & Young (2022) and other international studies, considering the Compliance 4.0 concept.)

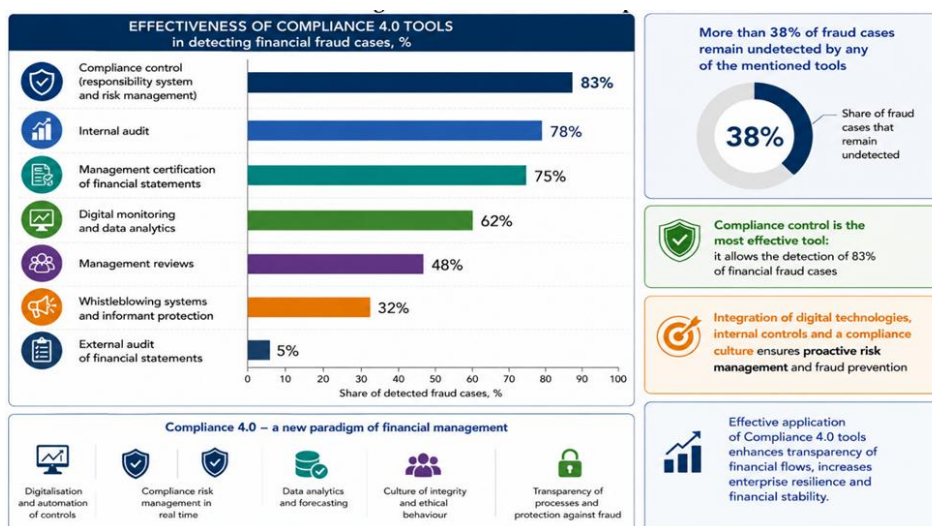


Figure 4. Effectiveness of Compliance 4.0 Tools in Detecting and Preventing Financial Fraud in Enterprises (Source: developed by the author based on data from ACFE reports (2022; 2024), Ernst & Young (2022), PricewaterhouseCoopers (2020; 2024), considering the Compliance 4.0 concept.)

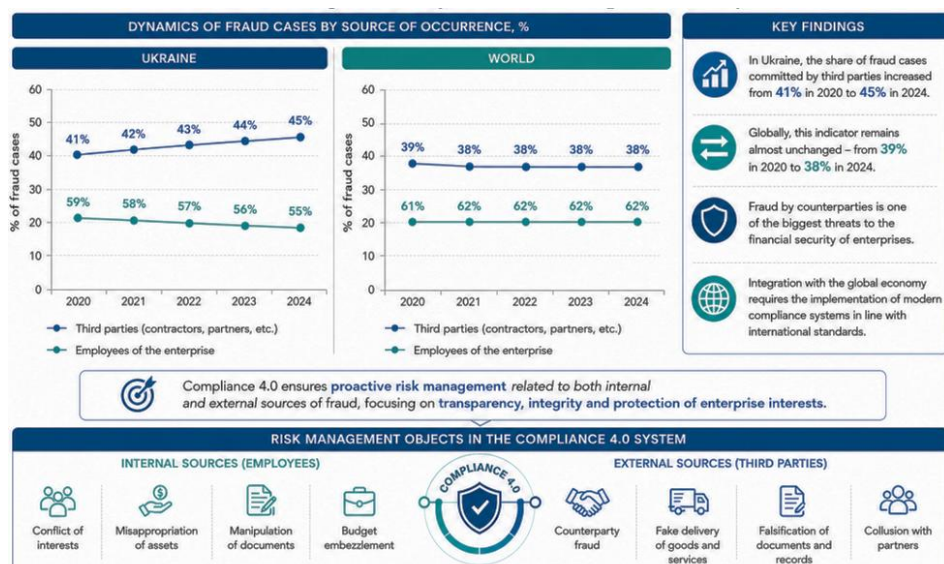


Figure 5. Sources of Financial Fraud in Enterprises as Risk Management Objects in the Compliance 4.0 System (Source: developed by the author based on data from ACFE reports (2022; 2024), PricewaterhouseCoopers (2020; 2024), Ernst & Young (2022), considering the Compliance 4.0 concept.)

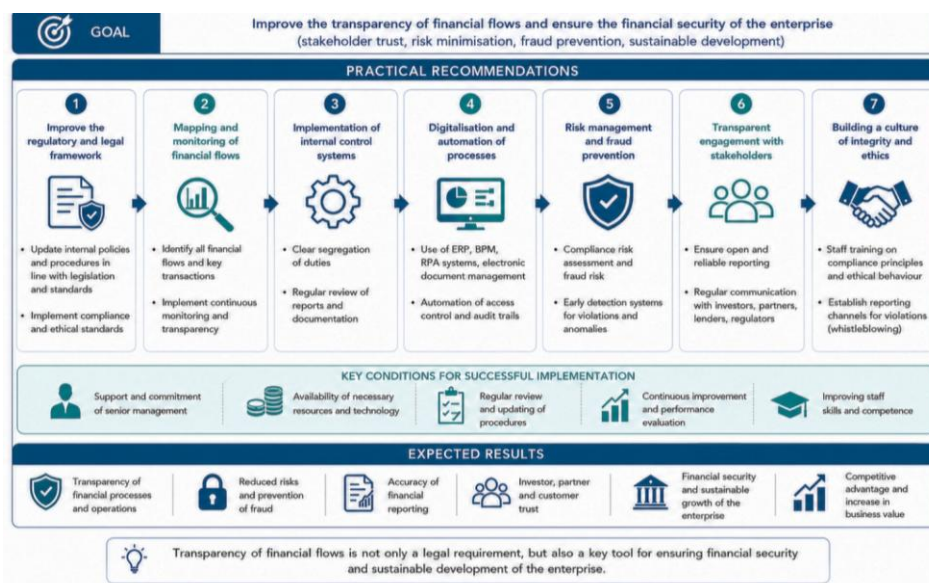


Figure 6. Architecture of Compliance 4.0 Implementation for Ensuring the Transparency of Financial Flows, Integrity, and Enterprise Protection Against Fraud (Source: author's)

The New Trends in Automobile Industry — Opportunities and Challenges for Bulgarian Participation in its Supply Chain ^[6]

Abstract:

The study is relevant because the global automotive industry is being reshaped by green transition, digitalisation, automation, protectionism, nearshoring, and the rapid expansion of electric and hybrid vehicles. The main research problem is whether Bulgaria can strengthen its position in the automotive supply chain despite not having national or foreign OEMs producing complete vehicles in the country. The novelty of the study lies in the author's adaptation of the EPIC framework to assess Bulgaria specifically as a component-supplier country within the automotive supply chain. The subject of the study is the set of economic, political, infrastructural, and competence-based factors that influence Bulgaria's integration into the automotive supply chain. The object of the study is the Bulgarian automotive sector in the context of current global transformations in automobile production and supply chains. The study aims to evaluate the opportunities and challenges for deeper Bulgarian participation in the automotive supply chain under the influence of recent global industry trends. The study applies analysis, induction, deduction, comparison, time-series analysis, factor analysis, and extrapolation based mainly on secondary statistical and institutional data. The literature review shows that the EPIC framework, alongside classical models of business environment and supply chain analysis, is the most suitable theoretical basis for evaluating Bulgaria's supply-chain potential. The study assesses Bulgaria through the adapted EPIC dimensions of economy, politics, infrastructure, and competence, showing favourable conditions such as low labour costs, tax stability, EU market access, developed logistics, and strong technical education. The author concludes that Bulgaria has significant prospects for stronger integration into the automotive supply chain, especially in electronics, components, EV-related production, and R&D, but must reduce dependence on European OEMs and diversify towards new investors, including Chinese companies in the region.

Keywords: automotive supply chain, EPIC model, Bulgarian business environment, professional engineering education.

Abbreviations:

ACB is Automotive Cluster Bulgaria,

EV is electric vehicle,

FDI is foreign direct investments,

HEV is hybrid electric vehicle,

ICEC is internal combustion engine vehicle,

IDB is Inter-American Development Bank,

IEA is International Energy Agency,

IPRI is International Property Rights Index,

LPI is logistics performance index,

MON is Ministry of Education and Science,

NEV is new energy vehicle,

OECD is Economic Co-operation and Development,

OEM is original engine manufacturer.

Introduction

The automotive industry has been undergoing significant transformation in recent years, especially since 2019. The most influential trend is the one brought about by the call for green transition. The emergence of EVs and HEVs has been followed by a sharp growth in their market share at the expense of ICEVs. After 2017, a decline in total car sales was observed, with an abrupt drop in 2020 during the Covid-19 pandemic. The rebound afterwards was not distributed uniformly between the three types of vehicles. Sales of ICEVs are still 30% lower than pre-pandemic levels, while global sales of EVs and HEVs in 2024 are more than 20% higher compared to their level in 2017 (*IEA, 2025*). What is more interesting for the goals of this study is the impact of the product transformation—the cars produced—on the configuration of the automotive supply chain and its leading participants. The most noticeable restructuring is observed among the main producers and exporters. In 2008, the global car-producing centres were Europe (25%), North America (25%), Japan (20%), China (10%) and South Korea (7%) (*IEA, 2025*). China's share of global production in 2025 is more than 40%.

Another well-expressed trend in the recent development of the automotive industry is the higher level of digitalisation and automation (*Russo et al., 2025*). In terms of supply chain configuration, the main semiconductor suppliers situated in South and Southeast Asia have come into focus. Their geographical position supports Chinese and Japanese car producers.

The car industry is also known for its considerable contribution to global GDP—1% direct and 3% indirect (*OECD, 2023*). Its share of national GDP has historically reached 3.0–3.5% for the USA and 7% of GDP for the EU (*OECD, 2023*). Given the great economic importance of the automobile industry in terms of its share in GDP, both globally and for leading car-producing countries, traditional producers from the EU and the USA are trying to protect their national production by imposing non-tariff and tariff measures. Non-tariff regulations now affect about two thirds of total world trade. Tariffs on trade in goods related to the automotive industry have surged from 2.9% to 7.3% globally (*UNCTAD, 2026*). The EU used predominantly non-tariff measures until 2024—a subtle expression of so-called “murky protectionism” (*Chitadze, 2022*). After 2024, open tariff measures were imposed as a counteraction to unfair practices in China. The EC added a new 17–20% to the standard 10% tariff on EV imports from major Chinese producers, whereas additional duties in the USA are much higher (*Reese, 2024*).

The main goal of this study is to establish the effect of the trends described above on Bulgarian participation in the automotive supply chain and to reveal the opportunities for more intensive integration and the obstacles to be overcome. In order to achieve this objective, the main concepts of supply chain configuration will be explored so that the most important conditions for positioning a facility or choosing a subcontractor from a certain country can be identified. At the core of the study is the assessment of a system of factors that can affect decisions on procurement, manufacturing, warehousing, logistics, distribution, and sales for the automotive industry in Bulgaria. This is done through the author's adaptation of the EPIC framework according to the peculiarities of the automotive supply chain and Bulgaria's place in it.

The results reveal potential opportunities and possible challenges for the industry's development, which can be of use to government bodies and industrial organisations in Bulgaria in adopting appropriate strategic measures.

Methods

The general scientific methods applied in the study include analysis, induction, and deduction. Through the analysis of the literature on supply chain configuration, the most appropriate instrument for conducting this research is chosen. The evaluation of the statistical data is carried out through comparison and time-series analysis.

Using the theoretical framework of the EPIC model, the author has adapted it in order to evaluate the growth potential of the automotive sector in Bulgaria. The variables are chosen on the basis of the general scientific methods of induction and deduction. The EPIC framework is adapted on the basis of the most important influencing factors for the development of the automotive supply chain in Bulgaria and its role in the studied supply chain configuration. Most of the included indicators derive from the standard framework but are modified (*Table 2*) so that they can portray the place of Bulgaria in the automotive supply chain over the last 10 years. In the economic dimension, indicators belonging to three groups are included: costs of doing business, the economic importance of the industry for Bulgaria, and currency stability. The political dimension includes indicators concerning political stability and the regulatory framework. Tax rates, such as corporate income tax, VAT, and tariffs on trade, are chosen as the most relevant for presenting the regulatory framework. The composite index—the IPRI, especially with the sub-index—is chosen as the most indicative.

The automotive companies in Bulgaria act as second-tier suppliers producing parts and components. There are neither national nor foreign OEMs in Bulgaria, so ready-made cars are not produced in Bulgaria, and the national market is also not targeted in terms of sales volume. More important are the costs of doing business in Bulgaria—namely labour wages, energy costs, and the purchase or rental price of industrial estates. The automotive companies in Bulgaria are mostly subsidiaries of foreign companies, and almost 100% of their manufacturing is exported.

The development of foreign direct investment in the automotive industry, the number of companies and employees, as well as the trend in the industry's share of GDP, describe its economic importance for the national economy and how it has changed over the last 10 years. The conditions favouring the development of the sector are the basis of the indicators associated with the costs of business, the legal and regulatory framework, the level of infrastructure and connectivity development, and the level of professional and logistics competence.

The information for the variables in the studied period mainly consists of secondary data gathered from official international, national, and industry-specific references, as well as studies by national agencies and industrial organisations. Time-series analysis is applied so that the trends in the development of the industry can be clarified. Factor analysis is carried out considering the influence of industry-specific trends in global development and the potential of the Bulgarian environment for tighter integration into the global automotive supply chain. Considering the positive interaction between the recent forces driving the industry and the conditions of the business environment, a prognosis for the sector's development in Bulgaria is drawn using the technique of extrapolation.

Literature Review

The theory on the strategic building of production, procurement, and distribution networks by multinational companies has developed increasingly with the spread of globalisation at the end of the 20th and the start of the 21st century. Academic insights are constantly provoked by increasing global competition in different industries and the constant challenge of achieving higher competitiveness among companies. Traditional models for the analysis of the business environment, such as PESTLE, Michael Porter's Diamond (1980), and Porter's Five Forces (1979), are fundamental for assessing the most influential environmental factors for successful business development. Bartlett and Ghoshal (1989) contribute to the body of concepts on international development through their idea of gradual evolution in the role of foreign subsidiaries. They also reveal the key role of the interaction of opposing driving forces for adaptation and globalisation so that the most appropriate strategy for a company's international development can be chosen. Ferdows (1997) concentrates on the different roles that foreign factories can perform and evaluates them in terms of enriching their activities both quantitatively and qualitatively by moving up to more value-added ones. In the works of Bennett (2001) and Vereecke and Van Dierdonck (2006), a general observation is that a wisely structured network of factories provides better global competitiveness for a company.

Many contemporary studies are devoted to the evaluation of factors affecting strategic supply chain design, e.g. (Song & Sun, 2016). The scientists from the University of Tennessee Knoxville's Global Supply Chain Institute developed a structured approach for assessing regions and national business environments in terms of supply chain activities taking place on their territories (Srinivasan et al., 2014). The framework is based on the evaluation of variables classified into four groups—economy (E), politics (P), infrastructure (I), and competence (C) (Table 1).

On the basis of data sources such as the World Bank World Development Indicators, the OECD, IDB, the IEA, etc., the scientists from the Global Supply Chain Institute calculated the EPIC index score for 64 countries that represent global trade and account for 94% of the world's gross domestic product in US dollars and 84% of the world population. The indexes for the studied countries for 2021 vary from 29.12 to 83.65. Bulgaria is not among these countries, and its index can only be inferred from those of the studied neighbouring countries: Romania (53.9), Turkey (62.56), and Greece (53). It is considered that the index for Eastern Europe varies between 50 and 60.

According to the scope and goal of this study, the EPIC model (Srinivasan et al., 2014) presents the most appropriate framework to be applied for evaluating the potential of Bulgaria for tighter integration into the automotive supply chain on the basis of recent trends developing in the industry.

Results

Economy: Costs of doing business

Major costs of the automotive manufacturing in Bulgaria are for land, energy and labour. The land costs in Bulgaria both to rent and buy vary widely across the country. They are highest

in the big cities Sofia, Plovdiv, Varna, Burgas—from 30 to 80 EUR/sqm and much cheaper in the North-West Region, North-Central Region and in the southern parts of the South-Central Region and South-East Regions—from 10 to 35EUR/sqm (*Real estate BG, 2026*). Although the prices of industrial land increased considerably in the last year the estates in the industrial zones are still the most affordable in Europe (*Bulgaria Estate, 2025*).

The cost of labour is of greater importance for the foreign investors in the automotive industry where both staff with professional secondary education and high technological competence is needed. In 2024, the average labour costs per hour of 10.6 EUR reported in Bulgaria are almost 3,2 times lower than the average in EU. In 2024, average labour costs per hour were estimated at 33,5 EUR in the EU and at 37,3 EUR in the Eurozone (*BCCI, 2025*). The monthly minimum wage in Bulgaria has been increased from 477 EUR to 551, EUR as of 1st of January 2025 according to EU Directive 2022/2041 of October 2022. Despite of the 15,4% increase the minimum wage in Bulgaria is still the lowest in Europe (*Table 3*).

Being a basic constituent of the costs in the production process, the energy prices will also be given attention. A considerable peak of business energy prices was observed in 2022–2023 as a result of geopolitical factors and sector transformation toward carbon emissions reduction. Despite the decrease with 1.5% in mid-2025 the business energy prices in Bulgaria remain among the highest in Europe—0.24 EUR per kWh, the highest price being that of Ireland—0.2726 EUR per kWh) and the lowest in Finland 0.0804 EUR per kWh. (*Eurostat, 2025*)

Macroeconomic stability

The analysed variable to describe the macroeconomic stability is inflation rate and currency stability. The inflation rate in Bulgaria is quite moderate (*Table 4*) with a peak in 2022–2023 provoked by the pandemic measures and energy crisis, factors with similar effect in all Europe. Over the studied period 2015–2025 Bulgarian lev has been pecked to the EUR which contributed to the macroeconomic stability. The final accession of the country to the Euro zone on 1st of January 2026 provides for smoother transactions with the European partners what are most of the customers and mother companies of automotive companies in Bulgaria.

Economic importance of the automotive industry for Bulgarian economy

The economic importance of the sector is principally associated with the fact that most of the activities in the process have a high value added. It also has a decisive role in providing employment both for highly trained engineers and professionals with technical secondary education. The increasing economic importance of the automotive industry for Bulgarian economy will be proved by portraying the trends in series indicators for the period 2015–2025. The chosen indicators are the share of automotive industry from Bulgarian GDP (*Table 5*), the growth rate of FDI in the industry (*Table 6*), the number of companies (*Table 7*) and number of employees (*Table 8*). The share of the studied sector from Bulgarian GDP shows regular expansion which is more than 3 times for the period 2015–2024. The reason for this can be found in the steady growth in FDI in the sector (*Table 6*).

The trend for increasing growth can be clearly seen at Figure 1. Given the am statistics on FDI in the automotive industry in Bulgaria it can be inferred that most of the companies are foreign companies. Among the leading ones being—Yazaki, Sensata Technologies, Montupet, Magna, Kostal, Festo, BHTC (Behr-Hella Thermocontrol), VOSS Automotive, Integrated Micro-electronics, ZS Europe, property of Shanghai Unison Aluminum Products. Most of them

are European but investments from the east also present. At the moment there is no OEM-s operating in Bulgaria and the companies are the 2nd and 3rd tier suppliers in the automotive supply chain. They are producing parts and components, whose scope includes harnesses, sensors, connectors, PCB assembly, plastics, metal stamping, mechatronics. As per ACB (2024) 80% of European car sensors are produced in Bulgaria. The specialization focus is on cable assemblies (a national specialty), electronics subassemblies and interior components. In the recent years moving toward R&D and high-tech components is observed. This process is stimulated by the increased production of for EV-s by the OEM-s abroad.

The number of companies has grown more than 9 time in the studied period (Table 7) and the trend for growth is portrayed at (Figure 2) The number of the employed in the industry also expands (Table 8) which can be expected given the trends in the number of companies and relatively low level of automatization and robotization. An inherent feature of the automotive business is the requirement for high volume of production to be reached so that economies of scale to be achieved. So, it is natural the existing companies not only to grow in number but also to expand as separate units in order to be more effective.

Considering the fact that most of the companies are subsidiaries of foreign companies or Bulgarian companies supplies of foreign system integrators or OEM-s, it can be definitely stated that 100% of the manufacturing is exported. The share of total export is between 3 and 5% for the recent years depending on the exact products as per HS codes included in the calculation (ACB, 2024).

It can be concluded that the costs of doing business and the macroeconomic stability favours the development of the automotive sector in Bulgaria, which is expressed in the increasing economic importance of the industry for the national economy, in the growth of its share as percentage of GDP, in the increase in of FDI, in the number of companies and employees.

Politics: Taxes and tariffs

Bulgarian regulations on taxes—corporate and personal income tax as well as VAT distinguish with stability and low levels (Table 9). The flat-tax system on personal and corporate income taxes is introduced in 2007–2008 and hasn't been changed since then. The VAT is set at 20% and has been reduced to 9% for certain more sensitive goods and services only during Covid-19 pandemic period. Bulgaria is said to be the 6th least tax burdened country in the EU by 2023. The overall tax-to-GDP ratio in Bulgaria is 29,9% in 2023, compared to an EU average of 40,6% (EC, 2024). The exemption from corporation tax in region with high unemployment rate is a strategies measure to attract investments in these regions. In 2024 about 61% of the municipalities—162 (of total 265 in Bulgaria) had 25% higher than the average rate of unemployment.

Being an EU member, Bulgaria benefits from the common market and free movement of goods and services in the Union. So, there are neither tariff nor customs procedures for the delivery to the European customers of Bulgarian automotive suppliers which is of crucial importance for the smooth and fast deliveries to the European destinations.

International Property Rights Index (IPRI)

According to the compound index IPRI which is computed at 6.185 (*Property Rights Alliance, 2025*) Bulgaria shows improvement with 20.5% from previous calculation and is ranked 9th in Central Eastern Europe and Central Asia, where most of competitive suppliers of the automotive supply chain are situated. It is a compound Index and it includes the Physical Property Rights Index (7.81), Intellectual Property Rights (5.67) and Legal and Political Index (5.076). The indexes for Legal and Political Stability and for Physical Property Rights show increase by previous computing whereas the Intellectual Property Rights Index is decreased but only with 0.013 points (*Property Rights Alliance, 2025*).

Thus, it can be assumed that as long as the positive development continues and the negative is reversed, the legal and political environment in Bulgaria seems welcoming for new foreign investments.

Infrastructure: Transportation Infrastructure and Connectivity

The strategic geographic location of Bulgaria provides for its connectivity both to the rest of Europe, Asian countries and North Africa. The availability of sea port in Bulgaria and the proximity to the Greek ports ensures for the connection to the overseas destinations. The access to major transport corridors provides for the fast delivery to North Europe. The geographic proximity of Eastern Europe to major OEM-s in Europe is a good reason to redirect their supplies from China and other Asian Countries. The deliveries to Europe where the main customers are positioned, is performed mainly by truck transport with groupage and dedicated trucks. The logistics service is very well developed in Bulgaria. The spectrum of participants includes subsidiaries of leading international forwarders like—DSV, M+M, Kuehne and Nagel (*A&A, 2024*) as well as national groupage operators like Unimasters, Transpress and many national carriers.

Telecommunications and Connectivity

As far as the telecommunication connectivity is concerned, Bulgaria is among the 10 countries with fastest mobile connectivity globally (*MTC, 2023*) and 5G coverage reaching 60% of the population. This provides for the smooth communication between suppliers and their customers in the automotive supply chain as well as for digital integration and transparency.

It can definitely be stated that the well-developed road and air services provide for the “just in time” deliveries approach assumed by the automotive companies while the maritime services emphasize on the economy of transport costs and carbon emissions’ reduction. The high level of telecommunication connectivity contributes for the integrity and transparency if the supply chains the country takes part in.

Competence: Logistics Competence

World bank (*2024*) calculates moderate LPI ranging from 3.2 to 3.3 for 2022 and 2023, the scale being from 1 to 5. The country’s performance in tracking, tracing and infrastructure is determined as stable. For 2023 Bulgaria takes on 51st place among 160 countries (*BCCI, 2025*).

Level of professional technical education.

Bulgaria has a strong tradition in engineering and technical education which is being revived in the recent years through both governmental measures and business initiatives. The automotive companies in Bulgaria need both low and medium-skilled professionals as well as

highly qualified specialists. At Table 10 (*Appendix*) are portrayed the number of secondary professional schools by cities. They are widely recognized vocational schools with technical profile whose students might be potential employees for the automotive industry. The positioning of most of these schools coincides with the clusters of the automotive industry in Bulgaria—Sofia, Plovdiv, Stara Zagora, Ruse, Lovech, Pleven. The universities providing highly qualified specialist are also concentrated in these regions (*Table 11*).

The ministry of Education and the different governmental institutions are well aware of the key role of providing properly educated professional staff for attracting investments in high value activities from the automotive supply chain. There are several programs and initiatives for improvement in both secondary and high/college education. The introduction of dual learning is such an initiative aiming to bridge the gap between education and industry needs. The building of STEM system is national program directed towards increasing the interest in engineering education from an early age. The Innovation strategy for Smart Specialization (IS3, ISSS, the Strategy) (*MII, 2015*) supports projects in engineering education for innovation in the production. The National card for the high education highlights the most needed engineering programs and encourages the universities to provide such. The ACB plays a crucial role in the cooperation between the business and educational institutions. There are also projects funded by European Structural and Investment Funds and managed by the MON directed towards modernization in the academic engineering programs e.g. Operational program “Science and Education for Intelligent Growth” (OP SEIG) which supports the engineering departments and provides scholarships for student in priority areas. The cooperation between business representatives and educational institutions is expressed in providing Summer Internship for high school and university students (ABB Bulgaria) and specialized courses e.g. Haycad Infotech operates the Haycad academy. The successful attracting of Bosch Automotive R&D centre in Sofia is a positive sign for climbing up the value-added chain in the automotive supply chain.

It can be concluded from the values of the studied variables in the different dimensions that the conditions of the business environment, governmental regulations and the labour potential favour the participation of the country in the automotive supply chain.

The upward trend for the future development of the studied sector in aspect of FDI can be extrapolated (*Figure 3*). The linear extrapolation assuming a constant growth presents a baseline scenario considering the potential risks and limitations concerning capacity limits and labour availability. The exponential extrapolation assuming a constant percentage growth represents rather the upper-bound, a boom forecast that is not so realistic. So, as per the linear extrapolation it can be expected the FDI in Bulgarian automotive industry to reach roughly 15–16 bn EUR by 2034 as long as there is no radical negative change in the four crucial dimensions of the adapted EPIC model or external shocks.

Discussion

As the main goal of the research is to estimate the impact of the new trends in the automotive industry on Bulgarian participation in the automotive supply chain, the influence of these trends will be discussed on the basis of the results in the previous subsection.

The well-expressed trend towards increased digitalisation and automation inevitably leads to a greater number of electronic components and more software development. Undoubtedly,

this requires more subcontractors and the expansion of the manufacturing facilities of existing ones in order to meet the need for more components. Having proven traditions in educating IT specialists, Bulgaria has good chances of attracting more R&D centres. The well-expressed governmental position in encouraging engineering education is a local factor amplifying the impact of the trend towards automation and digitalisation in the automotive industry.

The green transition also leads to a surge in the production of EVs, with electronic components and batteries needed for their manufacturing. This means more suppliers and, respectively, more suppliers from Bulgaria, given the country's good tradition and proven expertise in electrotechnics.

The trend towards nearshoring and regionalization in automotive supply chain configuration can also contribute to more active Bulgarian participation in it. Higher geopolitical risks, rigorous protectionist regulations, and ecological requirements for the reduction of carbon emissions are the main factors behind the recent inclination towards nearshoring. For the EU, this is expressed in a preference for outsourcing in Central and Eastern Europe rather than in Asia.

The protectionist measures by the EU towards Chinese OEMs lead to the establishment of production bases in Europe and in proximity to it by Chinese OEMs. BYD opens in 2025 a facility for the assembly of electric buses in Komárom, Hungary, and another one in Szeged, Hungary, for NEVs. Another production base in Izmir, Turkey, is expected to start manufacturing in March 2026 ([BYD, 2026](#)). This reconfiguration also creates opportunities for market diversification in the Bulgarian automotive sector. Attracting investment from Chinese companies and becoming suppliers to Chinese investors in Europe and the region represent important diversification of the customer spectrum of Bulgarian suppliers. It will help to balance the shrinking volume of orders from European customers in situations of cyclical recession, such as the one taking place in Germany since the second half of 2025. In fact, the suppressed economic activity of leading European countries, which are the main investors and customers of the automotive industry in Bulgaria, is the main challenge for Bulgarian participation in the automotive supply chain.

Conclusion

It can be concluded that there are good chances for increasing Bulgaria's integration into the automotive supply chain in the coming years, given the new trends developing in the industry. The contribution of this study is that it provides a specific adaptation of the EPIC framework for evaluating the strengths and weaknesses of the Bulgarian environment for procurement and the enlargement of the production base related to the automotive industry. The major environmental factors crucial for positive development are outlined. The persisting line in tax policy, educational priorities in technical sciences, and connectivity development emerge as driving forces for further integration of the country into the automotive supply chain, which will contribute to growth in national GDP and improve its export position in international trade.

Being mainly a supplier of European OEMs, the Bulgarian automotive sector is threatened by a decrease in the volume of orders as a result of the crisis that European auto producers are undergoing. The pressure comes from strong Chinese competition, high energy costs, and

insufficient domestic demand. In this situation, diversification of the customer spectrum towards Chinese investments in the region proves crucial for the development of the national industry.

A high strategic role will be played by the persistent efforts of government bodies, industrial organisations, and the academic community to produce engineering specialists so that high value-added activities in the automotive value chain can be successfully developed in the country.

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Conflict of Interest

The author declares that there is no conflict of interest.

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Appendix

Table 1. EPIC Framework

Dimension	Indicators
Economy (30%)	GDP, GDP FDI Currency stability, Inflation rate Balance of trade
Politics (20%)	Ease of doing business score Strength of legal rights index Political risk index International property rights index
Infrastructure (30 %)	Transportation Infrastructure Utility Infrastructure Telecommunications and Connectivity
Competence (20%)	Labor Force, Unemployment rate, Education Level Logistics Competence, Customs and Security

Source: *Srinivasan et al., 2014*.

Table 2. Adaptation of EPIC framework

Dimension	Indicator
Economy	<i>Cost of doing business</i> : labor costs, energy costs, industrial estates costs <i>Economic importance</i> : share of automotive industry as % of GDP, growth of the industry 2015-2025, contribution to export, number of companies, number of employees <i>Macroeconomic stability</i> : inflation rate, currency stability
Politics	<i>Legal and regulatory framework</i> : tax rates, tariff rates, International Property Rights Index (Sub-indexes)
Infrastructure	Transportation Infrastructure Telecommunications and Connectivity
Competence	Level of Professional education Logistics Competence

Source: Author's adaptation of EPIC model.

Table 3. European countries with minimum wage below 1000, EUR in 2025

Country	Monthly minimum wage in EUR
Bulgaria	551
Hungary	707
Latvia	740
Romania	814
Slovakia	816
Czechia	826
Estonia	886
Malta	961
Greece	968
Croatia	970

Source: Eurostat (2025)

Table 4. Average inflation rate in Bulgaria 2015-2025

2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
-1.07	-1.32	1.19	2.63	2.46	1.22	2.84	13.02	8.6	2.6	3.64

Source: Statista (2025)

Table 5. Share of automotive industry from Bulgarian GDP

2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
3.5%	4%	5%	5.5%	6.5%	8%	9%	10%	10%	11%

Source: Automotive Cluster Bulgaria (2024)

Table 6. FDI in automotive industry in Bulgaria in billion EUR

2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
2.88	3.43	3.4	3.88	4.21	5.26	6.09	8.26	8.40	9.39

Source: NSI, BG (2025)

Table 7. Number of companies in the automotive industry in Bulgaria

2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
40	100	130	190	250	300	310	320	370	380

Source: Automotive Cluster Bulgaria (2024)

Table 8. Number of employees in the industry

2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
33000	33000	50000	65000	65000	67000	67000	75000	75000	80000

Source: Colliers International (2019)

Table 9. Corporate income tax and VAT tax in European countries in % for 2024

Countries in Europe	Corporate tax	VAT TAX
Bulgaria	10	20
Rumania	16	19
Hungary	10.8	27
Czech Republic	19	21
Estonia	20	22
Cyprus	12.5	19
Lithuania	15	21
Slovakia	21	23
Latvia	20	21

Source: European Commission (2024)

Table 10. Secondary Professional Technical Schools by Region

City/Region in Bulgaria	Number of technical schools
Sofia	8
Varna	3
Stara Zagora	3
Plovdiv	4
Veliko Tarnovo	3
Pleven	3
Other cities	More than 10

Source: MON, BG (2026)

Table 11. Technical Universities and Universities with Strong Technical Programs

Public Technical Universities	General Universities with Strong Technical/IT Programs	Other Universities with Technical/IT-Relevant Programs
Technical University, Sofia Technical University, Varna Technical University, Gabrovo University of Chemical Technology and Metallurgy (UCTM)	Sofia University “St. Kliment Ohridski”, Sofia Plovdiv University “Paisii Hilendarski”, Plovdiv Ruse University “Angel Kanchev”, Ruse	New Bulgarian University, Varna Free University, Burgas Free University

Source: MON, BG (2026)

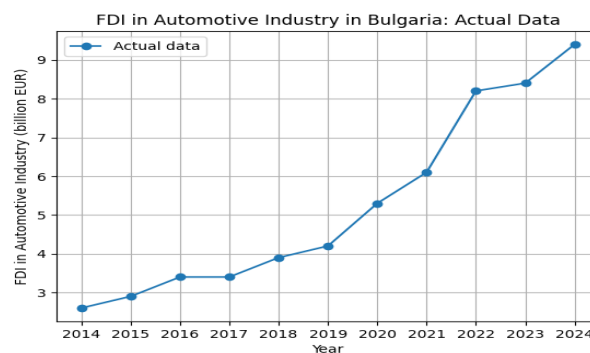


Figure 1. Trend in the FDI in Automotive Industry in Bulgaria

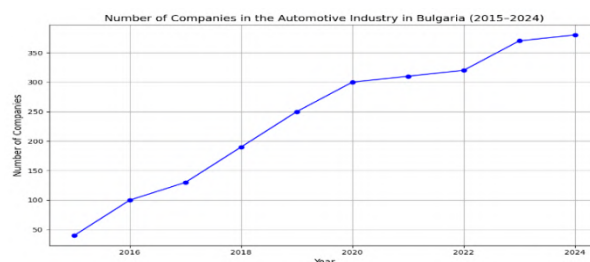


Figure 2. Trend in the number of the automotive companies in Bulgaria

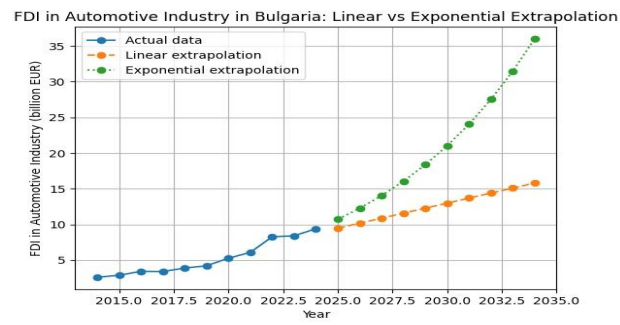


Figure 3. Projection for FDI in the Automotive sector in Bulgaria
Source: Autor's elaboration

Financial Instruments in the Economic and Business Environment: Globalization, Economic Transition, and Systemic Stability ^[7]

Abstract:

Financial instruments are not only technical contracts used by banks, corporations, governments, and investors; they are also institutional mechanisms through which modern economies allocate capital, distribute risk, create liquidity, and transmit economic expectations. This article examines financial instruments in the economic and business environment with particular attention to globalization and economic transition. The analysis argues that instruments such as loans, bonds, equities, guarantees, letters of credit, derivatives, securitized assets, and green finance products have become essential to investment, trade, corporate strategy, and macroeconomic stabilization. At the same time, their expansion has intensified systemic interdependence. The paper therefore evaluates financial instruments as dual-use economic technologies: they improve market coordination and risk management, but they may also amplify leverage, opacity, contagion, and crisis dynamics when governance is weak. The article develops an integrated framework connecting financial development, transition economics, international capital mobility, business financing, regulatory architecture, fintech, and sustainable finance. It concludes that the future of financial instruments depends less on innovation alone than on institutional quality, transparency, prudent supervision, and alignment with productive economic transformation.

Keywords: financial instruments, globalization, economic transition, capital markets, derivatives, trade finance, sustainable finance, systemic risk, business strategy.

Introduction

The contemporary economic and business environment is structured around financial instruments. Every act of investment, trade, corporate expansion, public borrowing, foreign exchange management, and long-term savings involves contractual claims that convert expectations into marketable or enforceable rights. A bond transforms a promise of repayment into a tradable security. An equity share converts corporate ownership into divisible claims on future income. A derivative converts exposure to uncertain prices into a contract that may hedge, transfer, or magnify risk. A letter of credit transforms trust in international trade into a bank-supported payment mechanism. These instruments are not peripheral to capitalism; they are part of its operating system (*Hull, 2018*).

The importance of financial instruments has increased under globalization. Since the liberalization of capital accounts, the expansion of multinational production networks, and the digitalization of trading infrastructure, capital has become more mobile and more sensitive to information. A decision made by a portfolio manager in London, New York, Frankfurt, Singapore, or Dubai can affect the borrowing cost of a government, the exchange rate of an emerging economy, or the investment capacity of a firm thousands of kilometers away. Financial instruments are the channels through which these decisions become economically effective. They allow capital to cross borders, but they also allow instability to cross borders (*Levine, 2005*).

Economic transition gives the subject additional importance. Transition economies—whether post-socialist states, developing countries undertaking liberalization, or economies shifting toward green and digital models—require institutional mechanisms capable of mobilizing savings and directing them toward productive investment. Without functioning

instruments of credit, equity, trade finance, insurance, and risk transfer, transition remains administratively declared rather than economically realized. Privatization, infrastructure investment, export development, banking reform, and foreign direct investment all depend on financial contracts that can be priced, enforced, monitored, and trusted (*European Bank for Reconstruction and Development, n.d.*).

The central argument of this article is that financial instruments must be analyzed simultaneously at three levels. At the microeconomic level, they serve the needs of firms, households, banks, and investors. At the macroeconomic level, they influence savings, investment, credit cycles, monetary transmission, and financial stability. At the global level, they connect economies through flows of debt, equity, trade credit, derivatives, and reserve assets. A narrow technical description is therefore insufficient. The same instrument may be a tool of efficiency in one institutional environment and a source of fragility in another.

This paper is organized as follows. In the Results, the 1st section defines financial instruments and explains their main categories. The 2nd section examines their theoretical foundations in capital allocation, risk management, liquidity, and information. The 3rd section analyzes globalization and cross-border financial integration. The 4th section focuses on economic transition and emerging markets. The 5th section examines business applications, including corporate finance and trade finance. The 6th section analyzes derivatives and systemic risk. The 7th section discusses regulation and governance. The 8th section examines fintech and digital instruments. The 9th section evaluates sustainable finance. The 10th section presents policy implications, and the final section concludes.

Methods

This study applies a qualitative institutional-economic research design aimed at examining financial instruments not only as technical financial contracts, but also as mechanisms that structure capital allocation, risk transfer, liquidity creation, business strategy, and macro-financial stability. Such a methodological approach is appropriate because the economic role of financial instruments cannot be fully explained by pricing formulas or formal classification alone. Their real effects depend on the interaction between contractual design, institutional quality, regulatory architecture, market liquidity, accounting treatment, business incentives, and the broader macroeconomic environment.

The research is conceptual and analytical in nature. It does not use a quantitative econometric model or a single-country statistical dataset. Instead, it develops an integrated framework based on the synthesis of financial theory, institutional economics, transition economics, international macroeconomics, corporate finance, regulatory studies, and development finance. This design makes it possible to analyse financial instruments across several interconnected levels: the microeconomic level of firms, banks, investors, and households; the macroeconomic level of credit cycles, monetary transmission, public borrowing, and systemic risk; and the global level of capital mobility, cross-border finance, trade finance, and international financial interdependence.

The source base of the study consists of academic literature, institutional reports, international standards, regulatory documents, and theoretical works on financial development, market liquidity, financial globalization, transition economies, derivatives, banking regulation,

sustainable finance, and digital assets. The study draws on the theory of finance and growth, which explains the relationship between financial development and economic performance (Levine, 2005; Rajan & Zingales, 1998); institutional approaches to economic development (Acemoglu & Robinson, 2012); theories of international macroeconomics and capital mobility (Obstfeld & Rogoff, 1996; Eichengreen, 2019); and classical corporate finance theory (Miller & Modigliani, 1958). It also uses literature on instability, leverage, and crisis dynamics, including Minsky's financial instability hypothesis and analyses of the global financial crisis (Gorton, 2010; Minsky, 1986; Reinhart & Rogoff, 2009).

The study also relies on international regulatory and standard-setting sources, including IFRS 9 on financial instruments, Basel III requirements, principles of securities regulation, and the Financial Stability Board's resolution and climate disclosure frameworks (Basel Committee on Banking Supervision, 2017; Financial Stability Board, 2014; Financial Stability Board, 2017; IFRS Foundation, n.d.; International Organization of Securities Commissions, 2017). These sources are important because the functioning of financial instruments depends not only on market demand, but also on accounting recognition, prudential supervision, transparency requirements, resolution regimes, and cross-border regulatory coordination.

The research procedure consisted of five analytical stages. At the first stage, the main categories of financial instruments were identified and systematised: debt instruments, equity instruments, derivatives, hybrid instruments, structured finance products, trade finance instruments, digital instruments, and sustainable finance instruments. This classification served as the conceptual basis for further analysis.

At the 2nd stage, the economic functions of financial instruments were examined. The study analysed how instruments support capital allocation, liquidity creation, price discovery, risk transfer, governance, trade facilitation, and business financing. Particular attention was paid to the dual nature of these functions: the same instrument may increase efficiency and resilience under sound institutional conditions, but may also amplify fragility, leverage, opacity, or contagion when governance is weak.

At the 3rd stage, the study applied an institutional-comparative approach to analyse financial instruments in different economic environments. This included advanced market economies, transition economies, emerging markets, and economies undergoing digital and green transformation. The comparative logic made it possible to show that the usefulness of a financial instrument depends on institutional fit. Instruments that function effectively in highly developed markets with strong disclosure, enforcement, and supervision may become destabilising in environments where accounting standards, judicial enforcement, investor protection, and regulatory capacity remain incomplete.

At the 4th stage, the study examined financial instruments from the perspective of systemic risk. This involved analysing the channels through which financial instruments may transmit instability: leverage, maturity mismatch, currency mismatch, collateral calls, counterparty exposure, liquidity spirals, rating dependence, and correlated market behaviour. The analysis distinguished between instruments used for genuine hedging and instruments used to create speculative exposure. This distinction is essential for assessing the social value of derivatives, structured products, and digital instruments.

At the 5th stage, the study developed policy and governance implications. These implications concern the sequencing of financial development, macroprudential regulation, corporate treasury governance, transparency of sustainable finance instruments, functional regulation of digital assets, and international cooperation in supervising cross-border financial flows. The policy analysis is based on the assumption that financial innovation should be evaluated not by complexity or novelty as such, but by its contribution to productive investment, risk management, resilience, transparency, and long-term economic transformation.

The analytical framework of the study is based on five guiding questions. First, what economic function does the instrument perform: financing, payment, hedging, liquidity creation, governance, speculation, or transformation of risk? Second, who ultimately bears the risk if market conditions change? Third, how transparent is the instrument to investors, regulators, auditors, counterparties, and end users? Fourth, how does the instrument behave under stress, especially when liquidity falls, correlations rise, and market confidence declines? Fifth, does the instrument support real economic transformation, or does it mainly increase financial claims, leverage, and short-term arbitrage?

This framework allows the study to distinguish between financial deepening and financial excess. Financial deepening occurs when instruments broaden access to productive credit, investment, insurance, trade finance, and risk management. Financial excess occurs when instruments multiply claims on existing assets without a corresponding increase in productive capacity, transparency, or risk-bearing capital. This distinction is especially important for transition economies, where the adoption of sophisticated instruments before the consolidation of basic institutions may increase fragility rather than development.

The limitations of the study should also be acknowledged. Since the article is conceptual and institutional in design, it does not test causal hypotheses through econometric modelling. It also does not provide a country-level statistical comparison of financial instruments. Instead, it offers an analytical synthesis and theoretical framework that may be used in future empirical research. Further studies may operationalise the framework through comparative case studies, cross-country indicators of financial development, crisis-period data, firm-level financing behaviour, or empirical assessment of sustainable and digital financial instruments.

Literature Review

The study of financial instruments is located at the intersection of finance theory, institutional economics, macroeconomics, corporate finance, international political economy, and regulatory studies. The literature shows that financial instruments are not neutral technical devices. They are contractual and institutional mechanisms through which economies organise savings, investment, ownership, debt, risk, liquidity, trade, and expectations. Their consequences depend on the quality of the institutional environment in which they operate.

A foundational body of literature concerns the relationship between finance and economic development. Levine (2005) argues that financial systems affect growth by mobilising savings, allocating capital, monitoring firms, managing risk, and facilitating transactions. Rajan and Zingales (1998) demonstrate that financial development is particularly important for industries dependent on external finance, since access to financial markets and institutions influences the ability of firms to invest and expand. Demirgüç-Kunt and Levine (2001) further show that

different financial structures, including bank-based and market-based systems, may support economic development in different ways. These works are central to the present study because they explain why financial instruments should be viewed as part of the productive architecture of the economy rather than as purely speculative or accounting categories.

The institutional dimension of financial instruments is developed in the literature on economic institutions and development. Acemoglu and Robinson (2012) emphasise that economic performance depends on inclusive institutions, property rights, enforcement, and the distribution of power. Applied to financial instruments, this means that a loan, bond, share, derivative, or guarantee can function productively only when rights and obligations are enforceable, information is credible, and market participants trust the rules of the game. In weak institutional settings, the same instruments may become tools of rent extraction, asset stripping, corruption, or unsustainable indebtedness. This perspective is particularly relevant for transition economies, where markets and legal institutions often develop unevenly.

A second major body of literature concerns the theory of financial markets and instruments. Markowitz (1952) established the foundations of portfolio selection and diversification, showing how risk and return can be evaluated within a portfolio framework. Miller and Modigliani (1958) developed the theory of capital structure, which remains central to understanding the choice between debt and equity financing. Hull (2018) provides a comprehensive treatment of options, futures, swaps, and other derivatives, explaining how such instruments may be used for hedging, speculation, and arbitrage. Mishkin (2019) situates financial instruments within the broader system of money, banking, interest rates, and financial markets. Together, these works show that instruments are designed to transform cash flows, allocate control rights, redistribute risks, and connect present decisions with uncertain future outcomes.

The literature on liquidity and market functioning is also essential. Biais, Rochet, and Woolley (2013) distinguish between market liquidity and funding liquidity, showing that the tradability of instruments depends not only on their formal design but also on the availability of funding, market-making capacity, confidence, and institutional infrastructure. During periods of stress, liquidity may disappear precisely when it is most needed. This insight is crucial for understanding why instruments that appear safe and liquid in normal times may become sources of systemic pressure during crisis.

A third field of literature concerns financial globalization and international capital flows. Obstfeld and Rogoff (1996) provide the theoretical basis for understanding international macroeconomic linkages, exchange rates, capital mobility, and current-account dynamics. Eichengreen (2019) traces the historical evolution of the international monetary system and shows how reserve currencies, capital mobility, and financial integration shape global economic power. Rodrik (2011) and Stiglitz (2002) offer more critical perspectives, arguing that globalization creates tensions between markets, national policy autonomy, democracy, and social stability. This literature is relevant because financial instruments are the channels through which globalization becomes operational: sovereign bonds, Eurobonds, syndicated loans, foreign exchange derivatives, equity flows, and trade finance instruments allow capital to cross borders, but also allow shocks to travel internationally.

The literature on economic transition provides another important foundation. The European Bank for Reconstruction and Development (*n.d.*) has consistently analysed the role

of structural reform, financial development, banking reform, capital markets, and institutional quality in transition economies. The United Nations Conference on Trade and Development (*n.d.*) and the World Bank (*n.d.*) also emphasise the importance of investment flows, financial inclusion, and development finance for emerging and transforming economies. The key conclusion from this literature is that economic transition requires financial instruments capable of mobilising domestic savings, attracting external capital, supporting enterprise restructuring, financing infrastructure, and managing risk. However, the literature also warns that financial liberalisation without institutional capacity can generate instability, currency mismatches, capital flight, and crisis.

A fifth area of scholarship concerns financial instability and systemic risk. Minsky (*1986*) argues that periods of stability can produce financial fragility because economic agents gradually increase leverage and risk-taking. Reinhart and Rogoff (*2009*) show that financial crises recur across centuries and are often preceded by credit booms, asset-price increases, and excessive confidence. Gorton (*2010*) analyses the panic of 2007 and demonstrates how structured finance, securitisation, short-term funding, and information opacity contributed to the global financial crisis. Persaud (*2000*) highlights the dangers of herding and market-sensitive risk management practices, showing how similar behaviour across institutions may amplify market movements. This literature is central to the article's argument that financial instruments have a dual character: they may distribute risk and improve efficiency, but they may also concentrate hidden leverage and transmit contagion.

The regulatory literature addresses the institutional response to these risks. The Basel Committee on Banking Supervision (*2017*) introduced post-crisis reforms aimed at strengthening capital, liquidity, and leverage standards. The Financial Stability Board (*2014*) developed key attributes for effective resolution regimes, recognising that the failure of financial institutions must be managed without systemic panic. The International Organization of Securities Commissions (*2017*) provides principles for securities regulation, including disclosure, market integrity, investor protection, and systemic risk reduction. IFRS 9 establishes accounting rules for financial instruments, including classification, measurement, impairment, and hedge accounting (*IFRS Foundation, n.d.*). These sources show that the governance of financial instruments requires accounting transparency, prudential discipline, disclosure standards, and mechanisms for managing institutional failure.

The literature on trade finance demonstrates the importance of instruments that support international commerce. The International Chamber of Commerce (*2007*) codified the Uniform Customs and Practice for Documentary Credits, which remains a key framework for letters of credit. Such instruments are important because global trade requires mechanisms that reduce uncertainty between buyers and sellers operating under different legal systems, currencies, and commercial practices. Trade finance links financial instruments directly with the real economy by enabling the movement of goods and services across borders.

Recent literature also focuses on fintech, digital assets, and the transformation of financial instruments. Nakamoto (*2008*) introduced the concept of Bitcoin as a peer-to-peer electronic cash system, opening the way to blockchain-based claims, tokenisation, decentralised finance, and new forms of digital settlement. Digital assets challenge traditional legal and regulatory categories because they may function as payment instruments, speculative assets, securities,

collateral, or programmable contracts depending on design and use. The emerging literature suggests that regulation should focus on economic function rather than technological label: if an instrument behaves like a security, deposit, derivative, or payment system, comparable safeguards should apply.

Sustainable finance has become another major field of scholarship. The OECD (2017) analyses the mobilisation of bond markets for a low-carbon transition, while the Financial Stability Board's Task Force on Climate-related Financial Disclosures links climate risk to financial reporting, investment decisions, and market discipline (*Financial Stability Board, 2017*). Green bonds, sustainability-linked bonds, transition bonds, ESG funds, climate-risk insurance, and carbon-market instruments show that financial instruments are increasingly used to direct capital towards environmental and social objectives. At the same time, the literature highlights the risk of greenwashing, weak verification, and insufficient connection between financial labels and real-economy transformation.

Despite the richness of the literature, several research gaps remain. First, many studies analyse specific types of instruments, such as derivatives, bonds, digital assets, or green instruments, but fewer works develop an integrated framework connecting these instruments to globalization, economic transition, business strategy, systemic risk, and institutional quality. Secondly, the literature often separates technical finance from development economics, although transition economies demonstrate that the developmental value of financial instruments depends on legal enforcement, trust, regulatory capacity, and productive use. Thirdly, the literature on financial innovation sometimes overemphasises complexity and market efficiency, while crisis literature sometimes overemphasises fragility. A balanced perspective is needed: financial instruments should be evaluated by their capacity to support productive transformation, manage uncertainty, and remain resilient under stress.

The present article addresses these gaps by treating financial instruments as institutional technologies. This perspective makes it possible to avoid two simplified positions: the assumption that all financial innovation is beneficial, and the assumption that complexity is inherently harmful. Instead, the article argues that the value of financial instruments depends on purpose, transparency, governance, regulation, and institutional fit. This approach is particularly important under conditions of globalization, economic transition, digital transformation, and sustainable development.

Results

Conceptual Foundations and Classification of Financial Instruments

A financial instrument may be defined as a contract that creates a financial asset for one party and a financial liability or equity claim for another. This definition is broad, but its breadth is necessary. It includes simple bank deposits, commercial loans, treasury bills, corporate bonds, shares, receivables, derivatives, guarantees, insurance-linked instruments, and structured products. The common element is that each instrument formalizes a claim over cash flows, ownership, collateral, or risk exposure. Accounting standards emphasize this contractual nature because the economic substance of the instrument depends on rights and obligations rather than on physical form (*IFRS Foundation, n.d.*).

Primary instruments are the foundation of finance. Loans and bonds represent debt claims. They provide borrowers with capital and give lenders contractual rights to repayment and interest. Equity instruments represent ownership claims. They provide firms with risk-bearing capital and allow investors to participate in residual profits. Trade receivables, deposits, and payment instruments provide working capital and liquidity. These instruments are often described as conventional, but they remain indispensable because most advanced financial structures ultimately rest on debt, equity, or payment claims.

Derivative instruments derive their value from an underlying asset, rate, index, or event. Futures, forwards, options, and swaps allow parties to transform exposure to prices, interest rates, exchange rates, commodities, credit events, or volatility. Their economic value lies in separation: an agent can retain an asset but transfer a specific risk, or acquire exposure without owning the underlying asset. This separation creates flexibility but also demands sophisticated valuation, collateral management, and counterparty discipline (*Hull, 2018*).

Hybrid instruments combine features of debt and equity. Convertible bonds, preferred shares, subordinated debt, contingent convertible securities, and mezzanine financing occupy intermediate positions in capital structure. Their design reflects the need to balance control, risk, cost, and regulatory treatment. In banking, hybrid capital instruments have often been used to absorb losses while preserving financial intermediation. In corporate finance, they may reduce immediate dilution while giving investors upside participation.

Structured finance instruments pool and repackage cash flows from underlying assets. Securitization transforms illiquid loans into tradable securities, while collateralized debt obligations and asset-backed securities allocate risk across tranches. In principle, structured finance can expand credit, diversify risk, and lower funding costs. In practice, it can also create opacity if investors rely mechanically on ratings, if originators weaken underwriting standards, or if leverage grows faster than transparency. The global financial crisis demonstrated that contractual sophistication does not eliminate fundamental credit risk; it may merely relocate and disguise it (*Gorton, 2010*).

Trade finance instruments deserve special attention because globalization depends on them. Letters of credit, documentary collections, bank guarantees, standby letters of credit, export credit insurance, and supply-chain finance reduce uncertainty between buyers and sellers operating across jurisdictions. In international commerce, the seller worries about payment, the buyer worries about delivery, and both face currency, legal, and political risks. Trade finance instruments convert these uncertainties into bank-mediated obligations and documentary procedures, thereby supporting flows of goods, commodities, and services (*International Chamber of Commerce, 2007*).

Economic Functions: Capital Allocation, Liquidity, Information, and Risk

The first economic function of financial instruments is capital allocation. Savings must be transformed into investment if economic growth is to occur. Financial instruments provide the channels through which surplus units transfer resources to deficit units. A household purchasing a bond finances a government or corporation. A bank deposit becomes part of a loan portfolio. A pension fund allocating capital to infrastructure securities supports long-term productive

assets. The quality of this allocation affects productivity, innovation, employment, and competitiveness (*Levine, 2005*).

A second function is liquidity creation. Economic agents value the ability to convert claims into cash without excessive loss. Liquid instruments reduce the cost of holding financial assets and allow investors to adjust portfolios as information changes. Liquidity, however, is not merely a property of instruments; it is also a property of market structure, dealer capacity, settlement systems, and confidence. During stress, instruments that appear liquid may become illiquid when buyers disappear or when funding markets contract (*Biais, Rochet, & Woolley, 2013*).

A third function is price discovery. Financial instruments traded in markets generate prices that incorporate information about expected cash flows, risk, inflation, policy, and uncertainty. Bond yields reveal market expectations about creditworthiness and interest rates. Equity prices reflect expectations about profitability and growth. Exchange rates reflect monetary, trade, and capital-flow conditions. Derivative prices reveal implied volatility and risk premia. These prices influence real decisions, including investment, hiring, borrowing, and trade.

A fourth function is risk management. Financial instruments make risk transferable. Firms use foreign exchange forwards to stabilize import and export revenues. Airlines use fuel hedges to reduce exposure to oil-price volatility. Banks use interest-rate swaps to manage maturity mismatches. Investors use options to protect portfolios against downside movements. Such contracts can improve planning and reduce financial distress. Yet risk transfer is not risk disappearance. The risk moves to counterparties, clearinghouses, insurers, or markets; if it concentrates in fragile institutions, system-wide vulnerability may increase (*Bank for International Settlements, n.d.*).

A fifth function is governance. Equity instruments create voting rights and ownership discipline. Debt instruments create covenants and repayment obligations. Venture capital contracts' structure control rights between entrepreneurs and investors. Project finance agreements allocate risk among sponsors, lenders, contractors, governments, and off-takers. Financial instruments therefore shape incentives, monitoring, and accountability. Good instrument design can reduce agency problems; poor design can encourage short-termism, excessive leverage, or opportunistic behavior.

The efficiency of these functions depends on institutional quality. Contract enforcement, insolvency law, accounting standards, auditing credibility, investor protection, regulatory supervision, and macroeconomic stability determine whether financial instruments serve productive development or speculative extraction. The same bond market that finances infrastructure in one country may finance unsustainable public deficits in another. The same derivative that hedges currency risk for exporters may become a leveraged speculative position for poorly supervised institutions. Instruments are therefore embedded in institutions (*Acemoglu & Robinson, 2012*).

Globalization and the Internationalization of Financial Instruments

Financial globalization has transformed instruments from domestic contracts into global channels of capital mobility. Eurobonds, syndicated loans, depositary receipts, cross-border equities, foreign exchange derivatives, sovereign bonds, and global custody systems allow investors and borrowers to operate beyond national financial boundaries. This

internationalization has increased opportunities for diversification and funding, but it has also increased exposure to external shocks, sudden stops, and global liquidity cycles (*Obstfeld & Rogoff, 1996*).

Cross-border debt instruments are particularly important. Governments issue sovereign bonds in domestic or foreign currency; corporations issue international bonds to access deeper markets; banks borrow through wholesale funding networks. These instruments can lower borrowing costs when confidence is strong. However, they may create currency mismatches if liabilities are denominated in foreign currency while revenues are domestic. During depreciation, the real burden of debt rises, potentially turning exchange-rate pressure into solvency pressure.

Equity instruments support globalization through foreign portfolio investment, cross-listings, and mergers and acquisitions. They allow firms to access international capital and investors to participate in global growth. Yet equity flows are often volatile because they respond quickly to changes in risk appetite. Emerging markets may experience strong inflows during periods of low global interest rates and abrupt outflows during global tightening. The result is a tension between the benefits of openness and the need for macroprudential management (*International Monetary Fund, n.d.*).

Foreign exchange instruments are central to global business. Firms engaged in imports, exports, commodity trading, tourism, shipping, and international services face exchange-rate uncertainty. Forwards, swaps, options, and natural hedges allow them to manage this uncertainty. Nevertheless, foreign exchange derivatives can become dangerous when firms enter contracts that exceed genuine commercial exposure. In several crises, corporate derivative losses emerged not because hedging was wrong, but because hedging instruments were used as speculative yield-enhancement products.

Globalization has also changed the geography of financial power. Major reserve currencies, especially the US dollar and the euro, structure global liquidity. Dollar funding markets influence banks and corporations far beyond the United States. European financial regulation affects firms accessing EU capital markets. Chinese financial expansion, including policy-bank lending and commodity-linked finance, has altered infrastructure and resource financing in many regions. Financial instruments therefore express not only market relations but also geopolitical and institutional hierarchy (*Eichengreen, 2019*).

The central contradiction of financial globalization is that it expands access to capital while weakening the insulation of national economies. Financial instruments allow risk to be diversified internationally, but they also allow panic to become international. The challenge for policymakers is not to reject globalization but to build resilience: adequate reserves, credible regulation, transparent debt structures, strong banking supervision, and instruments aligned with productive investment rather than short-term arbitrage (*Rodrik, 2011*).

Financial Instruments in Economic Transition

Economic transition is not a single historical episode but a recurring structural process. It includes the movement from planned to market economies, the shift from resource dependence to diversified production, the liberalization of closed financial systems, the transformation from informal to formal credit, and the current transition toward digital and low-carbon economies.

In each case, financial instruments mediate the movement from old structures to new possibilities.

In post-socialist transition economies, the creation of equity and debt instruments was linked to privatization. State-owned enterprises had to be valued, shares had to be issued, ownership had to be transferred, and corporate governance had to be constructed. Voucher privatization, public offerings, strategic investor sales, and debt restructuring all relied on financial instruments. Yet the mere creation of shares did not guarantee efficient capitalism. Without legal enforcement, transparent accounting, and shareholder protection, ownership instruments could become mechanisms of asset stripping rather than productive restructuring (*European Bank for Reconstruction and Development, n.d.*).

Banking instruments were equally important. Commercial loans, credit lines, guarantees, and deposits replaced administrative allocation of credit. Banks became institutions responsible for screening borrowers, pricing risk, and monitoring repayment. However, early transition banking systems often inherited weak balance sheets, political lending habits, and limited risk-management capacity. Non-performing loans became a major obstacle in many economies because instruments of credit existed before institutions of discipline were fully established.

Capital-market development is a core element of transition. Government bond markets create yield curves, support monetary policy, and provide benchmarks for corporate borrowing. Corporate bond markets diversify financing away from banks. Equity markets support risk capital and corporate governance. Money-market instruments support liquidity management. The sequence matters: if complex instruments develop before basic supervision and disclosure, markets may become fragile. If regulation is too restrictive, however, financial deepening may be delayed.

Foreign direct investment and portfolio investment interact differently with transition. FDI typically brings capital, technology, management, and market access, although it may also generate dependency if domestic linkages remain weak. Portfolio instruments bring liquidity and valuation discipline but may withdraw rapidly in stress. Successful transition economies combine external finance with domestic institutional development. Financial instruments are most productive when they support industrial upgrading, export capacity, infrastructure, and innovation rather than consumption booms financed by external debt (*United Nations Conference on Trade and Development, n.d.*).

Economic transition also requires social legitimacy. Financial instruments may be viewed with suspicion when associated with crisis, inequality, corruption, or foreign control. Building trust requires transparent rules, financial education, credible courts, and fair enforcement. In transition contexts, the legitimacy of capitalism often depends on whether financial instruments are perceived as tools of broad development or as devices for elite enrichment. This political economy dimension cannot be ignored.

Business Applications: Corporate Finance, Trade, and Strategy

At the firm level, financial instruments are strategic tools. Companies use debt to finance expansion, equity to absorb risk, leases to acquire productive assets, receivables finance to accelerate cash conversion, derivatives to hedge exposures, and guarantees to support contracts. The choice of instrument influences cost of capital, control, flexibility, tax treatment, covenant

restrictions, and vulnerability to shocks. Financial strategy is therefore inseparable from business strategy (*Miller & Modigliani, 1958*).

Capital structure decisions are among the most important applications. Debt may be cheaper than equity because interest is contractually defined and may receive favorable tax treatment, but excessive debt increases default risk and reduces strategic flexibility. Equity avoids fixed repayment obligations but dilutes ownership and may be expensive when markets undervalue the firm. Hybrid instruments can balance these concerns. The optimal structure depends on cash-flow stability, asset tangibility, growth opportunities, ownership preferences, and macroeconomic conditions.

Working-capital instruments are essential for operational survival. Trade credit, factoring, invoice discounting, revolving credit facilities, inventory finance, and supply-chain finance help firms bridge the timing gap between production, delivery, invoicing, and payment. In global supply chains, delays in payment can become a major source of stress for small and medium-sized enterprises. Financial instruments that shorten cash-conversion cycles can improve resilience, but they must be priced fairly and disclosed transparently to avoid hidden leverage.

Trade finance instruments reduce transactional uncertainty. A documentary letter of credit allows a seller to rely on a bank's payment undertaking when documents comply with agreed terms. A standby letter of credit or bank guarantee supports performance, advance payment, or repayment obligations. Export credit insurance protects against commercial or political non-payment. These instruments enable commerce between parties that do not fully know or trust one another and that operate under different legal systems (*International Chamber of Commerce, 2007*).

Risk-management instruments protect business plans from market volatility. A company importing inputs in dollars but selling in domestic currency may use forwards or options to manage exchange risk. A borrower with floating-rate debt may use swaps to stabilize interest payments. A commodity producer may hedge future sales to secure project financing. The key distinction is between hedging genuine exposure and creating speculative exposure. Sound governance requires board-level policies, exposure limits, valuation controls, and stress testing.

Financial instruments also influence competitive strategy. Firms with access to deep capital markets can invest counter-cyclically, acquire distressed competitors, and expand internationally. Firms lacking financial access may be forced to reduce investment precisely when opportunities arise. Financial development therefore shapes industrial structure. In transition economies, improving access to appropriate instruments for SMEs is often more important than attracting highly complex financial products. Development requires fit-for-purpose finance.

Derivatives, Leverage, and Systemic Risk

Derivatives are among the most powerful and controversial financial instruments. Their defenders emphasize hedging, price discovery, and market completeness. Their critics emphasize leverage, opacity, and contagion. Both perspectives are correct under different institutional conditions. A derivative used by an exporter to lock in an exchange rate can stabilize employment and investment. A derivative embedded in a leveraged structure and financed through short-term borrowing can threaten systemic stability (*Hull, 2018*).

The systemic importance of derivatives arises from interconnected obligations. Unlike a cash transaction, a derivative often creates continuing exposure between counterparties. If one counterparty fails, losses may spread to others. Collateral reduces this risk but introduces liquidity pressure because margin calls increase when market prices move. During stress, institutions may be forced to sell assets to meet collateral demands, reinforcing downward price movements.

Leverage is the central amplification mechanism. Derivatives can create large notional exposure with limited initial cash outlay. This is useful for hedging because it reduces transaction costs, but it can be dangerous when used to build speculative positions. Leverage transforms small price movements into large gains or losses. When many institutions hold similar leveraged positions, market corrections can become disorderly (*Minsky, 1986*).

The global financial crisis revealed how complex instruments can obscure risk. Mortgage-backed securities and collateralized debt obligations were often treated as diversified and highly rated, yet their performance depended on correlated housing-market assumptions and fragile funding structures. The crisis was not caused by complexity alone; it resulted from the interaction of weak underwriting, excessive leverage, regulatory gaps, rating failures, and misaligned incentives. Still, complexity made the system harder to understand and slower to stabilize (*Gorton, 2010*).

Central clearing, margin rules, trade repositories, and capital requirements have improved derivative-market transparency. Clearinghouses reduce bilateral counterparty risk by standing between buyers and sellers, but they also concentrate risk in central infrastructures. This makes governance, stress testing, default funds, and recovery planning crucial. A safer system does not eliminate risk; it relocates risk into institutions designed to manage it.

The lesson is not that derivatives should be avoided. Modern economies need instruments for risk transfer. The lesson is that derivative use must be governed by purpose, transparency, capital, and institutional capacity. Regulators should distinguish between hedging and speculative leverage, between standardized cleared instruments and opaque bespoke contracts, and between professional counterparties and vulnerable end users. The social value of derivatives depends on whether they support real economic resilience or merely expand private risk-taking with public consequences.

Regulation, Governance, and Institutional Quality

Financial instruments require regulation because private contracts can generate public externalities. A poorly underwritten loan affects not only lender and borrower if it contributes to banking instability. A derivative default affects not only counterparties if it undermines market confidence. A misleading security issuance affects not only investors if it raises the cost of capital for the broader economy. Regulation therefore seeks to align private incentives with systemic stability (*International Organization of Securities Commissions, 2017*).

Basel III represents one major response to crisis dynamics. It strengthened capital requirements, introduced liquidity standards, and emphasized leverage constraints. These rules matter because banks are central issuers, holders, and intermediaries of financial instruments. If banks are undercapitalized, instruments that should distribute risk may instead concentrate

fragility. Capital and liquidity buffers are not obstacles to finance; they are conditions for durable finance (*Basel Committee on Banking Supervision, 2017*).

Securities regulation focuses on disclosure, market integrity, investor protection, and fair trading. Financial instruments can be priced properly only when relevant information is available and credible. Prospectuses, audited financial statements, ongoing reporting, market-abuse rules, and governance standards reduce information asymmetry. In transition economies, strengthening disclosure may be more important than encouraging rapid product innovation.

Resolution regimes are another crucial element. Because financial instruments create networks of obligations, the failure of a bank, broker, insurer, or clearing institution must be managed without destructive panic. Effective resolution frameworks allow authorities to impose losses on shareholders and creditors, preserve critical functions, and avoid disorderly liquidation. This reduces the expectation that all large financial institutions will be rescued with public money (*Financial Stability Board, 2014*).

Accounting and valuation rules shape behavior. Fair-value measurement can improve transparency by reflecting market conditions, but it can also introduce volatility into balance sheets. Amortized-cost accounting may reduce volatility but hide losses. Expected-credit-loss models require forward-looking judgment. The treatment of financial instruments under accounting standards therefore influences lending, provisioning, capital, and investor confidence (*IFRS Foundation, n.d.*).

Good governance requires coordination between microprudential regulation, macroprudential policy, monetary policy, fiscal policy, and international cooperation. No single rule can manage all risks. Instruments evolve, markets innovate, and institutions adapt. The regulatory task is therefore dynamic: to preserve the benefits of financial innovation while preventing regulatory arbitrage, excessive complexity, and privatization of gains with socialization of losses.

Fintech, Digital Assets, and the Transformation of Instruments

Technological innovation is changing the form, distribution, and governance of financial instruments. Digital platforms reduce transaction costs, automate underwriting, expand access to payment systems, and increase the speed of trading. Artificial intelligence supports credit scoring, fraud detection, portfolio management, and risk analysis. Blockchain systems allow tokenized claims and decentralized settlement structures. These developments are not merely technological; they alter the institutional architecture of finance.

Fintech can improve inclusion by reaching customers excluded from traditional banking. Digital wallets, peer-to-peer lending, crowdfunding, invoice platforms, and mobile payments can provide instruments of savings, credit, and transfer to households and firms lacking access to conventional finance. However, inclusion without protection can become exploitation. High-cost digital credit, opaque fees, weak data privacy, and algorithmic discrimination may reproduce old financial problems in new forms.

Digital assets challenge traditional categories. Cryptocurrencies may function as speculative assets, payment tokens, or stores of value depending on context, although volatility limits many monetary functions. Stablecoins attempt to link digital tokens to reference assets, creating instruments that resemble private money-market claims. Tokenized securities represent

conventional assets recorded on distributed ledgers. Decentralized finance protocols create automated lending, exchange, and derivative structures without traditional intermediaries (Nakamoto, 2008).

The regulatory question is how to preserve innovation while preventing fraud, money laundering, market manipulation, consumer harm, and systemic risk. Digital instruments can grow rapidly because software scales faster than institutional oversight. If stablecoins or tokenized claims become widely used in payments or collateral systems, their failure could have broader consequences. Regulation must therefore focus on economic function rather than technological label: if an instrument behaves like a deposit, security, fund, derivative, or payment system, comparable protections should apply.

Technology also affects market speed. Algorithmic and high-frequency trading can improve liquidity under normal conditions but may withdraw during stress. Automated risk models can process information quickly but may create herding if many institutions use similar signals. Cyber risk becomes a financial-stability issue because settlement systems, exchanges, banks, and data providers are operationally interconnected. The future of financial instruments will depend on operational resilience as much as on legal design.

For transition economies, fintech offers an opportunity to leapfrog weak legacy systems, but it also creates dependence on platforms, data infrastructure, and external technology providers. The development strategy should not be to adopt every new instrument quickly. It should be to build digital public infrastructure, identity systems, payment reliability, consumer protection, and regulatory capacity so that innovation supports productive finance rather than speculative volatility.

Sustainable Finance and the Green Transformation of Instruments

Sustainable finance represents a major transformation in the purpose of financial instruments. Green bonds, sustainability-linked bonds, social bonds, transition bonds, ESG funds, carbon credits, catastrophe bonds, and climate-risk insurance connect capital markets to environmental and social objectives. These instruments recognize that financial value is increasingly affected by climate change, resource scarcity, regulation, technological disruption, and social legitimacy (OECD, 2017).

Green bonds finance projects with environmental benefits, such as renewable energy, energy efficiency, clean transport, water infrastructure, and climate adaptation. Their growth reflects investor demand for sustainable assets and issuer interest in diversifying funding sources. Yet credibility depends on standards, verification, reporting, and avoidance of greenwashing. A green label without measurable environmental impact undermines trust and may distort capital allocation.

Sustainability-linked instruments differ because their financial terms depend on the issuer meeting performance targets. A company may pay a higher coupon if it fails to reduce emissions or improve sustainability metrics. This structure can align financing cost with strategic transformation, but only if targets are ambitious, measurable, and independently verified. Otherwise, the instrument becomes a reputational device rather than a discipline mechanism.

Climate risk changes the valuation of conventional instruments. Physical risks affect real estate, agriculture, infrastructure, insurance, and municipal finance. Transition risks affect fossil-

fuel assets, energy-intensive industries, transport, and technologies exposed to regulation or changing demand. Banks and investors must incorporate these risks into credit analysis, duration management, collateral valuation, and portfolio strategy. Climate disclosure frameworks aim to make such risks visible (*Task Force on Climate-related Financial Disclosures, 2017*).

Sustainable finance is particularly important for economic transition. Developing and emerging economies need large investments in energy, transport, housing, water, agriculture, and industrial modernization. If green instruments reduce funding costs and attract long-term investors, they can accelerate development. However, unequal access to sustainable finance may widen global disparities if poorer countries face higher risk premiums or lack project-preparation capacity.

The future of sustainable instruments depends on integration with real-economy policy. Financial markets cannot decarbonize economies alone. They need carbon pricing, industrial policy, infrastructure planning, credible regulation, and technological innovation. Financial instruments are transmission mechanisms: they can mobilize capital at scale, but they require pipelines of bankable projects and policy credibility to convert capital into transformation.

Comparative Global Dynamics: United States, European Union, China, and Emerging Markets

The global use of financial instruments differs significantly across major economic systems. The United States has historically relied on deep capital markets, broad securitization, venture capital, corporate bond issuance, and market-based risk transfer. This model provides firms with strong access to equity and debt markets and supports rapid innovation, especially in technology sectors. It also creates sensitivity to asset-price cycles because household wealth, corporate financing, and institutional portfolios are strongly linked to market valuation.

The European Union combines bank-based finance with increasingly integrated capital-market initiatives. Many European firms, especially small and medium-sized enterprises, continue to depend on bank credit, while sovereign bond markets, covered bonds, and regulated investment funds play major roles in savings allocation. The European approach gives special importance to prudential supervision, consumer protection, and legal harmonization. However, fragmentation between national markets can limit the depth of risk capital and slow the development of a unified investment environment.

China represents a distinct model in which state influence, banking dominance, policy lending, capital controls, and rapidly developing digital finance coexist. Credit instruments have supported infrastructure, manufacturing capacity, and urbanization at extraordinary scale. At the same time, high leverage in property, local government financing vehicles, and shadow-banking channels has created vulnerabilities. China's experience shows that financial instruments can support accelerated development when coordinated with industrial policy, but they can also accumulate risks when credit growth becomes detached from sustainable cash flows.

Emerging markets face a different set of constraints. Their instruments often carry higher risk premiums because of currency volatility, institutional uncertainty, lower liquidity, and dependence on external financing conditions. Sovereign bonds, syndicated loans, development-bank guarantees, commodity-linked finance, and foreign direct investment become central tools.

The challenge is to attract capital without creating external fragility. Countries that borrow heavily in foreign currency may experience severe stress when global interest rates rise or when export revenues fall.

A comparative perspective shows that no financial model is universally superior. Market-based systems support innovation but can generate bubbles. Bank-based systems support relationship lending but may hide losses. State-guided systems can mobilize investment rapidly but may misallocate capital. Emerging-market systems can benefit from global capital but remain exposed to external cycles. The policy objective is therefore not imitation but institutional fit: instruments should match legal capacity, productive structure, regulatory skill, and development priorities.

International competition increasingly occurs through financial architecture. Control over payment networks, reserve currencies, rating systems, clearing infrastructures, development finance, sanctions, and investment standards affects the ability of firms and states to operate globally. Financial instruments are therefore part of economic power. A sovereign bond is not only a funding tool; it is also an expression of credibility. A currency swap line is not only a liquidity instrument; it is also a geopolitical relationship. A development loan is not only finance; it may shape infrastructure orientation and trade dependence.

Financial Instruments During Crisis, Recession, and Recovery

Crisis periods reveal the true quality of financial instruments and institutions. In expansion, many instruments appear liquid, safe, and profitable. During recession, assumptions about repayment, collateral, market depth, and counterparty strength are tested simultaneously. Instruments that were designed to distribute risk may instead reveal hidden concentrations. Credit lines are drawn, collateral values fall, margin calls increase, and investors demand liquidity at the same time.

During the global financial crisis, the failure of mortgage-related structured products demonstrated that risk transformation is not the same as risk elimination. Loans were originated, securitized, tranced, rated, sold, financed through short-term markets, and used as collateral. Each step appeared to distribute exposure, yet the system remained dependent on rising housing prices, refinancing capacity, and confidence in complex valuations. When those assumptions failed, instruments became channels of contagion.

During sovereign-debt stress, government bonds show their dual role. They are safe assets in some jurisdictions and sources of instability in others. Banks often hold large amounts of domestic sovereign debt, creating a sovereign-bank nexus. If investors doubt public debt sustainability, bond yields rise, bank balance sheets weaken, and the state may become less able to support the banking system. The same instrument that anchors financial markets under normal conditions can intensify crisis when fiscal credibility is questioned.

During recessions, trade finance instruments become especially important because exporters and importers face heightened counterparty uncertainty. Banks may reduce credit lines precisely when firms need support. Development banks, export-credit agencies, and guarantee schemes can stabilize trade by sharing risk and maintaining confidence. This is particularly relevant for small firms integrated into global supply chains, which may be financially healthy but vulnerable to delayed payments and reduced bank appetite.

Recovery depends on whether financial instruments are used to restore productive investment or merely to refinance unproductive debt. Public guarantees, central-bank liquidity facilities, corporate bond purchases, restructuring instruments, and concessional finance can prevent unnecessary bankruptcies. However, if support preserves non-viable firms indefinitely, capital remains trapped. Effective recovery finance must distinguish between liquidity problems and solvency problems, between temporary shock and structural decline.

The crisis lesson is that financial instruments require stress-oriented design. Covenants, collateral rules, margining, capital buffers, resolution clauses, and disclosure standards should be evaluated not only under normal market conditions but also under extreme scenarios. A system is resilient when instruments continue to perform their core functions during stress: payments settle, creditworthy borrowers access liquidity, losses are recognized, and failures are resolved without generalized panic.

Methodological Perspective and Analytical Framework

This article uses a qualitative institutional-economic framework rather than a narrow mathematical model. Such an approach is appropriate because financial instruments cannot be understood only through pricing formulas. Their economic consequences depend on contractual design, market liquidity, legal enforcement, accounting treatment, regulatory supervision, business purpose, and macroeconomic environment. A derivative with identical payoff characteristics may be stabilizing in a well-capitalized firm and destabilizing in a weakly governed institution. A bond may finance productive infrastructure or unsustainable deficits. A guarantee may unlock trade or conceal contingent liabilities.

The framework evaluates instruments through five analytical questions. First, what economic function does the instrument perform: financing, payment, hedging, liquidity, governance, or speculation? Second, who bears the final risk if conditions change? Third, how transparent is the instrument to investors, regulators, auditors, and counterparties? Fourth, how does the instrument behave under stress, especially when liquidity falls and correlations rise? Fifth, does the instrument support real economic transformation or mainly redistribute gains within the financial sector? These questions make it possible to connect micro-level contracts to macro-level outcomes.

A useful distinction must also be made between financial deepening and financial excess. Financial deepening occurs when instruments broaden access to savings, investment, insurance, trade, and productive credit. Financial excess occurs when instruments multiply claims on existing assets without corresponding growth in productive capacity or risk-bearing capital. The boundary is not always obvious, but warning signs include rapid leverage growth, maturity mismatches, weak underwriting, dependence on short-term wholesale funding, and rising complexity that even professional users cannot fully explain.

The analytical framework therefore treats financial instruments as institutional technologies. Like physical technologies, they can increase productivity when properly designed and governed. Like dangerous technologies, they can produce systemic harm when incentives are distorted or controls fail. This perspective avoids two simplistic views: the view that financial innovation is always beneficial and the view that complexity is always harmful. The real question

is whether the instrument improves the economy's capacity to allocate capital, manage uncertainty, and sustain development under realistic conditions.

The framework is also business-oriented. Managers do not select financial instruments in an abstract academic environment; they select them under uncertainty, negotiation pressure, tax constraints, accounting consequences, covenant limits, and competitive urgency. A theoretically efficient instrument may be inappropriate if it increases refinancing risk, damages stakeholder trust, or exposes the firm to losses that exceed its risk appetite. For this reason, the paper emphasizes practical governance, not only market theory.

Finally, the framework is developmental. In economies undergoing transition, the most important financial instruments are not always the most advanced ones. Simple, enforceable, transparent instruments can have greater developmental value than sophisticated contracts that exceed institutional capacity. The quality of finance must be judged by its contribution to investment, trade, innovation, resilience, social legitimacy, and durable institutional trust across economic cycles.

Policy Implications for Global and Transition Economies

The first policy implication is that financial-instrument development must be sequenced with institutional development. Complex products should not be introduced faster than the capacity to regulate, disclose, value, and resolve them. Transition economies should prioritize reliable payment systems, sound banking supervision, government bond markets, transparent accounting, insolvency procedures, and investor protection before encouraging highly complex derivatives or structured products.

The second implication is that openness should be managed rather than romanticized or rejected. Cross-border instruments bring capital, discipline, and diversification, but they can also produce sudden stops and currency mismatches. Macroprudential tools, reserve adequacy, stress testing, and debt-management strategies are necessary complements to financial globalization. The policy goal is resilient openness.

The third implication is that business use of financial instruments requires internal governance. Firms should maintain treasury policies that define permissible instruments, approved counterparties, hedging ratios, reporting requirements, and stress scenarios. Boards should understand whether instruments reduce risk or create hidden leverage. In many corporate failures, the problem was not the existence of financial instruments but weak oversight of their purpose and scale.

The fourth implication is that sustainable finance must be protected from credibility loss. Regulators and market associations should strengthen taxonomies, disclosure rules, external review, and impact reporting. Investors should evaluate use of proceeds, transition plans, and governance rather than relying solely on labels. Issuers should connect sustainable instruments to measurable strategy, not public relations.

The fifth implication is that digital finance requires function-based regulation. A token that represents a security should be regulated as a security. A stablecoin that performs payment and store-of-value functions should meet standards appropriate to reserves, redemption, governance, and operational resilience. A decentralized platform creating leverage should not escape scrutiny merely because it operates through code.

Finally, international cooperation is indispensable. Financial instruments cross borders more easily than regulatory authority. Crisis management, derivatives clearing, anti-money-laundering standards, climate disclosure, accounting convergence, and resolution planning all require coordination. Fragmented regulation can create arbitrage, while excessive uniformity may ignore local conditions. The best approach combines global principles with domestic institutional realism.

Discussion

The analysis demonstrates that financial instruments occupy a central position in the contemporary economic and business environment because they translate expectations, obligations, ownership claims, risk exposures, and liquidity preferences into enforceable contracts. They are not merely technical tools used by financial professionals. They are part of the institutional infrastructure through which modern capitalism organises investment, trade, public borrowing, corporate strategy, and macroeconomic adjustment.

The first major implication of the study is that financial instruments have a dual nature. On the one hand, they improve the functioning of the economy by allocating capital, creating liquidity, supporting price discovery, reducing transaction uncertainty, facilitating trade, and enabling risk management. On the other hand, they may generate leverage, opacity, maturity mismatch, currency mismatch, and systemic contagion. This duality explains why the same instrument may be socially useful in one context and destabilising in another. For example, a currency forward used by an exporter to hedge expected revenues can support employment and investment. However, a similar derivative used by a weakly governed firm to speculate on exchange rates may create losses that threaten solvency.

This finding has important theoretical significance. It suggests that financial instruments should not be evaluated in isolation from institutions. A purely technical classification of instruments into loans, bonds, equities, derivatives, structured products, and digital assets is insufficient. What matters is the institutional environment in which they operate: the enforceability of contracts, the credibility of accounting, the quality of supervision, the depth of markets, the transparency of information, and the capacity of institutions to absorb losses. This institutional perspective is consistent with the broader literature on development and financial systems, which emphasises that markets require rules, trust, and enforcement to function productively.

The 2nd implication concerns globalization. Financial instruments have become the operational channels of global economic integration. Sovereign bonds, cross-border bank loans, foreign exchange swaps, Eurobonds, depositary receipts, trade finance instruments, and global derivatives connect domestic economies to international capital markets. This integration creates opportunities for funding, diversification, and growth, but it also exposes economies to global liquidity cycles, sudden stops, exchange-rate pressure, and contagion. The article therefore supports a balanced interpretation of financial globalization: it should neither be rejected as inherently dangerous nor accepted as automatically beneficial. The policy issue is how to design resilient openness.

For transition economies, this point is especially important. The development of financial instruments is necessary for privatisation, enterprise restructuring, infrastructure finance, export

development, banking reform, and innovation. However, introducing complex instruments before establishing basic institutional capacity may increase fragility. Transition economies need sequencing: reliable payment systems, sound banks, transparent accounting, enforceable collateral rights, insolvency procedures, and government bond markets should precede the rapid expansion of highly complex derivatives or opaque structured products. In this sense, the developmental value of finance depends not on sophistication alone, but on institutional fit.

The 3rd implication concerns business strategy. At the firm level, financial instruments shape the cost of capital, ownership structure, liquidity, risk exposure, tax position, covenant flexibility, and resilience to shocks. Firms do not use instruments in an abstract market environment. They use them under pressure from competition, inflation, exchange-rate volatility, interest-rate movements, supply-chain disruption, and shareholder expectations. Therefore, the governance of financial instruments within firms is as important as market regulation. Boards and managers must distinguish between instruments that reduce risk and instruments that create hidden exposure. Treasury policies, stress testing, counterparty limits, hedge documentation, and transparent reporting should become integral elements of corporate governance.

The 4th implication relates to systemic risk. The global financial crisis showed that complex financial instruments can make risk less visible without making it disappear. Securitisation, collateralised debt obligations, and derivatives can distribute exposure across investors, but they can also create chains of dependence that are difficult to understand during stress. The problem is not complexity as such, but complexity combined with leverage, weak underwriting, short-term funding, excessive reliance on ratings, and misaligned incentives. A key lesson is that financial systems should be evaluated not only in normal conditions, but also under stress scenarios. Instruments that appear liquid and safe during expansion may behave very differently when collateral values fall, funding markets freeze, and market participants rush to reduce exposure simultaneously.

This discussion also clarifies the role of regulation. Regulation should not aim to suppress financial instruments, because modern economies need instruments for credit, investment, trade, and risk management. Instead, regulation should ensure that instruments remain transparent, adequately capitalised, appropriately disclosed, and aligned with their stated economic function. Prudential rules, securities regulation, central clearing, resolution regimes, accounting standards, and macroprudential tools should be viewed as complementary elements of the same governance system. The regulatory challenge is dynamic because instruments evolve, market participants adapt, and risk often migrates to less regulated areas.

The 5th implication concerns fintech and digital financial instruments. Digital platforms, artificial intelligence, tokenisation, stablecoins, decentralised finance, and algorithmic trading are transforming the form and speed of financial instruments. These developments can reduce transaction costs, expand access, and improve efficiency. However, they also introduce new risks: cyber vulnerability, algorithmic herding, data concentration, consumer exploitation, operational failures, and regulatory arbitrage. The article therefore argues for function-based regulation. If a digital instrument performs the function of a deposit, security, derivative, payment system, or investment fund, it should be subject to comparable standards, regardless of technological form.

For transition economies, fintech offers both opportunity and risk. Digital instruments may allow countries to overcome weak legacy infrastructures and expand access to payments, credit, savings, and investment. However, rapid adoption without regulation may create dependence on private platforms, unstable digital credit, data extraction, and speculative volatility. The appropriate development strategy is not to adopt every financial innovation quickly, but to build digital public infrastructure, consumer protection, cybersecurity capacity, reliable identification systems, and supervisory competence.

The 6th implication concerns sustainable finance. Green bonds, sustainability-linked bonds, transition bonds, ESG funds, and climate-risk instruments demonstrate that financial instruments are increasingly expected to support environmental and social transformation. This is a major change in the purpose of finance. Instruments are no longer evaluated only by return, risk, and liquidity, but also by their contribution to climate adaptation, decarbonisation, social development, and long-term resilience. However, sustainable finance can fulfil this role only if standards, taxonomies, verification, reporting, and impact measurement are credible. Otherwise, sustainable labels may become reputational devices that obscure weak environmental results.

The analysis also shows that sustainable finance is particularly important for economic transition. Developing and emerging economies need large-scale investment in energy, transport, water systems, housing, agriculture, and industrial modernisation. Sustainable instruments can mobilise long-term capital for these needs, but only if projects are bankable and policy environments are credible. Financial instruments cannot by themselves create a green transition. They transmit capital towards transformation when supported by industrial policy, carbon regulation, infrastructure planning, technological innovation, and institutional credibility.

A further contribution of the article is the distinction between financial deepening and financial excess. Financial deepening occurs when instruments expand access to productive finance, savings, insurance, trade, and risk management. Financial excess occurs when instruments multiply claims, leverage, and complexity without corresponding growth in productive capacity or risk-bearing capital. This distinction is essential for policymakers because the same indicator—growth in financial assets—may reflect either healthy development or dangerous imbalance. Warning signs of excess include rapid credit growth, weak underwriting, opaque structures, maturity mismatches, dependence on short-term funding, and widespread use of instruments that users do not fully understand.

The practical policy implication is that financial-instrument development should be sequenced and governed. In advanced economies, the priority is to manage complexity, systemic interdependence, digital risk, and sustainable finance credibility. In transition economies, the priority is to strengthen institutional foundations before expanding sophisticated markets. In emerging markets, the priority is to manage external vulnerability, currency mismatch, and dependence on global liquidity cycles. In all contexts, the goal is not maximum financial innovation, but appropriate financial innovation.

The article also has implications for future research. Empirical studies could test the proposed institutional framework by comparing countries with similar instruments but different institutional quality. Firm-level research could analyse how corporate governance affects the use of derivatives, trade finance, and hybrid instruments. Crisis-period studies could examine how specific instruments behave under liquidity stress. Research on digital assets could evaluate

whether function-based regulation is more effective than technology-specific regulation. Sustainable finance research could measure whether labelled instruments produce measurable real-economy transformation or mainly symbolic compliance.

The main limitation of the article is that it is conceptual and analytical rather than econometric. It does not measure the quantitative impact of particular instruments on growth, volatility, or crisis probability. However, this limitation is also a methodological choice. The purpose of the article is to develop an integrated institutional-economic framework that can guide further empirical research and policy analysis. Such a framework is necessary because financial instruments operate across legal, economic, technological, and political domains.

Overall, the discussion confirms the central argument of the article: financial instruments should be understood as dual-use institutional technologies. They can mobilise savings, finance productive investment, support trade, hedge risk, and accelerate transition. They can also amplify leverage, transmit shocks, conceal fragility, and destabilise economies when institutions are weak. The future of financial instruments therefore depends less on innovation alone than on the quality of governance, transparency, supervision, institutional trust, and alignment with productive economic transformation.

Conclusion

Financial instruments are among the most important institutions of the modern economic and business environment. They mobilize savings, finance investment, support trade, distribute risk, generate prices, and structure corporate strategy. In globalization, they connect national economies through flows of debt, equity, currency, credit, and derivatives. In economic transition, they provide the contractual architecture through which privatization, investment, market creation, and institutional modernization occur.

Yet financial instruments are not automatically beneficial. Their effects depend on purpose, design, governance, and institutional context. Instruments that hedge genuine exposure can stabilize business activity; instruments that create opaque leverage can destabilize entire systems. Instruments that finance infrastructure, innovation, and green transition can support development; instruments that finance speculative bubbles can produce crisis and inequality. The central issue is not finance versus the real economy, but whether finance is structured to serve productive transformation.

The analysis has shown that the future of financial instruments will be shaped by four major forces: continued globalization, the unfinished process of economic transition, digital innovation, and sustainability imperatives. Each force expands the demand for sophisticated instruments, but each also increases the need for regulation, transparency, and institutional competence. The most successful economies will not be those with the most complex financial products, but those able to align financial innovation with stability, inclusion, and long-term productivity.

For international scientific research, the topic requires interdisciplinary treatment. Financial instruments are legal contracts, economic mechanisms, accounting objects, technological structures, and political-economic tools. Their study therefore requires integration of finance theory, macroeconomics, business strategy, law, regulation, and development economics. Such integration is essential because financial instruments now shape not only markets but also the

path of globalization, the success of transition economies, and the sustainability of future growth.

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Strategies for Innovative Development of the Enterprise: Theoretical Foundations, Classification, and Modern Trends ^[8]

Abstract:

The article provides a comprehensive theoretical and methodological study of the processes involved in forming and implementing enterprise innovative development strategies within a turbulent economic environment. The author reveals the multifaceted nature of the “innovation strategy” concept, which in modern conditions is transforming from a mere tool for technological renewal into a fundamental philosophy for business survival and growth. The genesis of innovation theories is explored, ranging from J. Schumpeter's classical concepts to modern models of interactive engagement and the ecosystem approach. The paper proposes and details an extensive classification of innovation strategies based on several criteria: the nature of market behavior (violent, patient, experient, commutant), risk level, market coverage scale, and intensity of research and development (R&D) activities. Particular attention is paid to strategic ambidexterity as an enterprise's ability to balance the exploitation of existing competencies with the exploration of radically new opportunities. Furthermore, the study provides a detailed analysis of modern approaches to innovation management dictated by the challenges of digital transformation and the implementation of Industry 4.0 and 5.0 technologies. In the context of Ukrainian realities, the specifics of strategic planning under high military risks are examined, where innovations serve as tools for adaptability and relocation resilience. The necessity of integrating Environmental, Social, and Governance (ESG) principles and the circular economy into the general innovation framework of the enterprise is substantiated. The practical significance of the study is supported by an analysis of successful business model transformation cases (specifically, the evolutionary path of Tesla), which allowed for the identification of mechanisms for transitioning from the stage of risky pioneering to market dominance. Based on the conducted analysis, promising directions for the innovative development of domestic businesses are outlined, focusing on process digitalization, the use of artificial intelligence, and the development of open innovation ecosystems. Recommendations are formulated to overcome internal and external barriers to an innovation breakthrough in the context of post-war economic recovery.

Keywords: innovation strategy, innovative development, competitiveness, digital transformation, Industry 4.0, innovation management, strategic planning.

Abbreviations:

CVC is corporate venture capital,

ESG is Environmental, Social, and Governance,

IoT is Internet of Things,

KPI is key performance indicator,

MVP is minimum viable product,

R&D is research and development,

ROI is return on investment.

Introduction

In the current conditions of global economic instability, intensifying competition and accelerating technological change, the innovative development of an enterprise is transforming from a desirable growth factor into a critical condition for survival, adaptability and long-term competitiveness. For Ukrainian enterprises, this issue is of particular importance in the context

of wartime challenges, the destruction or disruption of traditional supply chains, forced relocation of business activities, resource constraints and the need for rapid adaptation to new conditions of doing business. Under such circumstances, innovation is no longer limited to the introduction of new products or technologies; it becomes a strategic mechanism for maintaining economic resilience, restoring market positions and ensuring the future development of enterprises.

The relevance of this study is determined by the growing role of innovation strategies in enterprise management under conditions of uncertainty, digital transformation and structural changes in the global economy. Modern enterprises operate in an environment where competitive advantages are increasingly formed through technological renewal, business model transformation, data-driven decision-making, digitalisation of processes, cooperation within innovation ecosystems and the integration of sustainability principles. The Fourth Industrial Revolution, artificial intelligence, the Internet of Things, big data, cloud technologies, blockchain and cyber-physical systems are radically changing the logic of value creation and require enterprises to reconsider traditional approaches to strategic planning (*Schwab, 2019*). At the same time, the principles of ESG-oriented development and the circular economy increasingly influence innovation priorities, investment attractiveness and consumer loyalty.

An innovation strategy is a key management tool that determines the direction of enterprise development in response to contemporary challenges. It ensures adaptation to the requirements of customers and markets, supports the transformation of internal business processes and ultimately contributes to increasing competitiveness. In this sense, an innovation strategy functions as a link between the general corporate strategy of an enterprise and its innovation activity, defining the priorities, directions, resources and mechanisms for implementing innovations. It also determines how an enterprise balances technological renewal, organisational transformation, market positioning, risk management and the commercialisation of new ideas.

The research problem lies in the fact that, despite the growing significance of innovation for enterprise competitiveness, many companies still lack a systematic approach to the formation and implementation of innovation strategies. In practice, innovation activity is often fragmented, reactive and weakly integrated into the overall strategic management system. Enterprises may introduce individual technological solutions, digital tools or new products without a coherent innovation portfolio, clear performance indicators, sufficient resource support or a mechanism for adapting strategy to changes in the external environment. This problem is especially acute for Ukrainian enterprises, which must simultaneously respond to military risks, financial constraints, labour migration, the depreciation of fixed assets, weak links between science and business, and regulatory barriers to innovation activity.

The scientific novelty of this study consists in the systematisation of theoretical approaches to the formation of enterprise innovation strategies and in the analytical integration of classical innovation theory with modern trends in digital transformation, open innovation, ESG-oriented development and strategic adaptability under crisis conditions. The study considers innovation strategy not only as a tool for technological renewal, but also as a complex category of strategic management that includes product, process, organisational, marketing, social and business model innovations. Particular attention is paid to the differentiation of innovation strategies according to competitive position, degree of radicality, source of innovation activity and object

of innovation, as well as to the need to adapt these strategies to the specific conditions of Ukrainian enterprises.

The object of the study is the innovative development of enterprises in a turbulent economic environment.

The subject of the study is the theoretical foundations, classification features, strategic tools and modern trends in the formation and implementation of enterprise innovation strategies.

The study aims to systematise theoretical approaches to the formation of enterprise innovative development strategies, analyse their classification, identify current trends in innovation management and formulate practical recommendations for the implementation of innovation strategies under conditions of digital transformation, sustainability requirements and heightened uncertainty.

To achieve this purpose, the following research tasks are set:

- to clarify the essence of the concept of “innovation strategy” and trace its evolution from the classical understanding of innovation to modern strategic management approaches;
- to systematise the main functions and principles of forming an enterprise innovation strategy;
- to analyse key classifications of innovation strategies according to competitive position, degree of radicality, source of innovation activity and object of innovation;
- to examine the influence of Industry 4.0 technologies on the transformation of innovation strategies;
- to determine the role of open innovation, network interaction and innovation ecosystems in modern enterprise development;
- to assess the significance of ESG principles and circular economy approaches for enterprise innovation policy;
- to identify the specific challenges and opportunities of innovative development for Ukrainian enterprises under wartime and post-war recovery conditions;
- to analyse strategic tools used in innovation management, including SWOT analysis, technological foresight, S-curve analysis, innovation portfolio management and the Stage-Gate process;
- to generalise practical cases of business model transformation and innovative development in global companies;
- to formulate recommendations for improving the strategic management of innovation in enterprises of different sizes and sectors.

The theoretical basis of the study is formed by classical and modern approaches to innovation theory and strategic management. Schumpeter’s theory of innovation as “new combinations” of production factors provides the foundation for understanding innovation as a driver of economic development and structural change (*Schumpeter, 2011*). The strategic management approaches of Ansoff and Porter make it possible to consider innovation strategy as an integrated part of corporate development and competitive positioning (*Ansoff, 2007; Porter, 2020*). The concept of open innovation introduced by Chesbrough expands the understanding of innovation sources by emphasising cooperation with external actors, including universities, start-ups, research centres and technological partners (*Chesbrough, 2003*). The Oslo Manual

provides a methodological framework for analysing different types of innovations and their measurement in business practice (*OECD & Eurostat, 2018*).

The theoretical significance of the study lies in deepening the understanding of innovation strategy as a multidimensional management category that combines technological, organisational, market, social and sustainability-oriented components. The study contributes to the development of the theoretical foundations of innovation management by clarifying the functions, principles and classification criteria of enterprise innovation strategies. It also strengthens the conceptual link between innovation strategy, strategic competitiveness, digital transformation, open innovation ecosystems and sustainable development. In addition, the study helps to adapt general theoretical models of innovation management to the specific conditions of enterprises operating under crisis, wartime and post-war recovery conditions.

The practical significance of the research results lies in the possibility of using the proposed generalisations and recommendations in the strategic management of enterprises. The study may be useful for managers, owners, consultants, analysts and policymakers involved in innovation development, digital transformation and competitiveness improvement. The systematised classification of innovation strategies can support more informed strategic choice depending on enterprise size, industry, resource potential, market position and risk tolerance. The analysis of modern tools, such as technological foresight, innovation portfolio management, Lean Startup, Design Thinking, Agile and Stage-Gate approaches, can be applied in the development and implementation of innovation projects. For Ukrainian enterprises, the results are particularly relevant because they help identify innovation strategies that consider military risks, relocation challenges, limited financial resources, digital opportunities, DefenseTech and AgTech development, access to grant financing and state innovation support programmes.

Thus, this study addresses an important scientific and practical problem: how enterprises can form and implement innovation strategies that ensure competitiveness, adaptability and sustainable growth under conditions of technological turbulence and economic instability. The proposed approach treats innovation strategy as a systemic element of strategic enterprise management and as a key instrument for overcoming crisis constraints, entering new markets, increasing productivity and supporting post-war economic recovery.

Methods

This study was designed as a theoretical and methodological investigation of enterprise innovative development strategies under conditions of economic turbulence, digital transformation and heightened uncertainty. Since the research focuses on the conceptual foundations, classification and contemporary trends of innovation strategy formation, a qualitative analytical research design was applied. The methodological logic of the study combined theoretical generalisation, comparative analysis, classification, content analysis of scientific and regulatory sources, case-based interpretation and strategic management analysis.

The theoretical basis of the research was formed by classical and contemporary works in the fields of innovation theory, strategic management and innovation management. Particular attention was paid to Schumpeter's concept of innovation as a new combination of production factors, Ansoff's and Porter's approaches to strategic management and competitive positioning,

Chesbrough's open innovation paradigm, Christensen's theory of disruptive innovation, and modern approaches reflected in the Oslo Manual. These sources were used to reconstruct the evolution of the concept of innovation strategy from a narrow technological and R&D-oriented category to a multidimensional strategic management construct that includes product, process, organisational, marketing, social and business model innovations.

The source base of the study included monographs, scientific publications, methodological documents, regulatory acts and analytical materials related to innovation activity, enterprise competitiveness, open innovation, digital transformation, Industry 4.0, ESG-oriented development and the circular economy. In order to ensure the relevance of the analysis, priority was given to sources that reflect both classical theoretical foundations and contemporary trends in innovation management. Ukrainian regulatory and statistical materials were also considered in order to identify the specific institutional and economic conditions under which domestic enterprises form their innovation strategies.

The study was conducted in several methodological stages. At the first stage, the conceptual apparatus was clarified. The term "innovation strategy" was analysed from the standpoint of its historical evolution, functional content and connection with the general corporate strategy of the enterprise. This made it possible to define innovation strategy as a long-term programme of actions that determines the goals, priorities, directions and mechanisms of innovation activity aimed at ensuring competitiveness and sustainable development.

At the second stage, the main functions and principles of innovation strategy formation were systematised. The analysis covered the goal-setting, adaptive, coordinating, distributive, motivational and control functions of innovation strategy. The principles of systemacity, adaptability, continuity, risk orientation, resource sufficiency and strategic balance were examined as methodological conditions for the effective formation and implementation of innovation strategies.

At the third stage, a classification analysis of enterprise innovation strategies was carried out. The strategies were grouped according to several criteria: competitive position, degree of innovation radicality, source of innovation activity and object of innovation. This made it possible to distinguish offensive, defensive, imitation and niche strategies; radical, strategic and incremental innovation strategies; closed, open and network-based innovation strategies; and product, process, marketing and organisational innovation strategies. Such classification was used to demonstrate that there is no universal innovation strategy suitable for all enterprises, since strategic choice depends on industry, enterprise size, resource potential, market position and risk tolerance.

At the fourth stage, the study analysed contemporary trends influencing the formation of innovation strategies. Special attention was paid to the impact of Industry 4.0 technologies, including the Internet of Things, artificial intelligence, big data, cloud technologies, blockchain and cyber-physical systems. These technologies were considered not only as individual instruments of digitalisation, but also as factors that transform business models, production processes, market interaction and the logic of value creation. The study also examined the increasing role of ESG principles, green innovation, the circular economy, social innovation and responsible governance as strategic components of modern enterprise innovation policy.

At the fifth stage, strategic tools used in innovation management were analysed. The study considered SWOT analysis, technological foresight, S-curve analysis, an adapted BCG matrix for innovation portfolios, the Stage-Gate process, Lean Startup, Agile, Scrum, Design Thinking and the Jobs-to-be-Done approach. These tools were examined in terms of their applicability to the identification of innovation opportunities, assessment of technological readiness, selection of innovation projects, risk reduction and monitoring of innovation strategy implementation.

At the sixth stage, the specific features of innovative development of Ukrainian enterprises were identified. The analysis focused on wartime risks, physical threats to production facilities, logistical disruptions, forced business relocation, limited access to financial resources, labour migration, depreciation of fixed assets, weak interaction between science and business, regulatory barriers and difficulties in protecting intellectual property. At the same time, the study considered the innovation potential of Ukrainian business, including the development of the IT sector, DefenseTech, AgTech, digital public services, access to international grant financing and state support programmes for innovative entrepreneurship.

At the seventh stage, a case-based analytical approach was applied to interpret practical examples of innovation strategy implementation. The study considered global cases of business model transformation and innovation management, including open innovation practices, digital transformation, sustainable innovation and radical innovation strategies. These examples were used to identify mechanisms through which enterprises move from technological experimentation to market leadership, ecosystem formation and long-term competitive advantage.

The methodological approach also included comparative analysis. Classical linear models of innovation, such as technology-push and market-pull models, were compared with contemporary interactive and ecosystem-based models. Closed R&D models were compared with open innovation strategies, while traditional strategic planning approaches were compared with flexible methodologies such as Lean Startup, Agile and Design Thinking. This comparison made it possible to reveal the transformation of innovation management from a hierarchical and internally controlled process into an adaptive, networked and customer-oriented system.

Generalisation and synthesis were used at the final stage of the research. On the basis of the theoretical analysis, classification, comparison and case interpretation, the study formulated conclusions regarding the strategic role of innovation in enterprise competitiveness. The synthesis made it possible to identify promising directions for the innovative development of enterprises, including process digitalisation, artificial intelligence implementation, open innovation ecosystems, ESG integration, innovation portfolio balancing and strategic adaptation under crisis conditions.

The reliability of the research results was ensured by the use of several complementary methods and source groups. Theoretical sources were combined with methodological documents, regulatory materials, statistical information and practical business cases. This triangulation made it possible to avoid a purely abstract interpretation of innovation strategy and to connect theoretical concepts with practical management conditions, including the specific constraints and opportunities of Ukrainian enterprises.

The methodological limitation of the study is that it is predominantly theoretical and analytical. It does not include direct empirical testing based on surveys, interviews or econometric modelling of enterprise innovation performance. Therefore, the conclusions should be interpreted as conceptual and methodological generalisations that require further empirical verification. Future studies may develop this research direction by applying quantitative methods to assess the impact of specific innovation strategies on enterprise productivity, profitability, export potential, resilience and post-war recovery performance.

Overall, the selected methodology made it possible to provide a comprehensive analysis of enterprise innovative development strategies, systematise their theoretical foundations and classifications, and identify the main contemporary trends affecting their implementation. The applied combination of theoretical generalisation, classification, comparative analysis and case-based interpretation corresponds to the purpose of the study and provides a structured basis for formulating practical recommendations for innovation strategy development.

Literature Review

The problem of enterprise innovative development has long occupied a central position in economic theory, strategic management and innovation studies. In classical economic thought, innovation was primarily interpreted as a driver of economic dynamics and structural transformation. Schumpeter's theory of economic development remains the conceptual foundation for understanding innovation as a "new combination" of production factors, including the creation of new products, the introduction of new production methods, access to new markets, the use of new sources of raw materials and the reorganisation of enterprise management structures (*Schumpeter, 2011*). This approach is important because it shifts the interpretation of innovation from a narrow technical improvement to a broader economic mechanism that changes market structures, competitive relations and the trajectory of enterprise growth.

In the second half of the twentieth century, the development of strategic management theory significantly influenced the interpretation of innovation at the enterprise level. The works of Ansoff and Porter made it possible to consider innovation not only as a technological phenomenon, but also as an element of corporate strategy, competitive positioning and long-term market behaviour (*Ansoff, 2007; Porter, 2020*). Within this paradigm, innovation strategy becomes a tool for aligning internal enterprise resources with external market opportunities and threats. It determines how an enterprise responds to competitive pressure, technological change and shifts in consumer demand. Therefore, innovation strategy should be regarded as an integrated component of the general development strategy rather than as an isolated functional plan limited to research and development.

The evolution of the concept of innovation strategy also reflects the transformation of innovation models. Early approaches were dominated by linear models, especially the technology-push and market-pull models. The technology-push model considered innovation as a sequence from scientific discovery to design, production and market introduction, whereas the market-pull model explained innovation as a response to consumer needs. Although these models are useful for describing basic innovation logic, they are insufficient for explaining contemporary innovation processes, which are interactive, networked and iterative. Modern

innovation increasingly emerges through feedback loops between scientific knowledge, technological capabilities, market demand, digital platforms, customers, suppliers, start-ups and research institutions.

The contemporary understanding of innovation strategy is strongly influenced by the open innovation paradigm. Chesbrough (2003) demonstrated that enterprises can no longer rely solely on internal research and development resources, especially under conditions of technological complexity and shortened innovation cycles. Open innovation assumes the active use of external knowledge, technologies and partnerships. It also implies that internal developments may be commercialised through external channels. This approach is especially relevant for enterprises operating in dynamic markets, where cooperation with universities, start-ups, research centres, suppliers and customers allows firms to accelerate innovation processes and reduce development risks. As a result, innovation strategy increasingly becomes ecosystem-oriented rather than exclusively firm-centred.

The classification of innovation strategies is one of the key theoretical problems in innovation management. One of the most widespread approaches is based on the enterprise's competitive position in the market. In this context, offensive, defensive, imitative and niche strategies are usually distinguished. Offensive innovation strategy is typical of market leaders and technological pioneers that introduce new products or technologies before competitors. Such a strategy requires substantial investment in research and development, strong technological capabilities and high-risk tolerance. Defensive innovation strategy is based on the rapid adoption and improvement of successful innovations introduced by competitors. Imitative strategy focuses on copying or adapting existing solutions, often with lower cost or localisation advantages. Niche strategy is aimed at serving narrow market segments with specific needs, where innovation is associated with deep specialisation and customer proximity (Kotler & Keller, 2016).

Another important classification criterion is the degree of innovation radicality. Radical or breakthrough innovation strategies involve the creation of fundamentally new products, technologies or markets and are associated with high uncertainty and potentially high returns. Christensen's theory of disruptive innovation is particularly relevant here, since it explains how new technologies and business models may initially appear inferior by traditional performance criteria but later transform entire industries (Christensen, 1997). Incremental innovation strategies, by contrast, involve continuous improvement of existing products, processes or services. They are less risky and more predictable, but their growth potential is usually more limited. Between these poles are strategic innovations, which may not radically change the product itself but transform the business model, value proposition or method of customer interaction.

Innovation strategies may also be classified according to the source of innovation activity. Closed innovation strategies rely mainly on internal research, development and commercialisation. Such strategies provide stronger control over intellectual property, technological secrecy and strategic direction, but they are often expensive and slow. Open innovation strategies combine internal and external sources of knowledge and allow enterprises to access broader technological opportunities. Network and collaborative strategies go further by forming innovation ecosystems, strategic alliances, clusters, joint ventures and technology

parks. These strategies are especially important in knowledge-intensive industries, where no single enterprise can independently control the full spectrum of required technologies and competences.

The Oslo Manual provides an important methodological basis for distinguishing the objects of innovation. According to this approach, innovation may relate not only to products, but also to processes, marketing methods and organisational arrangements (*OECD & Eurostat, 2018*). Product innovation strategies focus on the creation of new or improved goods and services. Process innovation strategies involve changes in production, logistics, management or service delivery. Marketing innovation strategies concern new methods of promotion, pricing, distribution and customer interaction. Organisational innovation strategies involve changes in management systems, business models, labour organisation and inter-firm cooperation. This classification is essential because modern enterprise competitiveness is often achieved through the combination of several innovation types rather than through product renewal alone.

The Fourth Industrial Revolution has significantly changed the content and priorities of enterprise innovation strategies. Schwab (*2019*) emphasised that Industry 4.0 technologies blur the boundaries between physical, digital and biological systems. For enterprises, this means that innovation strategies must increasingly integrate the Internet of Things, artificial intelligence, machine learning, big data analytics, cloud computing, blockchain and cyber-physical systems. These technologies transform production processes, supply chains, customer relations and business models. In particular, artificial intelligence enables predictive analytics and automated decision-making; big data creates opportunities for identifying hidden market patterns; IoT allows real-time monitoring and optimisation of operations; cloud technologies reduce entry barriers for digital projects; and blockchain increases transparency and trust in supply chains and transactions.

Digital transformation also changes the organisational logic of innovation management. Traditional long-term planning is increasingly supplemented by flexible methodologies that allow enterprises to test hypotheses, adapt to customer feedback and reduce the cost of failure. The Lean Startup approach is based on the rapid testing of business hypotheses through minimum viable products and the iterative cycle of “build–measure–learn” (*Ries, 2025*). Agile and Scrum support iterative development, cross-functional teamwork and constant customer feedback. Design Thinking focuses on human-centred problem-solving by combining empathy, creativity and rational analysis. These approaches are especially relevant in uncertain environments where customer needs, technologies and market boundaries are rapidly changing.

Another major trend in innovation strategy is the integration of sustainability principles. Enterprises increasingly incorporate ESG criteria into innovation activity, including environmental responsibility, social impact and transparent governance. Green innovation, circular economy models, recycling technologies, renewable energy solutions and socially oriented innovations are becoming sources of competitive advantage. This reflects a broader transformation of innovation policy: innovation is no longer evaluated only by its economic or technological results, but also by its environmental and social consequences. For investors, consumers and regulators, sustainability-oriented innovation is increasingly becoming a criterion of enterprise reliability and long-term development potential.

The literature also emphasises the importance of strategic tools for innovation management. SWOT analysis remains widely used, but in the context of innovation it should focus not only on general strengths and weaknesses, but also on technological capabilities, patent potential, innovation culture and threats from disruptive technologies. Technological foresight allows enterprises to anticipate long-term scientific and technological trends and prepare for the emergence of new markets. S-curve analysis helps managers determine the limits of existing technologies and identify the moment when investment in a new technological trajectory becomes necessary. Innovation portfolio management, including adapted BCG matrices, allows firms to balance projects according to risk, expected return, time horizon and strategic relevance. The Stage-Gate process provides staged control over the development and commercialisation of innovation projects, reducing the probability of large-scale financial losses from unviable initiatives.

The Ukrainian context adds specific dimensions to the theory of innovation strategy. The Law of Ukraine “On Innovation Activity” defines the institutional framework for supporting innovation, but practical implementation is complicated by financial constraints, regulatory barriers, weak science-business interaction and difficulties in intellectual property protection (*On Innovation Activity, 2002*). In addition, wartime conditions create unprecedented challenges for enterprise innovation. These include the destruction of production facilities, disruption of logistics, forced relocation, reduced access to capital, labour migration and increased operational uncertainty. Under such conditions, innovation strategy becomes not only an instrument of competitiveness, but also a mechanism of resilience, adaptation and survival.

At the same time, Ukrainian enterprises possess significant innovation potential. The development of the IT sector, DefenseTech, AgTech, digital public services and access to international grant financing creates opportunities for integration into global technological ecosystems. Statistical and analytical materials on innovation activity in Ukrainian industry indicate that domestic enterprises face serious structural constraints, but also demonstrate the capacity to develop digital, defence-oriented and export-oriented innovation models (*State Statistics Service of Ukraine, 2023–2025*). For small and medium-sized enterprises, open innovation, cooperation with universities and start-ups, cloud technologies and grant financing may be especially important. For large enterprises, innovation laboratories, corporate venture capital, ESG integration and systematic intellectual property management become more relevant.

International business cases also confirm the diversity of innovation strategy models. The transformation of Procter & Gamble through the “Connect + Develop” programme illustrates the practical potential of open innovation. Siemens demonstrates how a traditional industrial corporation can become a leader in digital industry through industrial software and IoT platforms. Patagonia shows that sustainability-oriented innovation can strengthen customer loyalty and market differentiation. Tesla represents a case of radical and disruptive innovation based on electric vehicles, vertical integration, battery production, charging infrastructure and software-based product development. These examples show that successful innovation strategies combine technological renewal with business model transformation, ecosystem creation and clear market positioning.

Despite the breadth of existing research, several gaps remain. First, many studies analyse innovation strategies in general terms but do not sufficiently integrate classical theories with contemporary digital, ESG and ecosystem-based trends. Secondly, classifications of innovation strategies are often presented separately, without showing how different classification criteria interact in real enterprise decision-making. Thirdly, limited attention is paid to the formation of innovation strategies under conditions of war, relocation risk and post-war recovery. Fourthly, the Ukrainian enterprise context requires further conceptualisation because standard global models cannot be directly transferred without considering institutional, financial and security constraints.

Therefore, the present study builds on existing theoretical approaches and seeks to systematise enterprise innovation strategies in a way that reflects both classical foundations and contemporary transformations. It considers innovation strategy as a multidimensional construct that includes competitive positioning, technological renewal, organisational change, digital transformation, open innovation, sustainability and crisis adaptation. This approach makes it possible to develop a more comprehensive understanding of how enterprises can form and implement innovation strategies under conditions of economic turbulence, technological change and structural uncertainty.

Results

The concept of “innovation strategy” has undergone a long evolution, from being identified mainly with R&D to becoming a complex category of strategic management. In the 1950s and 1960s, innovation was regarded primarily as a set of technical improvements, while strategy was reduced mainly to the planning of R&D budgets (*Chesbrough, 2003*). In the 1970s and 1980s, with the development of strategic planning approaches associated with I. Ansoff and M. Porter, innovation strategy began to be understood as an integrated component of corporate strategy. The contemporary stage, from the 2000s to the present, is characterised by the interpretation of innovation strategy as a dynamic system that encompasses not only technological, but also organisational, marketing and social innovations (*Porter, 2020; Ansoff, 2007*).

In essence, an enterprise innovation strategy is a long-term programme of action that defines the goals, priorities, directions and mechanisms of innovation activity, thereby ensuring the competitiveness and sustainable development of an enterprise through the creation, implementation and commercialisation of innovations.

The main functions and principles of innovation strategy formation should be considered. An innovation strategy performs the following key functions:

- goal-setting function, which involves the formulation of strategic objectives for innovative development;
- adaptive function, which ensures the enterprise’s adaptation to changes in the external environment;
- coordinating function, which aligns innovation activity with other functional strategies;
- distributive function, which determines the priorities for financing innovation projects;
- motivational function, which stimulates the creative activity of personnel and supports the formation of an innovation culture;

- control function, which establishes criteria for assessing the effectiveness of innovation activity.

At the same time, the principles of innovation strategy formation include the following:

- systemacity, which means considering innovation as an integral system connected with all aspects of enterprise activity;
- adaptability, which refers to the ability to adjust the strategy in response to environmental changes;
- continuity, which implies the constant search for and implementation of innovation opportunities;
- risk orientation, which requires taking into account uncertainty and the risks inherent in innovation activity;
- resource sufficiency, which means ensuring correspondence between innovation ambitions and available resources;
- balance, which involves the optimal combination of radical and incremental innovations.

The scientific literature presents a wide range of classifications of innovation strategies. The most widespread approaches are considered below.

The first approach is classification according to competitive position, following F. Kotler (*Kotler & Keller, 2016*). This classification is based on the role of the enterprise in competition.

The leader strategy, or offensive strategy, is used when an enterprise is the first to introduce new products or technologies to the market. It requires substantial investment in R&D, a strong scientific and technical base, and a high tolerance for risk. This strategy is typical of pioneering companies such as Apple, Tesla and Alphabet.

The follower strategy, or defensive strategy, is used when an enterprise does not seek to be first, but quickly adopts successful innovations introduced by competitors, improves them and reduces associated risks. This strategy requires well-developed benchmarking and engineering analysis skills.

The imitator strategy, or borrowing strategy, involves copying the leader's products with minimal improvements, often with an emphasis on a lower price or adaptation to the local market.

The dependent strategy, or niche strategy, is aimed at serving a narrow market segment with specific needs. In this case, innovation is directed towards deep specialisation.

At the same time, the founder of innovation theory, Joseph Schumpeter, as early as the beginning of the twentieth century, defined innovation as a “new combination” of production factors, which includes the creation of a new product, the introduction of a new method of production, the development of a new market, the attraction of new sources of raw materials or the reorganisation of the management structure (*Schumpeter, 2011*). In the second half of the twentieth century, linear models dominated:

Model 1, Technology Push: Science → Design → Production → Marketing.

Model 2, Market Pull: Market Needs → Development → Production.

The contemporary approach, represented by the interactive model, argues that innovation is not a linear process, but a complex network of feedback links between scientific knowledge, technological capabilities and consumer demand.

The second approach classifies innovation strategies according to the degree of innovation radicality.

The strategy of radical, or breakthrough, innovations involve the creation of fundamentally new products or technologies that transform the market landscape. It is characterised by high risk and significant investment, but also by potentially very high returns. An example is the transition from push-button mobile phones to smartphones.

Strategic innovations involve a change in the business model or in the method of creating value for the customer without necessarily radically changing the product itself. One example is the transition from selling a product to providing a service, as in the Product-as-a-Service model.

The strategy of incremental innovations involves the continuous improvement of existing products, processes or services. It is associated with lower risk and more predictable results, but also with more limited growth potential.

The third approach classifies innovation strategies according to the source of innovation activity.

A closed, or vertically integrated, strategy means that the entire innovation process is carried out internally, from fundamental research to commercialisation. Classical examples include Bell Labs and IBM in the twentieth century. The advantages of this strategy are full control and protection of intellectual property, while its disadvantages are high costs and slower implementation.

An open innovation strategy combines internal and external sources of knowledge. The enterprise actively uses start-ups, universities, research centres and crowdsourcing. The term was introduced by Henry Chesbrough in 2003 and has become a contemporary paradigm for most technology companies.

A network, or collaborative, strategy involves the creation of innovation ecosystems through strategic alliances, joint ventures, clusters and technology parks. The synergy of participants makes it possible to accelerate innovation processes.

The fourth approach classifies innovation strategies according to the object of innovation.

- A product strategy focuses on the creation of new products and services or the improvement of existing ones.
- A process strategy involves the introduction of new or improved production, logistics or management processes.
- A marketing strategy is based on the application of new methods of promotion, pricing and distribution.
- An organisational strategy involves the introduction of new organisational structures, management systems and business models (*Ries, 2025*).

With regard to innovative development in contemporary conditions, the following tendencies may be identified. The Fourth Industrial Revolution is radically transforming approaches to innovative development (*Schwab, 2019*). The key Industry 4.0 technologies that shape enterprise innovation strategies include the following:

- the IoT, which enables the creation of “smart” products and production systems, as well as real-time data collection for process optimisation;

- artificial intelligence and machine learning, which support the automation of decision-making, demand forecasting and personalised offers;
- big data, which enables the analysis of large datasets in order to identify hidden patterns and innovation opportunities;
- cloud technologies, which reduce entry barriers for innovation projects, provide scalability and ensure access to advanced digital tools;
- blockchain, which contributes to transparency, security and trust in supply chains and financial transactions;
- cyber-physical systems, which integrate computational and physical processes, including the development of digital twins.

At the same time, the global trend towards sustainable development significantly influences innovation strategies. Enterprises increasingly integrate ESG criteria, that is, Environmental, Social and Governance principles, into their innovation activities. This includes the implementation of green innovations, such as the development of environmentally friendly products, recycling technologies and renewable energy solutions; the transition to the circular economy through the creation of closed production cycles and waste minimisation; social innovations aimed at developing products and services that address social problems; and responsible governance based on transparent and ethical management practices.

Modern innovation management is also increasingly based on flexible methodologies. These include:

- Agile and Scrum, which involve the iterative development of innovative products with continuous customer feedback;
- Lean Startup, which focuses on rapid hypothesis testing through MVPs and the “build–measure–learn” cycle (*Ries, 2025*);
- Design Thinking, which represents a human-centred approach to innovation combining empathy, creativity and rational analysis;
- Jobs-to-be-Done, which focuses on the functional, social and emotional “jobs” that customers need to accomplish.

The process of forming and implementing an innovation strategy should be considered in more detail through the main stages of innovation strategy development.

At the first stage, the external environment is analysed through the assessment of technological trends, the competitive landscape, regulatory changes and macroeconomic factors. Tools such as PESTEL analysis and technological foresight may be used for this purpose.

At the second stage, the internal potential of the enterprise is assessed. This includes evaluating the scientific and technical base, R&D capabilities, innovation culture and financial resources. Relevant tools include VRIO analysis, technological audit and other diagnostic instruments.

At the third stage, strategic objectives are defined. This involves formulating long-term goals of innovative development, such as the share of innovative products in total sales, the number of patents, or the increase in market share achieved through innovation.

At the next stage, the type of innovation strategy is selected. Based on the results of the previous analysis, the enterprise chooses the most appropriate strategic option, such as an offensive, defensive, imitation or other type of strategy.

The following stage involves the development of an innovation portfolio. At this stage, a set of innovation projects is formed and balanced according to risk level, implementation horizon and expected return. Resource provision is also determined, including budget allocation, sources of financing, staffing requirements and infrastructure needs.

The final stage consists of implementation and monitoring. It includes the execution of innovation projects, control over the achievement of KPIs, and adjustment of the strategy in response to changes in internal and external conditions.

In the course of this study, it is also necessary to analyse the tools of strategic innovation analysis. The main tools should therefore be considered in more detail, beginning with SWOT analysis. In the context of innovative development, SWOT analysis shifts its focus towards assessing the technological capacity of the enterprise, identifying hidden patent opportunities and analysing threats posed by competitors' disruptive technologies. Technological foresight also plays an important role as a method for the systematic anticipation of long-term horizons of scientific and technological progress, enabling businesses to prepare in advance for the emergence of new markets. At the same time, the analysis of technology S-curves helps management clearly identify the performance limits of existing solutions and determine the critical moment for investing in fundamentally new developments in order to avoid technological lag. In parallel, the use of an adapted BCG matrix for innovation makes it possible to balance a portfolio of projects by distinguishing them according to expected profitability and required financing volumes. In combination with the implementation of the Stage-Gate process, this ensures strict stage-by-stage control over the implementation of ideas through a system of decision-making "gates", where each step is assessed in terms of commercial feasibility and technical implementability, thereby minimising financial losses from potentially unsuccessful innovation initiatives.

The effective application of the strategic analysis tools considered above, from SWOT matrices to technological foresight, allows companies to reduce uncertainty. However, their effectiveness in the real sector of the economy critically depends on the specific features of the national business environment. For domestic business entities, theoretical models of strategy selection inevitably encounter a unique complex of exogenous factors. This makes the transition from general global methodologies to the analysis of the specific features of innovative development in Ukrainian enterprises a logical and necessary step for understanding the real state of affairs. It is therefore appropriate to consider in more detail how global innovation tools are adapted to contemporary Ukrainian realities, where traditional approaches to development management are being tested by unprecedented challenges and, at the same time, open windows of new strategic opportunities.

When analysing the specific features of innovative development in Ukrainian enterprises, it is necessary first of all to emphasise unprecedented wartime risks. These include direct physical threats to production facilities, critical logistical complications and the need for forced business relocation. These challenges are accompanied by acute financial constraints, including a shortage of working capital, high interest rates and extremely limited access to venture capital.

The situation is further complicated by a large-scale brain drain caused by the emigration of leading scientists, engineers and IT specialists. In combination with the critical depreciation of fixed assets and the moral obsolescence of equipment, this significantly narrows the technological room for manoeuvre. At the same time, the imperfection of innovation infrastructure, weak links between science and business, systemic regulatory barriers and difficulties in protecting intellectual property create additional obstacles to strategic renewal (*On Innovation Activity, 2002*).

At the same time, despite these complex challenges, Ukrainian business demonstrates considerable innovation potential. A powerful driver is digital transformation and the success of global IT leaders, which creates a basis for integrating domestic companies into international technological ecosystems and value chains. The sphere of defence technologies, or DefenseTech, is gaining particular momentum, including the development of drones and cybersecurity systems. This trend is closely connected with the active implementation of agricultural innovations in the form of precision farming. In addition, expanded access to international grant financing, such as Horizon Europe, in synergy with state initiatives such as Diia.City and the Innovation Development Fund, opens new prospects for scaling Ukrainian start-ups at the global level (*State Statistics Service of Ukraine, 2023–2025*).

The formation of an effective innovation strategy requires a differentiated approach. For small and medium-sized enterprises, the open innovation model becomes a priority, as it involves active collaboration with universities and start-ups instead of maintaining expensive internal R&D departments. In this segment, the application of Lean methodologies for rapid hypothesis testing through MVPs is critically important, since it allows risks to be minimised at early stages. Equally important are niche specialisation and the active implementation of accessible digital tools and cloud services. Together with the attraction of non-traditional financing through crowdfunding and grant programmes, these factors create conditions for technological growth even under resource constraints.

For large enterprises, the strategic emphasis shifts towards the development of complex internal infrastructure, in particular through the creation of CVC funds and innovation laboratories operating in the format of “internal start-ups” for the search for breakthrough technologies. Large-scale businesses should focus on deep integration with the academic environment, the implementation of ESG principles to increase investment attractiveness and the development of a systematic intellectual property management policy. Such a policy includes the formation of strong patent portfolios and the licensing of proprietary developments in external markets.

The effectiveness of the selected strategic course is assessed through a system of KPIs, among which the share of innovative products in total sales, with a target benchmark of more than 20%, and the ROI in innovation are of particular importance. Alongside quantitative parameters, such as the number of products introduced or patent applications submitted, special attention is paid to dynamic characteristics, including time-to-market, the assortment renewal rate and the customer satisfaction index. Taken together, these indicators make it possible to objectively measure the impact of innovation on the market position and strategic resilience of the enterprise.

The analysis of international experience confirms that the success of an innovation strategy depends on a company's ability to adapt its business model to global trends. This is demonstrated by Procter & Gamble through its "Connect + Develop" programme. By transforming a closed R&D system into an open innovation model, the company ensured that more than 50% of new ideas came from external sources, which made it possible to increase development productivity by 60% while simultaneously reducing costs through the active use of online platforms for partner search and technology licensing. Similarly, the case of Siemens illustrates a deep digital transformation in which a traditional industrial giant became a leader in industrial software by creating the cloud-based IoT platform MindSphere and the Digital Industries division, enabling the share of digital services in revenue to exceed 30%.

Another vector of success is demonstrated by the Patagonia brand, which integrated sustainability principles directly into its innovation strategy by using recycled materials and implementing circular economy practices through repair services. This environmentally conscious position, reinforced by allocating 1% of revenue to environmental projects, paradoxically became a major driver of customer loyalty and financial growth (*OECD & Eurostat, 2018; Christensen, 1997*).

At the same time, Tesla represents a benchmark example of a radical innovation strategy. The company did not merely create an electric vehicle; it formed a new mobility ecosystem by combining vertical integration in battery production, the development of its own Supercharger charging network and regular functional updates of vehicles through software, including over-the-air updates. This enabled Tesla to transform the automobile into a "smartphone on wheels", secure the status of the world's most valuable car manufacturer and force the entire industry to accelerate the transition towards renewable energy sources.

Tesla implemented a disruptive innovation strategy aimed at the complete transformation of the energy and transport industries. Its key elements include vertical integration, particularly in-house battery production through Gigafactory facilities; the creation of a closed infrastructure of Supercharger charging stations; and the transition to the "car-as-a-service" model through continuous software updates. As a result, Tesla became a leader in the electric vehicle market with the highest market capitalisation in the industry, demonstrating the viability of a business model based on the combination of high technologies, energy efficiency and direct sales to consumers.

Discussion

The results of the study confirm that innovation strategy should be considered not as a narrow functional instrument of research and development management, but as a multidimensional component of strategic enterprise governance. The evolution of this concept from R&D planning to a complex system of technological, organisational, marketing, social and business model innovations reflects the broader transformation of the modern economy. In conditions of digital disruption, geopolitical instability, sustainability requirements and intensified global competition, innovation strategy becomes a critical mechanism through which enterprises ensure adaptability, competitiveness and long-term resilience.

The theoretical analysis demonstrates that the interpretation of innovation strategy must be grounded in both classical and contemporary approaches. Schumpeter's concept of

innovation as a “new combination” of production factors remains relevant because it explains innovation as a source of structural transformation and entrepreneurial renewal (*Schumpeter, 2011*). However, the contemporary enterprise environment requires a broader understanding of innovation. Innovation is no longer limited to the creation of new products or production methods; it also includes the redesign of business models, the restructuring of value chains, the digitalisation of operations, the formation of innovation ecosystems and the integration of sustainability principles. Therefore, the study supports the position that innovation strategy should be understood as a long-term system of decisions aimed at aligning technological opportunities, market needs, internal capabilities and strategic development priorities.

The classification of innovation strategies analysed in the study shows that enterprises have no universal model of innovative development. Offensive, defensive, imitative and niche strategies differ significantly in terms of risk level, resource requirements, expected returns and market behaviour. Offensive strategies are appropriate for enterprises with strong R&D capabilities, sufficient investment resources and high tolerance for uncertainty. Defensive and follower strategies may be more suitable for firms that seek to reduce risk by adopting and improving already tested solutions. Imitative strategies can provide short-term competitive advantages in cost-sensitive markets, whereas niche strategies are especially relevant for enterprises serving specialised customer segments. This confirms that the choice of innovation strategy should be contingent upon the enterprise’s competitive position, resource potential, industry dynamics and strategic ambitions.

The distinction between radical, strategic and incremental innovation is also important for understanding the logic of enterprise development. Radical innovations may transform markets and create new competitive spaces, but they require substantial investment and involve high uncertainty. Incremental innovations, by contrast, are more predictable and less risky, but their effect on long-term competitiveness may be limited. Strategic innovations occupy an intermediate position because they may not necessarily change the product itself, but they can transform the way value is created, delivered and monetised. This is particularly important in the contemporary economy, where business model innovation may generate competitive advantage even without a radical technological breakthrough.

The findings also confirm the growing role of open and network-based innovation strategies. Closed vertically integrated innovation models provide control over intellectual property and internal technological development, but they are increasingly difficult to sustain under conditions of technological complexity and shortened innovation cycles. The open innovation paradigm introduced by Chesbrough emphasises the strategic value of external knowledge sources, including universities, start-ups, research centres, crowdsourcing platforms and industrial partners (*Chesbrough, 2003*). For many enterprises, especially small and medium-sized firms, cooperation within innovation ecosystems becomes a more realistic and efficient path than maintaining expensive internal R&D departments. This is particularly relevant in economies with limited investment resources and fragmented innovation infrastructure.

The analysis of Industry 4.0 technologies demonstrates that digital transformation is not merely one of the directions of innovation activity, but a fundamental factor reshaping the entire system of enterprise strategy. Artificial intelligence, big data, cloud technologies, the Internet of Things, blockchain and cyber-physical systems alter the logic of production, logistics, customer

interaction and decision-making. In this context, innovation strategy must integrate digital technologies not as isolated tools, but as elements of a new architecture of enterprise competitiveness. Schwab's interpretation of the Fourth Industrial Revolution is relevant here because it emphasises the convergence of physical, digital and organisational systems ([Schwab, 2019](#)). For enterprises, this convergence means that innovation strategy must simultaneously address technology adoption, organisational readiness, data governance, cybersecurity, human capital development and changes in business models.

The discussion of ESG principles and the circular economy shows that sustainability has become an integral part of innovation strategy. Previously, environmental and social considerations were often perceived as external constraints or reputational obligations. In contemporary business practice, however, sustainability-oriented innovation may become a direct source of competitive advantage. Green technologies, recycling systems, circular production models, responsible governance and social innovation can increase investment attractiveness, strengthen customer loyalty and open access to new markets. Therefore, the integration of ESG principles into innovation strategy should not be considered supplementary; it is becoming one of the conditions for long-term strategic legitimacy and competitiveness.

The study also highlights the methodological importance of flexible innovation management approaches. Agile, Scrum, Lean Startup, Design Thinking and Jobs-to-be-Done reflect the transition from rigid long-term planning to iterative, customer-oriented and hypothesis-driven innovation processes. This transformation is especially important under uncertainty, where enterprises cannot rely only on linear planning and complete information. The Lean Startup logic of rapid hypothesis testing through minimum viable products reduces the cost of failure and accelerates learning ([Ries, 2025](#)). Design Thinking enhances the human-centred dimension of innovation, while Agile and Scrum support continuous adaptation. Together, these approaches make innovation strategy more dynamic and better suited to unstable market conditions.

The strategic tools considered in the study—SWOT analysis, technological foresight, S-curve analysis, innovation portfolio management, the adapted BCG matrix and the Stage-Gate process—are important for transforming innovation strategy from a declarative intention into a manageable process. SWOT analysis helps identify technological strengths and vulnerabilities; technological foresight supports anticipation of future technological trajectories; S-curve analysis enables management to identify the maturity and limits of existing technologies; portfolio tools help balance risk and return; and Stage-Gate procedures create structured control over the movement of ideas from concept to commercialisation. The combined use of these tools increases the rationality of innovation decision-making and reduces the probability of resource dispersion across weak or strategically irrelevant projects.

The Ukrainian context gives the problem of innovation strategy particular practical significance. For Ukrainian enterprises, innovation is not only a means of growth, but also a mechanism of survival and recovery. Wartime risks, destruction of production facilities, disruption of logistics, forced relocation, shortage of working capital, high credit costs, labour migration and weakened investment capacity create a specific environment in which standard strategic models require adaptation. The Law of Ukraine “On Innovation Activity” provides a formal institutional framework, but the effectiveness of innovation development depends on

the ability to overcome gaps between science and business, regulatory barriers, insufficient protection of intellectual property and limited access to long-term financing (*On Innovation Activity*, 2002).

At the same time, the analysis shows that Ukrainian enterprises possess significant innovation potential. The development of the IT sector, DefenseTech, AgTech, digital public infrastructure and access to international grant programmes creates opportunities for integration into global innovation ecosystems. In this sense, the wartime economy generates not only constraints, but also new innovation impulses. Defence technologies, cybersecurity, drone systems, precision agriculture, cloud services and digital platforms may become areas in which Ukrainian enterprises can build specialised competitive advantages. Therefore, innovation strategy in the Ukrainian context should combine resilience-oriented measures with long-term technological positioning.

A differentiated approach to innovation strategy is particularly important for enterprises of different sizes. Small and medium-sized enterprises should focus on open innovation, cooperation with universities and start-ups, rapid market testing, digital tools, cloud services, niche specialisation and grant or crowdfunding mechanisms. Such enterprises usually lack the resources to maintain full-scale R&D structures, but they can achieve flexibility and speed through external collaboration and lean innovation methods. Large enterprises, by contrast, should develop corporate venture capital mechanisms, internal innovation laboratories, systematic intellectual property management, ESG integration and partnerships with academic institutions. This distinction is important because applying the same innovation management model to enterprises of different scale may lead to inefficient resource allocation.

The cases discussed in the study illustrate different models of successful innovation strategy. Procter & Gamble demonstrates the potential of open innovation through the transformation of a closed R&D model into a network-based system of external knowledge acquisition. Siemens illustrates how digital transformation can allow a traditional industrial corporation to become a leader in industrial software and IoT platforms. Patagonia shows that sustainability-oriented innovation can strengthen brand loyalty and financial performance. Tesla represents a radical and disruptive innovation model in which product innovation is combined with vertical integration, infrastructure creation, software-based updates and direct customer interaction. These cases demonstrate that successful innovation strategies rarely rely on a single factor; they combine technology, business model redesign, ecosystem logic, customer value and strategic consistency.

An important conclusion arising from the study is that innovation performance must be evaluated through a multidimensional system of indicators. Traditional quantitative indicators, such as the number of new products, patent applications or R&D expenditures, are insufficient for assessing the strategic effect of innovation. More comprehensive assessment should include the share of innovative products in sales, return on innovation investment, time-to-market, assortment renewal rate, customer satisfaction and the contribution of innovation to market position and resilience. Such an approach corresponds to the modern understanding of innovation as a process that affects not only technological output, but also business sustainability, adaptability and competitive advantage.

The theoretical contribution of the study lies in the systematisation of innovation strategy as a complex strategic management category. The research integrates classical innovation theory, strategic management, open innovation, digital transformation, sustainability and crisis adaptation into a single conceptual framework. This makes it possible to move beyond fragmented interpretations of innovation strategy and to view it as a coordinated system of goals, tools, resources, partnerships and performance indicators. The study also contributes to the adaptation of global innovation management approaches to the specific conditions of Ukrainian enterprises operating under extreme uncertainty.

The practical contribution lies in the possibility of using the proposed classifications, strategic tools and recommendations for enterprise-level decision-making. Managers can apply the results to select an innovation strategy consistent with their company's resources, market position and risk tolerance. Policymakers can use the findings to improve innovation support mechanisms, strengthen science-business cooperation and facilitate access to financing. For Ukrainian enterprises, the proposed approach may help identify realistic innovation priorities during wartime and post-war recovery, including digital transformation, open innovation, ESG integration, DefenseTech, AgTech and participation in international innovation programmes.

However, several limitations of the study should be acknowledged. The research is primarily theoretical and analytical, and therefore its conclusions require further empirical verification. The study does not include quantitative modelling of the relationship between innovation strategy and enterprise performance, nor does it provide survey-based evidence from Ukrainian companies. In addition, the international business cases considered in the article are illustrative rather than statistically representative. They demonstrate strategic patterns, but they cannot be directly generalised to all enterprises or sectors without taking into account differences in institutional environment, financial capacity, technological maturity and market structure.

Future research should therefore focus on empirical testing of the proposed conceptual framework. It would be useful to conduct surveys or interviews with Ukrainian enterprises in order to identify which innovation strategies are actually used under wartime and post-war recovery conditions. Quantitative studies could examine the relationship between innovation strategy type and indicators such as productivity, export performance, profitability, resilience, digital maturity and market share. Sector-specific research is also needed, particularly for IT, manufacturing, agriculture, logistics, energy and defence-related industries. Another promising direction is the development of models for assessing the effectiveness of open innovation ecosystems and public-private partnerships in supporting enterprise recovery and technological modernisation.

Overall, the discussion confirms that innovation strategy is one of the central instruments of enterprise competitiveness in the contemporary economy. Its effectiveness depends on the ability to combine strategic vision, technological capabilities, market orientation, organisational flexibility, external cooperation and sustainability principles. Under conditions of economic turbulence and wartime uncertainty, this role becomes even more significant. For Ukrainian enterprises, innovation strategy should be viewed not only as a mechanism for growth, but also as a foundation for resilience, reconstruction and integration into global technological value chains.

Conclusion

Thus, innovation strategy is a critical element of strategic management in a modern enterprise. In a dynamic competitive environment, it is impossible to ensure long-term business competitiveness without a systematic approach to innovation. At the same time, there is no single universally correct innovation strategy. Instead, there is a variety of strategic choices, and the selection of a particular strategy depends on numerous factors, including industry characteristics, enterprise size, resource potential, competitive position and the level of risk tolerance.

Based on the results of this study, it can be argued that open innovation is becoming the dominant paradigm of innovative development. Under conditions of increasing technological complexity, the effectiveness of closed R&D models is declining. Cooperation with external partners, including universities, start-ups and research centres, provides enterprises with access to advanced global knowledge, technologies and competencies.

Digital transformation has become a key driver of innovation. Industry 4.0, artificial intelligence, the Internet of Things and cloud technologies create fundamentally new opportunities for business by transforming not only products, but also business models, processes and methods of interaction with customers. With regard to sustainable development, it is increasingly becoming a source of competitive advantage. The integration of ESG principles into innovation strategy not only corresponds to global trends and regulatory requirements, but also opens up new market opportunities, increases investment attractiveness and strengthens consumer loyalty.

For Ukrainian enterprises, innovation strategy must take into account specific wartime risks and constraints while simultaneously using unique opportunities, including a strong IT sector, access to grant financing, the development of DefenseTech and AgTech, and state innovation support programmes such as Diia.City.

Therefore, the successful implementation of an innovation strategy requires a systematic management approach. This includes the presence of clear KPIs, a balanced innovation portfolio, a developed innovation culture, adequate resource provision and sufficient flexibility to adapt to change.

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Artificial Intelligence in HR Analytics: Enhancing Strategic Personnel Management ^[9]

Abstract:

In the context of digital economic transformation, the use of data-driven approaches in human resource management is becoming increasingly important for enhancing organisational competitiveness and improving the quality of managerial decision-making. This study examines the application of artificial intelligence technologies in HR analytics within modern human resource management processes. The purpose of the article is to substantiate the role of artificial intelligence in HR analytics and to determine its impact on the effectiveness of managerial decision-making in personnel management. The study employs general scientific methods, including analysis, synthesis, comparison, and generalisation, as well as HR analytics tools used to interpret personnel data and assess the effectiveness of HR decisions. The study identifies key areas of AI application in HR analytics, including employee turnover prediction, recruitment automation, performance evaluation, employee development personalisation, and employer branding analysis. The findings indicate that the use of AI enhances the accuracy, speed, and objectivity of decision-making and supports the transition from intuitive and reactive HR management to data-driven, predictive, and proactive personnel management. At the same time, the study highlights the main limitations of AI implementation, including data quality issues, algorithmic bias, ethical concerns, legal restrictions, insufficient transparency of automated decisions, and limited organisational readiness for digital transformation. The findings emphasise the need for a balanced approach that combines technological solutions with human expertise, ethical governance, and the development of analytical competencies among HR professionals. It is concluded that AI-based HR analytics can become an important strategic tool for improving personnel management, strengthening organisational adaptability, and supporting sustainable competitive development.

Keywords: HR analytics, artificial intelligence, strategic HR analytics, personnel management, employer branding, organisational behaviour, digital transformation.

Abbreviations:

AI is artificial intelligence

HR is human resources

EVP is employer value proposition

KPI is key performance indicator

Introduction

In today's era of digital economic transformation, effective human resource management is becoming critical to ensuring organisations' competitiveness. Exponential business data growth drives the demand for advanced processing and interpretation tools. In this context, HR analytics is becoming particularly relevant, as it enables data-driven management decisions. At the same time, the integration of artificial intelligence technologies opens up new opportunities for improving forecasting accuracy, automating HR processes and optimising HR strategies.

The object of the study is HR management processes in modern organisations. The study focuses on AI integration within HR analytics to enhance management efficiency.

The aim of the article is to investigate the specific features of applying artificial intelligence in HR analytics and to determine its impact on the effectiveness of management decisions in the field of HR management. To achieve this objective, the following tasks have been identified:

to analyse the essence of HR analytics in the context of digitalisation; to investigate the possibilities of using artificial intelligence technologies in HR processes; to determine the impact of AI tools on managerial decision-making; to outline the main limitations and risks of their application.

General scientific methods were used in the research, in particular analysis and synthesis—to summarise scientific approaches to understanding HR analytics and artificial intelligence; comparison—to contrast traditional and modern HR management tools; and generalisation—to draw conclusions regarding the effectiveness of AI application in HR analytics. Among the specialised methods, the HR analytics method was used, which allows for the interpretation of personnel data and the evaluation of the effectiveness of management decisions.

The theoretical framework of the study is based on the works of domestic and international scholars in the fields of human resource management, HR analytics and digital technologies, in particular studies focusing on data-driven approaches to management, the application of artificial intelligence in business processes, and the transformation of the HR function in the context of digitalisation.

The practical significance of the results lies in their potential use by organisational leaders, HR managers and analysts to enhance the effectiveness of human resource management through the implementation of artificial intelligence tools in HR analytical processes.

Methods

The methodological basis of the study consists of a combination of general scientific and specialised methods, ensuring a comprehensive approach to analysing the use of artificial intelligence in HR analytics.

General scientific methods include analysis, which facilitated a systematic review of theoretical frameworks surrounding HR analytics and AI evolution, as well as investigation of their role in personnel management systems. The synthesis method was applied to combine individual theoretical propositions into a coherent concept of AI use in HR analytics. The comparison method was used to contrast traditional approaches to human resource management with modern data-driven practices. The generalisation method enabled conclusions to be drawn regarding the effectiveness of applying artificial intelligence in management processes.

Specialized HR analytics was applied to transform raw personnel data into actionable insights for strategic decision-making. The application of this method made it possible to identify key areas for the use of artificial intelligence in the analysis of HR processes, in particular forecasting staff turnover, assessing employee performance and optimising recruitment processes. In addition, elements of a systems approach were utilised, ensuring that HR analytics is considered as a component of the overall organisational management system.

Thus, the use of these methods has enabled a comprehensive investigation of the possibilities for integrating artificial intelligence into HR analytics and an assessment of its impact on the effectiveness of personnel management.

Literature Review

Contemporary research in the field of human resource management is increasingly focusing on the use of analytical approaches and digital technologies to enhance the effectiveness of managerial decisions. In particular, considerable attention is being paid to the development of HR analytics as a tool for data-driven management.

The use of analytics in organisational management is thoroughly examined by Davenport and Harris (2007), who justify the concept of data-driven management as a key factor in competitive advantage. Further development of this idea is presented in the works of Marler and Boudreau (2017), who provide a systematic review of HR analytics and define it as an important tool for improving the effectiveness of human resource management. Minbaeva (2018) expands on this perspective, emphasising the development of analytical competence within organisations, which enables the achievement of sustainable competitive advantages. Thus, these sources form the theoretical basis for the study of HR analytics as a component of modern management.

A separate line of research concerns the critical analysis of the implementation of HR analytics in management practice. In particular, Angrave et al. (2016) highlight the gap between the potential of analytics and the actual capabilities of the HR function to utilise it, which is due to insufficient analytical skills and organisational change. Rasmussen and Ulrich (2015) stress the need to integrate analytics into strategic human resource management to prevent it from becoming a passing management trend. Boudreau and Cascio (2017) also highlight the challenges of implementing analytical approaches, particularly organisations' insufficient readiness to use data in decision-making. Including these sources allows exploration of the challenges of the practical application of HR analytics and justifies the need for its improvement.

An important aspect of the research is the use of artificial intelligence technologies in human resource management. Tambe, Cappelli, and Yakubovich (2019) examine the potential applications of AI in HR processes, particularly in recruitment and employee performance analysis, making their work crucial for understanding current trends in the development of HR analytics. Upadhyay and Khandelwal (2018) investigate the use of artificial intelligence in recruitment, highlighting its effectiveness in automating candidate selection. Jarrahi (2018) analyses the interaction between humans and artificial intelligence in the management decision-making process, emphasising the importance of combining the two. Brynjolfsson and McAfee (2014) view AI as a factor in the transformation of business processes in general. Recent developments in generative AI have further expanded the analytical and decision-support capabilities of HR technologies, particularly through intelligent automation, talent acquisition support, and advanced data interpretation. Thus, these sources provide an understanding of the role of artificial intelligence in the transformation of the HR function.

A separate group comprises studies devoted to the impact of digital technologies on human resource management and the future of work. Stone et al. (2015) analyse the impact of technologies on the transformation of the HR function, highlighting the changing role of the HR manager. Kaplan and Haenlein (2019) explore the nature of artificial intelligence and its application in business, providing a deeper understanding of these technologies. Wang and Siau (2019) investigate the impact of automation and AI on the future of work, establishing a broader

research context. Kaur et al. (2023) explores the role of human trust in AI, identifying it as a cornerstone for successful technology adoption.

Particular attention in academic research has been paid to the ethical aspects of using artificial intelligence in HR. In particular, Leicht-Deobald et al. (2019) emphasise ethical risks, specifically addressing algorithmic bias and the lack of transparency in automated decisions.

Thus, this literature review leads to the conclusion that there is considerable academic interest in the use of HR analytics and artificial intelligence in human resource management. At the same time, there is a need for further research into the integration of AI into HR analytical processes, taking into account both their capabilities and limitations.

Results

1. The essence of HR analytics and the role of artificial intelligence

In the current context of the digital economy's development, HR analytics is emerging as a key tool for human resource management, enabling data-driven decision-making. Unlike traditional approaches, which rely on managers' intuition and experience, HR analytics involves the systematic collection, processing and interpretation of personnel data to improve the efficiency of management processes. It covers a wide range of metrics, including employee productivity, staff turnover, employee engagement and training effectiveness. Thus, HR analytics transforms the approach to personnel management from intuitive to evidence-based, which helps improve the quality of management decisions.

The evolution of HR analytics is closely linked to the development of information technology and the increasing volume of data available to organisations. Whereas in the early stages analytics was limited to descriptive metrics, modern approaches include diagnostic, predictive and prescriptive analytics, which allow not only the analysis of past events but also the forecasting of future trends and the formulation of recommendations for management actions. In this context, the integration of artificial intelligence plays a key role, significantly expanding the capabilities for processing large datasets and improving the accuracy of analytical models. Thus, the development of HR analytics reflects the general trend towards data-driven management within organisations.

Artificial intelligence serves as a technological foundation for automating complex analytical processes in HR analytics and enhancing their efficiency. Machine learning algorithms make it possible to identify hidden patterns in workforce data that are often inaccessible through traditional analytical methods. In particular, AI can support employee turnover prediction, talent potential assessment, team performance analysis, and recruitment optimisation. An important advantage of AI lies in its ability to process large volumes of structured and unstructured data, including résumés, employee feedback, and sentiment survey results. This significantly improves the accuracy, speed, and objectivity of HR analytics. Thus, the integration of artificial intelligence expands the analytical capabilities of human resource management.

At the same time, the use of artificial intelligence in HR analytics is transforming the role of the HR function within an organisation. Whereas HR managers previously performed mainly administrative tasks, today they are increasingly involved in strategic management, using analytical tools to inform decision-making. This requires the development of new competencies, in particular analytical thinking, an understanding of how algorithms work, and the ability to

interpret the results of analysis. Thus, the integration of AI into HR analytics contributes to the transformation of the HR function from an operational to a strategic one.

2. The use of artificial intelligence in HR analytics

One of the key areas of application for artificial intelligence in HR analytics is the prediction of staff turnover. The use of machine learning algorithms enables the analysis of historical employee data, including satisfaction levels, performance review results, frequency of job changes, engagement levels and other factors that may influence the decision to resign. Based on this data, predictive models are developed that enable the identification of employees with a high probability of leaving and the timely implementation of management measures. This not only reduces costs associated with staff turnover but also enhances the organisation's operational stability. Thus, the application of artificial intelligence in predicting staff turnover facilitates the transition from reactive to proactive HR management. Key areas of artificial intelligence application in HR analytics are systematised in the Appendix (*Table 1*).

Modern AI-based systems are capable of processing large volumes of CVs, analysing candidates' suitability for job requirements, and assessing their potential based on prior experience and behavioural characteristics. Furthermore, AI-driven systems facilitate automated initial screenings by evaluating both verbal responses and non-verbal behavioural cues, thereby enhancing the objectivity of the selection process. Automating these processes significantly reduces the time taken for recruitment and minimises the influence of human bias. Thus, the use of artificial intelligence in recruitment enhances the efficiency, speed and quality of the candidate selection process.

Another key area is the assessment of employee performance and the management of their productivity. Artificial intelligence enables the analysis of various employee performance indicators in real time, including task completion results, KPI achievement levels, participation in team processes, and other metrics. Analytical reports are generated based on this data, helping managers make informed decisions regarding staff development, motivation and resource allocation. Furthermore, AI can be used to personalise employee training and development, taking into account their individual needs and potential. Thus, the application of artificial intelligence in performance evaluation contributes to increased labour productivity and staff development.

Of particular importance is the use of artificial intelligence to analyse the organisation's external environment, specifically competitors in the labour market and the development of the employer brand. Modern AI tools enable the processing of data from open sources, such as job vacancies, career websites, social media and employee review platforms, allowing for the analysis of salary levels, candidate requirements, competitors' offers and their employer value proposition (EVP). This enables organisations to refine their HR strategy, enhance their employer appeal and position themselves more effectively in the labour market. Thus, the use of artificial intelligence to analyse the competitive environment contributes to the development of a competitive employer brand and improves the effectiveness of recruitment.

3. The Impact of Artificial Intelligence on Management Decision-Making in Human Resources

One of the key advantages of using artificial intelligence is the ability to forecast future trends and scenarios in HR processes. Thanks to the use of predictive analytics, managers are

able not only to react to existing problems but also to prevent them from arising. For example, forecasting staff turnover or a decline in productivity allows for the timely implementation of measures to retain employees or boost their motivation. This significantly enhances the strategic level of HR management and enables decision-making that takes long-term consequences into account. Thus, the use of AI facilitates the transition to proactive management within organisations.

An important aspect is the enhancement of the objectivity of management decisions by minimising the influence of the human factor. Artificial intelligence is capable of analysing data without bias, which helps reduce the risks of discrimination or subjective assessment of employees. This is particularly relevant in recruitment processes, performance evaluation, and decision-making regarding career development. At the same time, completely eliminating the human factor is impractical, as interpreting analysis results and making final decisions require managerial experience and a contextual understanding of the situation. Thus, the most effective approach is to combine the capabilities of artificial intelligence with the professional expertise of managers.

Furthermore, the use of AI in HR analytics helps to speed up management decision-making. The automation of data collection and analysis processes significantly reduces the time between identifying a problem and resolving it. This is critically important in a highly dynamic business environment, where the speed of decision-making often determines an organisation's competitiveness. At the same time, speed must not compromise the quality of decisions, which requires proper verification and interpretation of analytical results. Thus, the use of artificial intelligence strikes a balance between the speed and soundness of management decisions.

4. Limitations and risks of using artificial intelligence in HR analytics

Despite the significant advantages of using artificial intelligence in HR analytics, its implementation is accompanied by a number of limitations and risks that must be taken into account when making management decisions. One of the key issues is the dependence of the quality of analysis results on the quality of input data. Poor data quality—whether incomplete or biased—compromises analytical integrity and leads to flawed management strategies. This is particularly relevant in situations where employee data is collected from various sources and may contain errors or subjective assessments. Thus, the effectiveness of artificial intelligence directly depends on the quality and representativeness of the data.

Another significant limitation is the issue of algorithmic bias, which may arise from the use of historical data reflecting existing social or organisational inequalities. In such cases, artificial intelligence algorithms may reproduce or even exacerbate these biases, leading to unfair management decisions, particularly in recruitment or employee assessment processes. This creates risks of discrimination and may negatively impact the organisation's reputation as an employer. Consequently, the use of AI in HR analytics requires constant monitoring and adjustment of algorithms to ensure their objectivity and ethicality.

Ethical and legal restrictions on the use of artificial intelligence are also an important aspect. Handling sensitive workforce data necessitates robust security frameworks to prevent privacy breaches and ensure regulatory compliance and adherence to relevant regulations. Furthermore, the use of AI in management decision-making may lead to mistrust among employees, particularly where the principles underlying the algorithms are not sufficiently transparent. This

can have a negative impact on organisational culture and staff engagement levels. Consequently, the implementation of artificial intelligence must be accompanied by measures to ensure transparency, ethical standards and data protection.

Another limitation is the lack of readiness among organisations to implement artificial intelligence technologies. This is due both to the absence of the necessary technical infrastructure and to a lack of digital and analytical skills among staff. Implementing AI requires significant investment, as well as changes to business processes and corporate culture. Without proper preparation, this can lead to the inefficient use of technologies or even their rejection within the organisation. Thus, the successful integration of artificial intelligence into HR analytics requires a comprehensive approach, including skills development, process adaptation and strategic change management.

Discussion

The results of the study confirm that the integration of artificial intelligence into HR analytics represents not only a technological innovation, but also a structural transformation of human resource management. AI-based HR analytics changes the logic of personnel management by shifting it from retrospective reporting and managerial intuition towards predictive, evidence-based and strategically oriented decision-making. This transformation is especially important in the context of digital economic development, increasing labour market volatility and the growing need for organisations to respond quickly to changes in employee behaviour, workforce expectations and competitive conditions.

The findings are consistent with the broader concept of data-driven management, according to which organisational competitiveness increasingly depends on the ability to collect, process and interpret data for managerial decision-making (*Davenport & Harris, 2007*). In the field of human resource management, this means that HR departments are no longer limited to administrative functions such as documentation, payroll support or operational recruitment. Instead, they gradually become analytical and strategic units capable of forecasting workforce risks, evaluating employee performance, supporting talent development and strengthening employer positioning in the labour market. This corresponds to the argument that HR analytics should be considered a strategic instrument for increasing organisational effectiveness rather than a secondary technical function (*Marler & Boudreau, 2016; Minbaeva, 2018*).

One of the most significant implications of the study is the confirmation of the proactive potential of AI in HR analytics. Traditional HR management often reacts to problems after they have already occurred: employees leave the organisation, productivity declines, recruitment takes too long or employee engagement decreases. AI-based analytics makes it possible to identify early signals of such problems and respond before they become critical. For example, predictive models of employee turnover can reveal risk patterns based on engagement indicators, performance dynamics, job mobility, satisfaction data and other variables. This allows organisations to implement retention measures in advance and reduce the costs associated with staff replacement, adaptation and loss of organisational knowledge.

The analysis also shows that AI has particular value in recruitment and selection. Automated CV screening, natural language processing, video analysis and behavioural assessment tools can reduce the duration of recruitment cycles and improve the consistency of

candidate evaluation. These findings correspond to studies emphasising the potential of artificial intelligence to increase the efficiency of recruitment processes and support candidate-job matching (*Tambe et al., 2019; Upadhyay & Khandelwal, 2018*). However, the use of AI in recruitment should not be interpreted as a simple replacement of human recruiters. Recruitment decisions involve contextual judgement, organisational culture, ethical responsibility and long-term assessment of candidate potential. Therefore, AI should function as a decision-support tool rather than as an autonomous decision-maker.

The role of AI in performance management is also significant. Real-time KPI dashboards, productivity monitoring systems and personalised employee development recommendations can improve the quality of managerial decisions related to motivation, training and resource allocation. Such tools allow managers to move beyond episodic performance reviews and towards continuous assessment of employee development. At the same time, this creates a new managerial challenge: performance data should be interpreted carefully and ethically. Quantitative indicators may show trends, but they cannot fully capture employee motivation, creativity, interpersonal contribution, emotional labour or contextual difficulties. Therefore, performance analytics must be combined with qualitative managerial judgement.

An important contribution of the article lies in emphasising external HR analytics and employer branding. In contemporary labour markets, organisations compete not only through salaries and job descriptions, but also through employer value propositions, reputation, corporate culture and career development opportunities. AI tools can process data from open sources, job platforms, social networks, review websites and competitors' vacancies in order to assess labour market positioning and improve employer branding strategies. This expands the traditional boundaries of HR analytics: it becomes not only an internal management instrument, but also a tool for analysing the external labour market environment and strengthening organisational competitiveness.

The findings also confirm that AI transforms the professional role of HR managers. As HR analytics becomes more technologically advanced, HR professionals need new competencies: data literacy, understanding of algorithmic logic, ability to interpret analytical outputs, ethical awareness and strategic thinking. This supports earlier arguments that the implementation of HR analytics may fail if HR departments do not develop sufficient analytical capabilities and organisational influence (*Angrave et al., 2016; Boudreau & Cascio, 2017*). Therefore, the effectiveness of AI in HR analytics depends not only on software or data infrastructure, but also on the ability of HR specialists to translate analytical results into meaningful managerial decisions.

A central issue emerging from the study is the balance between automation and human judgement. AI can improve the speed, accuracy and objectivity of HR decisions, but it cannot fully replace managerial interpretation. Organisational decisions concerning recruitment, promotion, employee development, dismissal or talent retention involve not only statistical probability, but also ethical, psychological and strategic considerations. This supports the concept of human-AI symbiosis in organisational decision-making, according to which the most effective decisions arise from the combination of machine analytical capacity and human contextual understanding (*Jarrabi, 2018*). In HR management, this balance is especially

important because decisions directly affect people's careers, income, motivation and professional dignity.

The study also highlights a number of risks that should be taken seriously. The first of these is data quality. AI systems depend on the completeness, accuracy and representativeness of input data. If HR data are incomplete, inconsistent or historically biased, AI models may produce misleading conclusions. Poor-quality data can lead to incorrect predictions of turnover, unfair performance assessments or inaccurate recruitment recommendations. Therefore, before implementing AI-based HR analytics, organisations must develop reliable data governance systems, standardise HR metrics, ensure data integration and regularly verify the quality of personnel datasets.

The second major risk is algorithmic bias. AI models trained on historical organisational data may reproduce existing inequalities or discriminatory practices. For example, if previous recruitment decisions were biased in favour of certain groups, an AI system trained on such data may continue to privilege similar candidates. This confirms the concerns raised in the literature regarding algorithm-based HR decision-making and personal integrity ([Leicht-Deobald et al., 2019](#)). Consequently, organisations must regularly audit algorithms, test models for bias, document decision rules and ensure that automated recommendations do not violate principles of fairness, equal opportunity and non-discrimination.

The third risk concerns transparency and trust. Employees may perceive AI-based HR analytics as a form of surveillance if organisations do not explain what data are collected, how they are analysed and how the results influence management decisions. Trust in AI is a key condition for its successful adoption ([Kaur et al., 2023](#)). If employees do not understand the logic of AI tools or believe that decisions are made by opaque algorithms, their engagement and organisational commitment may decrease. Therefore, organisations should develop transparent communication policies, explain the purpose of AI use, ensure data protection and provide mechanisms for human review of automated recommendations.

The fourth risk is organisational readiness. The implementation of AI in HR analytics requires not only technological infrastructure but also changes in processes, skills, culture and governance. Organisations may invest in AI tools without having sufficient analytical competence or managerial readiness to use them effectively. In such cases, AI may become a formal innovation that does not significantly improve decision-making. This reflects the broader warning that HR analytics can become a management trend rather than a real strategic capability if it is not integrated into organisational decision processes ([Rasmussen & Ulrich, 2015](#)).

From a theoretical perspective, the study contributes to the understanding of HR analytics as a strategic management mechanism. It shows that AI-based HR analytics connects several dimensions of organisational development: data-driven decision-making, strategic workforce planning, employee performance management, employer branding and organisational behaviour. This broader interpretation is important because HR analytics is sometimes reduced to technical measurement or operational reporting. The present analysis demonstrates that its strategic value lies in the ability to connect personnel data with organisational goals, competitive positioning and long-term workforce sustainability.

From a practical perspective, the study suggests that organisations should implement AI in HR analytics gradually and systematically. The first stage should include an audit of HR data

quality and the development of unified personnel metrics. The second stage should focus on selecting appropriate AI tools for specific HR tasks, such as turnover prediction, recruitment automation, performance analysis or employer branding. The third stage should involve training HR professionals and managers to interpret analytical results. The fourth stage should introduce ethical governance mechanisms, including algorithmic audits, transparency policies, data protection rules and procedures for human review. Such a staged approach can reduce implementation risks and increase the effectiveness of AI-based HR analytics.

The results also have implications for organisational strategy. AI-based HR analytics can strengthen workforce stability, reduce recruitment costs, improve employee development and support employer competitiveness. However, these benefits can be achieved only when analytics is connected to real managerial action. Predicting turnover has little value if the organisation does not develop retention measures. Analysing employee performance is ineffective if it is not linked to development plans. Studying employer branding is insufficient if the organisation does not improve its employee value proposition. Therefore, AI-based analytics should be embedded in the full cycle of HR strategy, from diagnosis to action and evaluation.

The limitations of the study should also be acknowledged. The article is conceptual and analytical in nature and does not include empirical testing of AI-based HR analytics tools in a specific organisation. It does not compare the effectiveness of different AI models or quantify their impact on HR performance indicators. In addition, the study focuses on the general potential and risks of AI in HR analytics rather than on sector-specific or country-specific implementation conditions. These limitations open directions for further research.

Future research should examine the practical effectiveness of AI tools in different HR processes and organisational contexts. Empirical studies may analyse how AI-based turnover prediction affects retention outcomes, how automated recruitment tools influence candidate diversity, how AI-supported performance management changes employee motivation and how external HR analytics contributes to employer brand competitiveness. Further research should also focus on ethical governance models, algorithmic transparency, employee trust and the relationship between AI adoption and organisational culture. Comparative studies across industries and countries would help determine how organisational size, sector, digital maturity and regulatory environment influence the success of AI implementation in HR analytics.

Overall, the discussion confirms that artificial intelligence has the potential to significantly enhance HR analytics and strategic personnel management. Its value lies in improving the accuracy, speed and predictive capacity of managerial decision-making. At the same time, AI should not be treated as a universal solution to HR problems. Its effectiveness depends on data quality, ethical governance, organisational readiness and the professional competence of HR managers. The most promising model is a balanced approach in which artificial intelligence supports human decision-making, while managers retain responsibility for interpretation, ethical evaluation and strategic action.

Conclusions

Our findings confirm that HR analytics is a vital engine for organisational transformation, shifting management from intuition to evidence-based strategy, facilitating the transition from an intuitive to a data-driven approach in managerial decision-making. The study demonstrates

that the integration of artificial intelligence significantly expands the capabilities of HR analytics, in particular through the automation of data processing, improved forecasting accuracy, and the identification of hidden patterns in HR processes.

The main areas of application of artificial intelligence in HR analytics have been examined, including forecasting staff turnover, automating recruitment processes, assessing employee performance, as well as analysing the competitive environment and building an employer brand. The findings indicate that the application of AI in these areas contributes to increased labour productivity, the optimisation of HR processes, and the improvement of the quality of management decisions.

The results confirm that the use of artificial intelligence is transforming the nature of human resource management, facilitating a shift towards a proactive and strategic approach. The findings demonstrate that AI enables greater objectivity, speed and efficiency in managerial decision-making, whilst preserving the important role of the human factor in interpreting analysis results and formulating managerial actions.

At the same time, the main limitations of using artificial intelligence in HR analytics have been identified, including dependence on data quality, risks of algorithmic bias, ethical and legal aspects, as well as organisations' insufficient readiness to implement such technologies. The study shows that the effective use of AI is only possible provided there is a comprehensive approach, which includes ensuring data quality, developing staff competencies, and implementing the principles of ethical management.

Thus, the results of the study confirm the advisability of integrating artificial intelligence into HR analytics as an important tool for improving the effectiveness of personnel management, providing a strategic framework for organisational resilience and sustainable growth.

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Conflict of Interest

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Appendix

Table 1. Conceptual Framework of AI Application in HR Analytics

Application Area	AI Tools and Technologies	Practical Application	Strategic Management Impact
Employee Turnover Prediction	Machine Learning, Predictive and Prescriptive Analytics	Identifying turnover risks and early retention signals through historical data analysis	Reduced turnover costs and improved workforce stability through proactive management
Recruitment and Selection	NLP, AI Screening, Video Analysis and Non-verbal Cue Assessment	Automated candidate sourcing, CV screening, and initial behavioural evaluation	Faster hiring cycles, enhanced selection objectivity, and minimized human bias
Performance Management	AI Monitoring Tools, Real-time KPI Dashboards	Real-time productivity assessment and personalized employee development plans	Improved decision quality in resource allocation and increased labour productivity
External HR Analytics and Employer Branding	Big Data Analytics, External Market Intelligence Tools	Competitor EVP analysis and labour market positioning based on open-source data	Enhanced employer brand competitiveness and stronger data-driven positioning in the labour market

Hydropower and Industrial Transformation: The Construction of the Tereble–Rika Hydroelectric Power Station in Transcarpathia ^[10]

Abstract:

The purpose of this study is to conduct a comprehensive analysis of the construction process of the Tereble–Rika Hydroelectric Power Station (1949–1956) in the Zakarpattia region, to identify the main engineering, organizational, economic, and social factors that influenced the timeline of the project's implementation, and to evaluate the contribution of the power station to the development of regional energy infrastructure. The research is based on archival analysis of project documentation, including technical and economic reports, annual investment project lists, consolidated financial and economic plans, and acceptance reports for completed construction works. The study also involves a comparative examination of engineering solutions and the material and technical support of the project. Particular attention is paid to the geographical and hydrological conditions of the area, especially the significant altitude difference between the Tereblia and Rika rivers, the planning of a reservoir with a capacity of 24 million cubic meters, the construction of a concrete dam 45 meters high and 153 meters long, the development of a diversion tunnel with a length of 3.7 km and a diameter of 2.15 m, and the installation of a pressure pipeline 380 meters long with an internal diameter of 2.2 m. The hydroelectric station was equipped with three hydraulic turbines with a nominal capacity of 9 MW each. The results of the research show that the construction process was accompanied by considerable difficulties caused by a shortage of qualified workers and engineers, limited availability of construction materials such as cement, steel, and timber, difficult logistical conditions in mountainous terrain, and frequent technical failures of equipment. Analysis of annual construction plans indicates delays in the construction of the dam, diversion tunnel, turbine hall, and narrow-gauge railway, which resulted in postponing the completion of the project from 1954 to 1956. At the same time, the study reveals effective management of financial resources, the development of residential and social infrastructure for workers, the construction of transport and engineering networks, and the integration of international equipment, including turbines manufactured in Finland and generators produced in the Ural region. During the construction process more than 2,000 workers were employed, with a peak workforce of 2,736 people in 1954. Approximately 420,000 cubic meters of concrete and 84,000 tons of cement were used. The total cost of the project exceeded 200 million rubles, while the reservoir covered an area of approximately 80 hectares.

Keywords: hydropower engineering, Tereble–Rika HPP, archival research, construction logistics.

Introduction

The water resources of the Zakarpattia region possess significant potential for the development of hydropower due to considerable altitude differences, a dense network of mountain rivers, and favourable natural conditions for the creation of hydraulic structures. Among the most important examples of the use of this potential is the Tereble–Rika Hydroelectric Power Station, which became one of the key infrastructure projects in the post-war transformation of the regional energy system. The construction of this station was based on the original engineering idea of using the natural difference in elevation between the Tereblia and Rika rivers, which flow almost parallel to one another but are located at different hypsometric levels.

The idea of constructing a hydroelectric power station on the Tereblia and Rika rivers emerged in the early twentieth century and was further developed during the period when the region belonged to the Czechoslovak Republic. However, due to unfavourable historical and

political circumstances, the practical implementation of the project was postponed. The actual construction of the Tereble–Rika Hydroelectric Power Station began only in the late 1940s and continued until the mid-1950s. This period was marked by the inclusion of Zakarpattia into the Soviet economic and administrative system, the need to modernise the regional energy infrastructure, and the broader post-war industrial transformation of the region.

The relevance of this research is determined by the need for a comprehensive analysis of the historical, economic, technical, organisational, and social aspects of the construction of the Tereble–Rika Hydroelectric Power Station. The project was not merely an engineering undertaking; it also involved complex processes of financial planning, labour mobilisation, transport infrastructure development, settlement construction, resettlement of local inhabitants, procurement of materials, and coordination between different institutions and regions. Therefore, the study of this project makes it possible to understand not only the technological history of hydropower development in Zakarpattia, but also the mechanisms through which large-scale infrastructure projects were implemented under difficult geographical, economic, and administrative conditions.

The research problem lies in the insufficiently comprehensive study of the relationship between engineering planning, material and technical supply, workforce organisation, financial management, construction logistics, and the actual timeline of the project. Previous studies have mainly focused on the general history of the Tereble–Rika Hydroelectric Power Station or on its technical characteristics. At the same time, archival materials related to annual investment plans, financial estimates, labour resources, housing and social infrastructure, construction delays, equipment failures, and logistical difficulties have not been fully systematised. As a result, the reasons for the deviation of the project from the initial construction schedule and the broader socio-economic significance of the construction process remain insufficiently clarified.

The scientific novelty of the study consists in the use of archival materials to reconstruct the construction process of the Tereble–Rika Hydroelectric Power Station as a complex historical and infrastructural phenomenon. The article analyses not only the technical parameters of the hydropower facility, but also the organisational, financial, logistical, and social factors that influenced the implementation of the project. Particular attention is paid to the comparison between planned construction indicators and the actual state of work performed, which makes it possible to identify the main reasons for delays and to assess the effectiveness of project management under the conditions of mountainous terrain, shortage of qualified personnel, limited material resources, and technical difficulties.

The object of the study is the construction of the Tereble–Rika Hydroelectric Power Station in the Zakarpattia region during 1949–1956 as a major hydropower and infrastructure project.

The subject of the study is the engineering, organisational, economic, logistical, and social factors that influenced the construction process, the timing of implementation, and the formation of the regional energy infrastructure.

The article aims to conduct a comprehensive analysis of the construction process of the Tereble–Rika Hydroelectric Power Station in the Zakarpattia region, to identify the main factors that influenced the course and duration of construction, and to evaluate the significance of the station for the development of regional hydropower and industrial infrastructure.

To achieve this aim, the study addresses the following objectives:

- to trace the historical development of the idea of constructing a hydroelectric power station on the Tereblia and Rika rivers from the early engineering concepts to its practical implementation;
- to analyse the geographical and hydrological conditions that determined the engineering logic of the project;
- to examine the main technical characteristics of the hydroelectric complex, including the dam, reservoir, diversion tunnel, pressure pipeline, turbine hall, and generating equipment;
- to study archival materials concerning project planning, annual investment lists, financial estimates, and construction documentation;
- to identify the main organisational and logistical difficulties that affected the construction process;
- to analyse the impact of shortages of qualified workers, engineers, construction materials, equipment, and energy supply on the pace of construction;
- to examine the development of residential, transport, social, and auxiliary infrastructure connected with the construction site;
- to determine the reasons for the postponement of the completion of the project from the originally planned date to 1956;
- to evaluate the contribution of the Tereble–Rika Hydroelectric Power Station to the development of the regional energy system and the industrial transformation of Zakarpattia.

The theoretical significance of the research lies in deepening the historical understanding of hydropower development in Zakarpattia and in clarifying the role of large-scale infrastructure projects in regional industrial transformation. The study contributes to the historiography of Soviet-era infrastructure construction, regional energy policy, and the economic history of Transcarpathia. It also demonstrates the importance of analysing infrastructure projects not only through their final technical results, but also through the processes of planning, financing, labour organisation, logistics, and social adaptation.

The practical significance of the study lies in the possibility of using its results for further research on hydropower engineering, regional infrastructure development, historical geography, economic history, and the management of large-scale construction projects in mountainous areas. The archival evidence analysed in the article may also be useful for specialists studying the historical development of the energy sector, the transformation of industrial regions, the planning of infrastructure facilities, and the social consequences of major engineering projects. The experience of the Tereble–Rika Hydroelectric Power Station demonstrates the importance of effective resource management, workforce organisation, logistical planning, and coordination between technical and social infrastructure in the successful implementation of complex hydropower projects.

Methods

The study is based on a qualitative historical and archival research design aimed at reconstructing the construction process of the Tereble–Rika Hydroelectric Power Station as a

complex engineering, economic, organisational, logistical, and social phenomenon. This methodological approach is appropriate because the construction of the hydroelectric power station cannot be analysed only as a technical event. It involved long-term project planning, financial management, labour mobilisation, supply of materials, resettlement of the local population, creation of transport and social infrastructure, and adaptation of engineering solutions to mountainous geographical conditions.

The chronological framework of the study covers the period from the first engineering concepts of the Tereblia–Rika hydropower project in the early twentieth century to the official commissioning of the hydroelectric power station in 1956. Particular attention is paid to the period from 1949 to 1956, when the practical implementation of the project took place. This period makes it possible to analyse the transition from the design stage to construction, the dynamics of annual planning, the emergence of technical and logistical difficulties, and the reasons for the postponement of the project's completion from the originally planned date.

The source base of the research consists primarily of archival materials from the State Archive of the Zakarpattia Region. The study uses documents from Fond R–1097 and Fond R–1914, which contain project, administrative, technical, financial, and construction-related materials concerning the Tereble–Rika Hydroelectric Power Station. These archival sources include annual title lists of investment projects, financial and economic plans, reports on the performance of construction and installation works, correspondence between construction organisations and ministries, acceptance acts for completed works, documents concerning the supply of materials and equipment, records on workforce numbers, and materials related to housing construction, social infrastructure, land withdrawal, compensation, and resettlement.

The archival method was used as the central specialised method of the study. It made it possible to identify, systematise, and interpret primary documents related to the construction of the hydroelectric power station. Archival analysis was applied not only to extract factual data, but also to reconstruct the administrative and economic logic of the project. Particular attention was paid to documents that reflect the discrepancy between planned and actually completed works, since these sources reveal the internal difficulties of the construction process more clearly than retrospective descriptions.

The method of source criticism was applied to evaluate the reliability, completeness, and interpretative value of the archival materials. Since the documents were produced within the administrative and technical system responsible for the construction project, they contain both factual information and institutional perspectives. Therefore, the study considered the purpose of each document, its administrative context, the type of data presented, and its relation to other archival materials. This approach helped reduce the risk of treating planning documents, reports, estimates, and correspondence as neutral records without considering their function within the construction management system.

The historical method was used to trace the evolution of the Tereble–Rika project from its initial conception to its final implementation. This method allowed the study to reconstruct the sequence of key events: the emergence of the engineering idea, the preparation of design documentation, the beginning of construction in 1949, the development of the reservoir and dam, the construction of the diversion tunnel and pressure pipeline, the creation of railway and road infrastructure, the expansion of the workers' settlement, and the commissioning of the

station in 1956. The historical method also made it possible to connect the project with broader processes of post-war industrialisation and regional energy development in Zakarpattia.

The historical-genetic method was used to analyse the origin and transformation of the engineering concept of the hydroelectric power station. This method helped identify how the natural difference in elevation between the Tereblia and Rika rivers became the basis for a specific hydropower solution involving water diversion through a tunnel and pressure pipeline. It also made it possible to examine how earlier Czechoslovak and Hungarian engineering ideas were later incorporated into the Soviet construction project.

The systemic method was applied to examine the construction of the Tereble–Rika Hydroelectric Power Station as an integrated system consisting of several interdependent components. These included the main hydraulic structures, transport routes, energy supply, material procurement, labour resources, housing, social facilities, financial planning, administrative management, and technical supervision. The systemic approach made it possible to demonstrate that delays in one component, such as material supply, energy provision, tunnel construction, or workforce qualification, affected the progress of the entire project.

The comparative method was used to compare planned construction indicators with the actual volume of work completed in different years. This method was particularly important for identifying the reasons for delays in the construction of the dam, diversion tunnel, turbine hall, narrow-gauge railway, high-voltage transmission line, and auxiliary infrastructure. Comparative analysis also allowed the study to assess the difference between the planned commissioning dates and the real pace of construction. The comparison of archival plans and acceptance reports made it possible to determine how resource shortages, logistical constraints, and technical failures influenced the overall implementation schedule.

The quantitative-descriptive method was used to analyse numerical data contained in archival documents. This included information on the estimated and actual cost of works, annual volumes of construction and installation activities, workforce numbers, salary indicators, quantities of concrete and cement used, the scale of land withdrawal, the number of resettled households and inhabitants, reservoir dimensions, and technical parameters of the hydraulic structures. Although the study is not econometric in nature, the use of quantitative indicators strengthens the historical analysis by showing the real scale of the project and the material intensity of construction.

The technical and economic analysis method was applied to evaluate the interaction between engineering decisions and economic resources. The study analysed the parameters of the dam, reservoir, diversion tunnel, pressure pipeline, turbines, generators, railway infrastructure, and auxiliary facilities in relation to financial expenditures, material supply, and construction capacity. This method helped demonstrate that the implementation of the project depended not only on the correctness of the engineering solution, but also on the availability of construction materials, specialised equipment, qualified personnel, transport infrastructure, and stable energy supply.

The logistical analysis method was used to examine the influence of mountainous terrain and transport limitations on the construction process. The location of the project required the delivery of large quantities of cement, steel, timber, rails, equipment, and machinery to a difficult-to-access area. The study therefore considered the role of the 750 mm narrow-gauge

railway, road reconstruction, internal transport routes, and the supply of construction materials. This method made it possible to identify logistics as one of the central factors that delayed the construction process and increased organisational complexity.

The socio-economic analysis method was applied to examine the human and social dimensions of the construction project. The study analysed the mobilisation of the workforce, the shortage of qualified workers and engineers, labour turnover, accommodation conditions, construction of dormitories and residential buildings, creation of medical, educational, cultural, and everyday infrastructure, as well as the resettlement of households affected by the formation of the reservoir. This method helped show that large-scale hydropower construction was not only an engineering process, but also a social transformation of the surrounding territory.

The method of infrastructure history was used to interpret the Tereble–Rika Hydroelectric Power Station as part of the broader industrial transformation of Zakarpattia. The power station is analysed not as an isolated facility, but as a node within a developing regional energy system. This perspective made it possible to assess how the construction of the station contributed to electrification, industrial development, transport modernisation, settlement formation, and integration of the region into wider economic and infrastructural networks.

The research procedure consisted of several stages. At the first stage, archival sources related to the construction of the Tereble–Rika Hydroelectric Power Station were identified and grouped according to their thematic content: technical documentation, financial planning, annual construction plans, acceptance reports, labour records, material supply documents, correspondence, and social infrastructure materials. At the second stage, the chronology of construction was reconstructed on the basis of these sources. At the third stage, the planned indicators were compared with the actual progress of construction. At the fourth stage, the main factors causing delays were identified and classified. At the fifth stage, the technical, economic, logistical, and social significance of the project was evaluated.

The study has certain limitations. First, the research is based primarily on archival documents preserved in the State Archive of the Zakarpattia Region, and therefore reflects the available documentary record rather than the full range of possible oral, personal, or local community perspectives. Secondly, many archival sources were created by institutions involved in construction management, which means that they may emphasise administrative and technical aspects more strongly than everyday experiences of workers or resettled inhabitants. Thirdly, some quantitative indicators differ across documents because they were produced at different stages of planning, reporting, or acceptance of works. For this reason, the study uses cross-checking between sources wherever possible.

Despite these limitations, the selected methodology makes it possible to provide a comprehensive analysis of the construction of the Tereble–Rika Hydroelectric Power Station. The combination of historical, archival, systemic, comparative, quantitative-descriptive, technical-economic, logistical, and socio-economic methods allows the project to be studied not only as a hydropower facility, but also as a major infrastructure undertaking that reflected the engineering ambitions, organisational constraints, resource limitations, and regional transformation processes of the post-war period.

Literature Review

Recent studies have examined individual aspects of the construction of the Tereble–Rika Hydroelectric Power Station, including technical engineering solutions, the social consequences of population resettlement, and the organization of construction works. Earlier research has provided a general understanding of the project; however, most studies were limited primarily to chronological descriptions or superficial analyses of the technical characteristics of the hydroelectric facility.

At the same time, the relationship between material and technical supply, workforce composition, logistics, and construction efficiency has remained insufficiently studied. Furthermore, the influence of external factors—such as historical, political, and socio-economic conditions—on the timeline of project implementation has not been comprehensively assessed.

The study relies on archival materials that make it possible to analyze these relationships in greater detail and to identify the reasons for deviations from planned construction indicators.

Unresolved Issues of the Research Problem: Several issues remain insufficiently explored in previous research:

- a comprehensive evaluation of archival materials concerning financing, technical decisions, and the development of social infrastructure;
- the impact of shortages of qualified personnel and material resources on the pace of construction;
- the relationship between engineering structures and the development of social and transport infrastructure;
- the reasons for delays in the implementation of construction plans and their consequences for the project;
- the practical significance of the experience of the Tereble–Rika Hydroelectric Power Station for modern hydropower projects.

Addressing these gaps highlights the scientific novelty of the study and emphasizes its significance for both academic research and practical applications.

Results

A Czech engineer, Křižka, proposed an original engineering concept in 1923, which was based on the rational use of the natural difference in elevation between the Tereblia and Rika rivers. Similar hydrotechnical solutions were also developed by Hungarian specialists both before and after the Czech projects.

The project envisaged the construction of a hydraulic structure in the form of a dam on the Tereblia River with a height of approximately 45 meters and a reservoir with a useful capacity of up to 45 million cubic meters. Both rivers flow almost parallel along the Bovtsarsky Ridge but are located at different hypsometric levels.

The riverbed of the Tereblia River is approximately 200 meters higher than that of the Rika River, while the distance between their upper courses does not exceed four kilometers. According to the project, water was to be continuously diverted from the Tereblia River to the turbines of the planned hydroelectric power station located on the Rika River through a

diversion tunnel with a diameter of 2.7 meters and a length of 3,700 meters, followed by transmission through a pressure pipeline (*State Archive, Sprava 3, Ark. 1–7*).

At the time when the project was initially developed, the region belonged to Czechoslovakia. Due to unfavorable historical and political circumstances, however, the project was not implemented and remained limited to the preparation of technical and design documentation.

After Zakarpattia became part of the Soviet Union, the Ukrainian branch of the scientific research and design institute Hydroenergoproekt initiated comprehensive studies of the region's hydropower potential. The research was carried out by a Lviv-based project and survey group.

As a result of these investigations, February 1949 was determined as the starting date for the construction of the Tereble–Rika Hydroelectric Power Station. Initially, the duration of the project was planned for four years, but later it was extended by an additional three years.

During the construction period from 1949 to 1956, the project involved specialists, technical equipment, and labor resources from various regions of the Soviet Union, as well as from Czechoslovakia and the German Democratic Republic.

In accordance with reparation agreements, hydro-turbine equipment was manufactured by a Finnish company producing Francis turbines, while electric generators were supplied by industrial enterprises in the Ural region. In addition, Finnish manufacturers produced the metal pressure pipeline, which was 380 meters long with a diameter of 2.15 meters and was installed along the mountain slope (*State Archive, Sprava 3, Ark. 1–7*).

The water discharge in the pressure pipeline reached 18 cubic meters per second. The tunnel, constructed in rocky formations, had an inclination of approximately 37 degrees relative to the horizontal plane, ensuring the necessary hydraulic head for water flow. The water was then transported through a metal pipeline approximately 350 meters long.

The pipeline manufactured in Finland had wall thicknesses of 2.5 centimeters and an internal diameter of 2.2 meters. Within this section the water gained considerable velocity before entering three hydro turbines installed in the main turbine hall of the hydroelectric station (*State Archive, Sprava 3, Ark. 1–7*).

The turbines used at the power station were manufactured by the UralElectropribor enterprise located in Sverdlovsk (USSR). Oil systems required for the stable operation of the turbines were supplied from Finland, while the equipment responsible for regulating rotational frequency was developed and produced in Sweden.

Each turbine unit generated up to 9 MW of electrical power under nominal operating conditions. The turbines operated at a rotational speed of approximately 600 revolutions per minute (*State Archive, Sprava 19, Ark. 1–7*).

Before the start of construction, a specialized construction and installation organization was established on the basis of the DniproHESBud trust, operating under the name ZakarpattiaHESBud. In order to initiate construction activities, the parent organization transferred part of its technical and production resources to the newly created structure.

The construction of the hydroelectric power station required the creation of extensive infrastructure and a large construction workforce. At the initial stage of the project, the management organization prepared a detailed financial and material balance in order to ensure the provision of necessary equipment and construction materials.

Archival documentation indicates that the first section of the financial plan, entitled “Planned Works and Procurement”, allocated the entire amount of funding to the purchase of construction equipment and necessary materials. During this period, construction machinery and specialized equipment that had previously been lacking were purchased.

The analysis of archival documents also indicates the formation of significant stocks of raw materials. This measure allowed the construction administration to ensure a continuous and organized start of the building works.

In addition to these documents, archival materials contain general financial estimates for the entire project. One of the key documents was the “Annual Title List of Investment Projects”, which was compiled annually to determine the cost of construction works planned for a given year.

According to the investment plan approved on 26 October 1950, the total estimated cost of constructing the hydroelectric power station amounted to 186,265.9 thousand rubles in prices as of 1 January 1950. According to these records, during 1950 the construction trust ZakarpattiaHESBud carried out construction and installation works for the hydroelectric station in the amount of 25,850 thousand rubles (*State Archive, Sprava 45, Ark. 1–3*).

These data indicate that in 1950 priority was given primarily to preparatory works. The largest share of financial resources was directed to the construction of the diversion tunnel, electrification of the construction site, and the construction of both temporary and permanent residential buildings for workers.

An important role was also played by scientific and technical activities, including geodetic surveys, which were necessary for the correct positioning of the main hydraulic structures.

The construction of the hydroelectric power station began with the establishment of a workers’ settlement and the formation of the future reservoir. This required the withdrawal of significant areas of land totaling 662 hectares.

The implementation of such large-scale territorial changes required appropriate legal regulation and administrative management in order to protect the property rights of individuals and organizations affected by the construction works.

For this purpose, a special commission was created to assess the damages caused to land plots and private property during the implementation of the project (*State Archive, Sprava 12, Ark. 1–47*).

Archival materials from the State Archive of the Zakarpattia Region indicate that as a result of the project 160 households were resettled in the village of Vilshany, affecting 1,229 residents.

Additionally, 21 households in the villages of Bovtsar and Nyzhnii Bystryi were also relocated.

The total amount of compensation paid to the affected population amounted to 1.497 million rubles, while the total damage caused by flooding and other economic interventions was estimated at 8 million 887 thousand rubles (*State Archive, Sprava 13, Ark. 1–42*).

The reservoir of the hydroelectric power station was put into operation in 1955.

The surface area of the reservoir varied between 72 and 90 hectares, depending on the water level, with an average value of approximately 80 hectares. The maximum depth reached 8 meters, while its length exceeded 10 kilometers and the average width was approximately 100 meters.

The useful storage capacity of the reservoir amounted to 24 million cubic meters.

The dam constructed for the hydroelectric power station had a height of 45 meters and a length of 153 meters. Approximately 200,000 cubic meters of concrete were used during its construction (*State Archive, Sprava 18, Ark. 1–19*).

The first head of the construction project was Viktor Lyovushkin, while Mykola Zinevych, head of the DniproHESBud trust, served as chief engineer. The engineering staff included 11 engineers and technical specialists, while financial operations were supervised by a chief accountant (*State Archive, Sprava 20, Ark. 1–4*).

In 1950, the Council of Ministers of the USSR assigned the Ministry of Energy the task of constructing a 750 mm narrow-gauge railway with a total length of 35 kilometers.

The railway connected the village of Tereblia with the dam construction site and passed through the settlements of Bushtyno, Tereblia, Kolodne, Krychevo, Drahovo, and Vilshany.

The railway line was intended to ensure the delivery of construction materials and to improve transportation connections with nearby districts.

Finnish PT-4 narrow-gauge steam locomotives were used on this line, with a maximum speed of 35 km/h (*State Archive, Sprava 50, Ark. 1–6*).

The construction process was accompanied by considerable difficulties. These problems were described in detail by Hryhoruka, head of ZakarpattiaHESBud, in a letter addressed to Deputy Minister Ivan Dmitriev in April 1952.

According to the report, the total demand for construction materials amounted to 4,080.5 thousand rubles, while by 1 April only 1,795.2 thousand rubles worth of materials had been delivered. This created a shortage of 2,285.3 thousand rubles, significantly slowing down the progress of construction works.

Additional problems arose with railway rails: instead of the planned rails, heavier types were supplied, which increased costs by 400 thousand rubles.

Furthermore, timber of lower quality was used for sleepers and bridge structures instead of the materials originally planned (*State Archive, Sprava 192, Ark. 1–18*).

The construction of the hydroelectric station required the creation of a large number of auxiliary facilities intended to meet the social and everyday needs of the construction workers and future residents of the settlement.

Archival documents show that the initial construction plans included:

- 25 residential houses
- 29 dormitories with 2,039 places
- a kindergarten for 25 children
- a school for 40 pupils
- a hospital with 25 beds
- an outpatient clinic
- a maternity ward
- a bakery
- a medical centre
- a cultural club
- a cinema (*State Archive, Sprava 26, Ark. 1–10*).

In addition, the construction plans included the creation of a permanent settlement that would contain a horse-riding arena, five dining facilities, a bathhouse with showers, and 17 industrial facilities, including a stone crushing plant.

Transport infrastructure was also developed, including routes through the Bovtsarsky Ridge, rural roads, and internal railway lines intended to support further construction activities (*State Archive, Sprava 26, Ark. 1–10*).

Further archival research also revealed additional planning documents, including the “Consolidated Economic and Financial Plan”. This document contained detailed information regarding housing construction, workforce numbers, and financial expenditures related to the project.

Archival data indicate that the construction of the hydroelectric power station required a large labour force and the construction of numerous residential facilities. Workers were accommodated in dormitories where the living space per person was approximately 4 square meters, while the rent amounted to 42 rubles per month.

In 1951, with an average occupancy of 800 dormitory places, the total income generated from housing rental amounted to 249,660 rubles, while the maintenance costs of these facilities exceeded 402,822 rubles (*State Archive, Sprava 87, Ark. 1–3*).

During the middle of 1951, when construction work was already underway for approximately two and a half years, the Ministry of Energy of the USSR established a special commission to evaluate the progress of construction.

According to the original plans, the first production unit of the hydroelectric power station was expected to start operating at the end of 1952, while the complete construction of the facility was scheduled for 1954. However, archival materials indicate that under the existing conditions these deadlines were unrealistic (*State Archive, Sprava 111, Ark. 1–21*).

An analysis of the two-year construction plans revealed significant delays, particularly in the construction of the dam and the turbine building.

The main reasons for these delays included:

- a shortage of qualified personnel (e.g., only 3 of 9 managers possessed appropriate qualifications, and among 19 drilling specialists only 4 were properly trained);
- a lack of specialized workers and high labour turnover;
- logistical problems caused by poor road conditions and long transportation routes;
- low efficiency of the available vehicle fleet;
- energy supply limitations, as only 10–25% of the required electricity supply was available;
- delays in the launch of high-voltage power lines for approximately one and a half years.
- In order to overcome these difficulties, several measures were proposed:
 - expansion of the Uzhhorod thermal power plant;
 - reconstruction of the Khust–construction site road;
 - delivery of 250 units of construction equipment;
 - establishment of a concrete production plant directly at the construction site;
 - deployment of additional cranes and technical specialists;
 - support for tunnel construction works by nearby collective farms.

More than 2,000 workers participated in the construction process, with the highest number reaching 2,736 workers in 1954.

All engineers and technical specialists involved in the project were transferred from the DniproHESBud construction trust in Zaporizhzhia.

The average annual salary of construction workers was approximately 7,297 rubles, while the estimated total value of construction works as of 1 July 1950 was approximately 213.3 million rubles (*State Archive, Sprava 34, Ark. 1–5*).

After the inspection conducted in 1951, the construction policy was revised. Additional funding was allocated to the project, and more construction works were performed to accelerate the completion of the Tereble–Rika Hydroelectric Power Station (*State Archive, Sprava 165, Ark. 1–6*).

The results of 1952 indicate that the construction trust ZakarpattiaHESBud planned to perform works amounting to approximately 15 million rubles more than in 1951, which represented an increase of nearly 50% and approximately 70% of the total construction volume carried out during the previous three years.

The largest share of funding was directed toward the construction of the dam, the diversion tunnel, the narrow-gauge railway, and the main power station building.

The 110 kV high-voltage power transmission line was more than 90% completed, while automobile roads and the residential district continued to develop rapidly, including improvements in housing capacity and living conditions (*State Archive, Sprava 165, Ark. 1–6*).

Despite these efforts, construction of the dam, diversion tunnel, railway line, and turbine hall still lagged behind schedule. The first generating units, originally planned to be launched during the second half of 1952, could not be commissioned due to the unfinished main building and dam.

The most significant progress was observed in the development of the railway infrastructure, which reached 33% completion by the end of 1952.

However, the overall readiness level of the main hydroelectric structures reached only 12.75%, making it impossible to commission the station in 1954.

The most active stage of construction occurred during 1953–1954, as confirmed by archival acceptance reports. In 1954 alone, 114 acceptance acts were recorded.

Most of these documents concerned the installation of individual concrete blocks forming the dam structure.

During the construction works, numerous technical malfunctions were recorded, primarily related to electrical equipment. These failures were caused by manufacturing defects, equipment wear, insufficient staff training, and frequent interruptions in electricity supply (*State Archive, Sprava 370, Ark. 1–114*).

In 1953, one of the smallest volumes of construction work during the entire building period was completed. According to the work plans for 1954, by the beginning of that year construction works worth 114,500 thousand rubles had been completed.

Based on the completed portion of the 1952 construction plan, the total value of works performed in 1953 amounted to approximately 20,000 thousand rubles (*State Archive, Sprava 344, Ark. 1–5*).

In 1954, the volume of construction work doubled compared to the previous year. The planned value of works reached 40,000 thousand rubles, of which approximately 80% were related to construction activities.

This year is considered the most productive period of the entire construction process (*State Archive, Sprava 344, Ark. 1–5*).

During the fifth year of construction, total expenditures reached 40 million rubles, with approximately 80% allocated to construction works. The largest share of these funds was spent on the construction of the dam (46% of the construction budget) and the diversion tunnel (32%). Together they accounted for 78% of the total construction expenditures (*State Archive, Sprava 344, Ark. 1–5*).

At the same time, plans included the completion of roads, residential houses, fire stations, garages, and bridges, as well as the narrow-gauge railway and the high-voltage power transmission line.

Significant funds were also spent on the demolition of buildings in resettled villages in order to prepare the territory for the formation of the reservoir (*State Archive, Sprava 344, Ark. 1–5*).

By the beginning of 1954, the average completion rate of the hydroelectric power station was approximately 62.75%. The narrow-gauge railway had reached 85% readiness, while deviations of up to 1.5 meters were recorded in the dam structure, requiring additional corrections.

In August 1955, a commissioning commission headed by engineer Kozhevnikov was established. The commission discovered several problems related to financial reporting, the absence of certain technical documents, and the absence of key specialists.

After these issues were resolved, the hydroelectric power station was successfully commissioned in 1956.

The final hydroelectric complex included:

- a concrete dam 45 meters high,
- a reservoir covering 1.6 sq. km,
- diversion tunnels 3.7 km long (2.15 m diameter) and 100 m long (7 m diameter),
- hydraulic structures measuring $37 \times 16.4 \times 19.1$ meters.

Construction delays were primarily caused by technical difficulties, logistical problems, and shortages of qualified personnel.

Discussion

The construction of the Tereble–Rika Hydroelectric Power Station demonstrates that large-scale hydropower projects in mountainous regions should be analysed not only as technical achievements, but also as complex historical, organisational, economic, logistical, and social processes. The archival materials examined in this study show that the implementation of the project depended on the interaction of several factors: the natural hydrological potential of the area, the engineering feasibility of the diversion scheme, the availability of financial and material resources, the organisation of labour, the development of transport infrastructure, the provision of housing and social services, and the capacity of the construction administration to respond to delays and technical failures.

The first important issue concerns the engineering logic of the project. The Tereble–Rika Hydroelectric Power Station was based on the rational use of the natural altitude difference between the Tereblia and Rika rivers. This geographical condition made it possible to create a hydropower system in which water from the Tereblia River was accumulated in a reservoir and then transferred through a diversion tunnel and pressure pipeline to the turbines located on the Rika River. From an engineering perspective, this solution was highly efficient because it transformed the specific relief of the region into an energy resource. The project therefore illustrates how mountainous geography, which often creates transport and construction difficulties, can simultaneously become a strategic advantage for hydropower development.

At the same time, the results of the study confirm that engineering feasibility does not automatically guarantee successful project implementation. Although the basic technical concept was well justified, the construction process was significantly affected by organisational and resource-related constraints. The original plan envisaged the completion of the power station earlier, but the actual commissioning took place only in 1956. This delay was not caused by a single factor. It resulted from the combined influence of shortages of qualified personnel, insufficient supply of construction materials, difficult logistics in mountainous terrain, limitations in energy supply, technical malfunctions of equipment, and the need to build extensive auxiliary infrastructure almost simultaneously with the main hydropower facilities.

The shortage of qualified workers and engineers was one of the most serious constraints. Archival evidence indicates that the construction administration lacked a sufficient number of trained managers, drilling specialists, engineers, and technical personnel. This problem was especially important because the project required specialised knowledge in tunnel construction, concrete works, installation of hydraulic equipment, operation of heavy machinery, railway construction, and high-voltage transmission infrastructure. In such conditions, labour quantity alone could not compensate for the deficit of technical competence. Even though more than two thousand workers participated in the construction process, the efficiency of construction depended on the availability of skilled specialists capable of performing complex and high-risk operations.

The material and technical supply problems also had a decisive influence on the pace of construction. The shortage of cement, steel, timber, rails, equipment, and machinery created direct obstacles to the fulfilment of annual construction plans. The archival data show that the construction organisation often received fewer materials than planned, and in some cases the supplied materials did not correspond to the required technical characteristics. Such discrepancies increased costs, complicated construction logistics, and slowed down the implementation of key works. This confirms that large infrastructure projects are highly sensitive not only to the total volume of financing, but also to the rhythm, quality, and timeliness of material supply.

Logistics represented another structural challenge. The construction site was located in a mountainous area where the delivery of materials and equipment required special transport solutions. The construction of the narrow-gauge railway, roads, bridges, and internal transport routes was therefore not a secondary element of the project, but a necessary precondition for its implementation. The fact that railway infrastructure itself lagged behind schedule demonstrates a typical problem of large infrastructure construction: the main project depends

on auxiliary infrastructure that must be developed under the same difficult conditions. In the case of the Tereble–Rika Hydroelectric Power Station, transport limitations affected the delivery of concrete, cement, metal structures, technical equipment, and workforce resources, thereby influencing the overall construction schedule.

The study also shows that the power station cannot be understood only through the construction of the dam, tunnel, pressure pipeline, and turbine hall. The project required the creation of an entire construction and settlement environment. Residential houses, dormitories, dining facilities, medical institutions, a school, a kindergarten, a bakery, cultural facilities, workshops, and auxiliary industrial sites were planned and developed to support the workforce and ensure the continuity of construction. This aspect is important because it reveals the social dimension of hydropower development. The construction site functioned not merely as a technical workplace, but as a temporary and partly permanent social space created around the needs of industrial construction.

The resettlement of local inhabitants and the withdrawal of land for the reservoir represent another significant aspect of the project. The creation of the reservoir required the transformation of the local landscape and affected households in nearby settlements. Compensation mechanisms were introduced, but the archival evidence also indicates the scale of economic damage and social disruption caused by flooding and territorial reorganisation. This demonstrates that hydropower projects produce not only energy and infrastructure benefits, but also social costs. In historical analysis, these costs should not be treated as marginal, because they shaped the lived experience of local communities and formed part of the broader consequences of industrial transformation.

The financial dimension of the project also deserves attention. The annual investment lists, financial plans, and reports on completed works make it possible to reconstruct the changing rhythm of construction. The data show that some years were marked by slow progress, while others, especially 1954, became periods of intensified construction activity. This unevenness reflects the dependence of the project on administrative decisions, additional funding, availability of materials, workforce mobilisation, and correction of earlier delays. The increase in funding after inspections and the revision of construction policy demonstrate that project management was adaptive, but often reactive: additional measures were introduced after accumulated problems had already affected the schedule.

The comparison between planned and actual construction indicators is particularly important for understanding the internal dynamics of the project. The delay in the construction of the dam, diversion tunnel, turbine hall, narrow-gauge railway, and other facilities shows that the original schedule underestimated the complexity of the work. This does not necessarily mean that the planning was technically incompetent. Rather, it suggests that the planners did not fully account for the cumulative impact of personnel shortages, logistical difficulties, unstable energy supply, technical failures, and the need to develop social and transport infrastructure in parallel with the main hydropower works. The case therefore demonstrates the importance of integrated planning in complex infrastructure projects.

The international dimension of the project is also notable. The use of equipment manufactured in Finland and the involvement of technologies and resources from different parts of the Soviet Union and other countries show that the Tereble–Rika Hydroelectric Power

Station was not a purely local construction project. It was embedded in broader post-war economic, technological, and political networks. Finnish turbines, metal pressure pipeline components, equipment from the Ural region, and technical solutions associated with earlier Czechoslovak and Hungarian concepts illustrate the transregional and international nature of the project. This aspect complicates a narrow regional interpretation and shows that the station was part of a wider system of post-war industrial reconstruction and technological exchange.

From the perspective of regional history, the construction of the Tereble–Rika Hydroelectric Power Station was an important element of the industrial transformation of Zakarpattia. The station contributed to the development of the regional energy system and strengthened the infrastructure basis for further economic activity. Its significance should be evaluated not only in terms of installed capacity, but also in terms of the broader infrastructural changes associated with its construction: roads, railway connections, settlements, transmission lines, construction enterprises, and technical labour experience. In this sense, the power station functioned as a catalyst of regional modernisation.

However, the project also reveals the contradictions of post-war industrialisation. On the one hand, it mobilised substantial resources, introduced advanced engineering solutions, developed infrastructure, and expanded the energy potential of the region. On the other hand, it was implemented under conditions of administrative pressure, resource scarcity, labour shortages, social displacement, and repeated delays. This duality is important for historical interpretation. The Tereble–Rika Hydroelectric Power Station should not be presented only as a story of technical success or only as a story of construction difficulties. It was both: an ambitious and ultimately successful hydropower project whose implementation exposed the organisational and social costs of rapid infrastructural development.

The findings of this study are relevant for the analysis of modern hydropower and infrastructure projects. Contemporary projects also require careful assessment of terrain conditions, resource availability, transport logistics, workforce competence, environmental consequences, social impacts, financing, and project risk management. The historical experience of the Tereble–Rika Hydroelectric Power Station shows that delays often arise not from the main engineering design itself, but from the interaction of supporting systems: roads, material supply, energy provision, housing, labour organisation, documentation, and coordination between institutions. Therefore, modern infrastructure planning should pay particular attention to auxiliary and social infrastructure as integral components of project success.

The study also demonstrates the value of archival research for infrastructure history. Archival documents make it possible to move beyond general descriptions of construction and to identify specific mechanisms of implementation: how much funding was allocated, which works were prioritised, where delays occurred, what materials were lacking, how labour was organised, what technical failures were recorded, and how administrative decisions changed over time. This level of detail is essential for understanding the real history of infrastructure projects. It also allows historians to reconstruct the relationship between policy, engineering, economy, and everyday organisation of construction.

At the same time, several limitations should be acknowledged. The study relies primarily on administrative, technical, and financial documentation preserved in archival fonds. Such sources are highly valuable for reconstructing the construction process, but they reflect mainly

the perspective of institutions responsible for planning and implementation. They provide less direct information about the everyday experiences of workers, resettled inhabitants, and local communities. Future research could therefore supplement the archival documentation with oral history, local memory studies, visual materials, and comparative analysis of other hydropower projects in mountainous regions.

Further research may also focus on the environmental consequences of the creation of the reservoir and the long-term operation of the hydroelectric power station. The present article concentrates mainly on construction history, logistics, financing, engineering decisions, and organisational difficulties. However, a comprehensive history of the Tereble–Rika Hydroelectric Power Station should also include the transformation of river ecosystems, changes in land use, the impact on local settlements, and the station's role in later regional energy policy. Comparative studies with other hydropower projects in the Carpathian region would also help clarify what was unique and what was typical in the Tereble–Rika case.

Overall, the discussion confirms that the construction of the Tereble–Rika Hydroelectric Power Station was a complex infrastructural process in which natural conditions, engineering innovation, administrative planning, financial resources, labour organisation, logistics, social infrastructure, and regional industrial policy were deeply interconnected. The project became an important milestone in the development of Zakarpattia's energy sector, but its delayed completion demonstrates the practical difficulty of implementing large hydropower projects in mountainous areas under conditions of material scarcity and organisational pressure. The historical significance of the station lies not only in its final technical parameters, but also in the experience of planning, constructing, financing, and socially supporting a major infrastructure project in a challenging regional environment.

Conclusion

The construction of the Tereble–Rika Hydroelectric Power Station between 1949 and 1956 became one of the most significant infrastructure projects for the energy sector of the Zakarpattia region.

The main challenges faced during the construction process included a shortage of qualified workers, limited availability of construction materials such as cement, steel, and timber, and complex logistical conditions caused by the mountainous terrain. These factors ultimately led to the postponement of the completion of the project from the originally planned year 1954 to 1956.

During construction, approximately 420,000 cubic meters of concrete and 84,000 tons of cement were used. The total cost of the project exceeded 200 million rubles.

Despite numerous difficulties, the Tereble–Rika Hydroelectric Power Station was successfully completed and became a crucial component of the regional energy system. The project also provided valuable experience in organizing large-scale infrastructure construction in mountainous areas.

The analysis of archival sources demonstrates the importance of effective workforce organization, resource management, and logistical planning in the successful implementation of complex hydroengineering projects. The construction of the Tereble–Ritskaya hydroelectric power station (1949–1956) was a key project for the Transcarpathian energy sector. The main

problems are a shortage of skilled workers, a shortage of materials (cement, steel, wood) and difficult logistics conditions in the mountainous area, which delayed completion from 1954 to 1956.

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Conflict of Interest

The author declares that there is no conflict of interest.

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Comparative Assessment of Oral Hygiene Status and Periodontal Condition Among Different Tobacco Product Users: A Cross-Sectional Study ^[17]

Abstract:

The widespread use of diverse tobacco products, including conventional cigarettes, heated tobacco products (HNB systems), and smokeless tobacco (pouches), poses significant challenges for oral health assessment. Different delivery mechanisms may produce distinct patterns of oral tissue damage, yet comparative data across product categories remains limited. The study aims to compare oral hygiene status, gingival condition, and dental caries experience among users of conventional cigarettes, heat-not-burn (HNB) tobacco systems, and smokeless tobacco pouches. The author uses the following methods: A cross-sectional study was conducted among 44 adult tobacco users divided into three groups: Group 1 — conventional cigarette smokers (n=15); Group 2 — HNB system users (n=15); Group 3 — smokeless tobacco/pouch users (n=14). Clinical assessment included the Debris Index (DI-S), Calculus Index (CI-S), Oral Hygiene Index-Simplified (OHI-S), Modified Gingival Index (MGI), and DMFT index. Data were analyzed using one-way ANOVA with post-hoc Tukey's HSD test ($\alpha=0.05$). Conventional cigarette smokers demonstrated significantly higher values across all indices compared to HNB and smokeless tobacco users ($p<0.05$). Specifically, OHI-S scores were 3.47 ± 0.54 , 2.90 ± 0.48 , and 2.70 ± 0.44 for Groups 1, 2, and 3, respectively ($p=0.002$). MGI scores were 2.21 ± 0.38 , 1.87 ± 0.33 , and 1.74 ± 0.30 ($p=0.004$). DMFT values followed the same pattern: 14.3 ± 2.8 , 12.6 ± 2.4 , and 11.9 ± 2.2 ($p=0.041$). Post-hoc analysis revealed no significant difference between Group 2 and Group 3 for any index ($p>0.05$). Conclusion: Conventional cigarette smoking is associated with the most pronounced deterioration of oral hygiene and periodontal status among tobacco product categories studied. HNB systems and smokeless tobacco pouches showed comparable, though still elevated, indices relative to non-smoking norms. These findings support differentiated oral health monitoring strategies for distinct tobacco user populations.

Keywords: oral hygiene, tobacco, heated tobacco products, smokeless tobacco, OHI-S, periodontal index, DMFT, cross-sectional study, dental caries, gingival inflammation.

Introduction

Tobacco use remains one of the most significant modifiable risk factors for oral disease globally. The oral cavity represents the primary site of tobacco contact and accumulation of toxic metabolites, making it particularly vulnerable to tobacco-related pathological changes (*Warnakulasuriya & Straif, 2018*). While the deleterious effects of conventional cigarette smoking on oral health are well documented, the rapid expansion of alternative tobacco and nicotine delivery systems—particularly heat-not-burn (HNB) products and smokeless tobacco pouches—has introduced new clinical challenges that have not been fully characterized.

Conventional cigarettes deliver combustion products including tar, carbon monoxide, and hundreds of carcinogens directly to oral tissues. These compounds promote plaque accumulation, alter the subgingival microbiome, suppress local immune responses, and impair tissue perfusion, collectively resulting in increased susceptibility to periodontal disease and dental caries (*Warnakulasuriya et al., 2010; Johnson & Hill, 2004*). In contrast, HNB systems heat tobacco to temperatures below combustion, theoretically reducing the concentration of harmful combustion by-products. Smokeless tobacco pouches (e.g., nicotine pouches without tobacco leaf) represent yet another category, delivering nicotine through oral mucosa while avoiding inhalation entirely (*Robichaud et al., 2021*).

Despite marketing claims suggesting reduced harm, the differential impact of these product categories on measurable oral hygiene and periodontal indices remains incompletely understood. Clinicians require evidence-based, quantitative comparisons to guide patient counselling and implement appropriate preventive strategies. The Oral Hygiene Index-Simplified (OHI-S), which combines the Debris Index (DI-S) and Calculus Index (CI-S), provides a standardized and reproducible measure of oral hygiene status (*Greene & Vermillion, 1964*). The Modified Gingival Index (MGI) enables sensitive assessment of gingival inflammation without relying on bleeding provocation, while the DMFT index quantifies the burden of dental caries experience (*Lobene, 1986*).

The objective of this cross-sectional study was to compare oral hygiene status, gingival condition, and caries experience across three groups of tobacco product users—conventional cigarette smokers, HNB system users, and smokeless tobacco pouch users—using standardized clinical indices. The study was conducted in the context of the growing diversification of tobacco use behaviors observed in Ukraine and across Central and Eastern Europe.

Methods

Study Design and Participants

A cross-sectional comparative study was conducted at the Department of Dentistry, Shupyk National Healthcare University of Ukraine, Kyiv. Adult participants (≥ 18 years) were recruited consecutively between September 2023 and April 2024. Inclusion criteria required active use of a single tobacco product category for at least 12 months, with no concurrent use of other tobacco or nicotine products. Exclusion criteria included: use of systemic antibiotics within the preceding 3 months, systemic diseases known to affect periodontal status (uncontrolled diabetes mellitus, immunodeficiency conditions), pregnancy, and current active orthodontic treatment.

A total of 44 eligible participants were enrolled and allocated to three groups: Group 1—conventional cigarette smokers ($n=15$); Group 2—heat-not-burn (HNB) tobacco system users ($n=15$); Group 3—smokeless tobacco pouch users ($n=14$). The study was approved by the Ethics Committee of Shupyk National Healthcare University of Ukraine and conducted in accordance with the Declaration of Helsinki. Written informed consent was obtained from all participants.

Clinical Assessment

All clinical examinations were performed by a single calibrated examiner to eliminate inter-examiner variability. Calibration was achieved through preliminary examination of 10 volunteers (not included in the main study sample) with repeated measurements demonstrating intra-examiner agreement ($\kappa > 0.80$).

The following indices were recorded for each participant:

- Debris Index—Simplified (DI-S) and Calculus Index—Simplified (CI-S), combined as the Oral Hygiene Index—Simplified (OHI-S) according to the criteria described by Greene and Vermillion (*Greene & Vermillion, 1964*). Six index teeth (16, 11, 26, 36, 31, 46) were examined on buccal surfaces of upper teeth and lingual surfaces of lower teeth. Each component was scored 0–3, and the OHI-S was calculated as the sum of DI-S and CI-S (range 0–6).

- Modified Gingival Index (MGI), assessed according to Lobene et al. (1986), evaluating gingival inflammation on a 0–4 scale for each of the six index teeth without gingival probing, thereby avoiding stimulation of bleeding in participants with inflamed gingiva.
- DMFT Index (Decayed, Missing, Filled Teeth), recorded according to WHO criteria (World Health Organization, 2013). All permanent teeth were examined using a standard dental mirror and CPI probe under artificial illumination.

Statistical Analysis

Descriptive statistics were calculated for all continuous variables as mean $\pm$ standard deviation (SD). Normal distribution was confirmed using the Shapiro-Wilk test. Homogeneity of variance was assessed by Levene's test. Between-group comparisons were performed using one-way analysis of variance (ANOVA). Where significant differences were identified ($p < 0.05$), post-hoc pairwise comparisons were conducted using Tukey's Honestly Significant Difference (HSD) test. Statistical analyses were performed using IBM SPSS Statistics, Version 26.0. The significance threshold was set at $\alpha = 0.05$.

Literature Review

The association between conventional cigarette smoking and impaired oral health is extensively documented in the international literature. Warnakulasuriya et al. (2010) conducted a systematic review demonstrating that smokers present with significantly higher plaque and calculus scores compared to non-smokers, with a dose-dependent relationship between pack-years and periodontal attachment loss. The proposed mechanisms include nicotine-induced vasoconstriction masking clinical signs of inflammation, impaired neutrophil chemotaxis, and direct cytotoxic effects of tobacco metabolites on gingival fibroblasts (Johnson & Hill, 2004).

Heat-not-burn tobacco products represent a relatively recent category. Prototype devices heat tobacco to approximately 250–350°C, generating a nicotine-containing aerosol while avoiding full combustion. A review by Simonavicius et al. (2019) found that HNB aerosols contain substantially lower concentrations of harmful and potentially harmful constituents (HPHCs) compared to cigarette smoke. However, evidence specifically addressing periodontal and oral hygiene outcomes in HNB users remains limited. Preliminary clinical data suggest that while HNB users may present with less severe gingival inflammation than cigarette smokers, measurable deviations from healthy non-tobacco-user baselines persist (Gholami et al., 2022).

Smokeless tobacco—including traditional chewing tobacco and contemporary oral nicotine pouches—represents a further diversification of nicotine delivery. Unlike combustion-based products, pouches deliver nicotine via the oral mucosa and have been positioned by manufacturers as a reduced-risk alternative. Robertson et al. (2020) reviewed clinical data on smokeless tobacco users and reported that while these users avoid combustion-related systemic exposure, direct mucosal contact with tobacco-derived compounds may still produce local inflammatory responses and gingival recession. Comparative evidence between pouch users and cigarette smokers in standardized clinical settings, particularly within Eastern European populations, is sparse.

The indices selected for this study—OHI-S, MGI, and DMFT—are internationally validated, widely employed in epidemiological dental research, and recommended by WHO for population-level oral health surveys (World Health Organization, 2013). Their combined

application enables comprehensive characterization of oral hygiene status, periodontal inflammation, and caries burden within a single clinical visit, making them suitable for cross-sectional comparative studies across diverse tobacco-using populations.

Results

Participant Characteristics

The final study sample comprised 44 participants (Group 1: n=15; Group 2: n=15; Group 3: n=14). The three groups were comparable with respect to age and sex distribution ($p>0.05$ for both). Mean duration of tobacco product use was similar across groups (Group 1: 8.4 ± 3.1 years; Group 2: 3.2 ± 1.4 years; Group 3: 2.8 ± 1.2 years). All participants reported no history of professional oral hygiene procedures within the preceding 6 months. Thus, observed differences in clinical indices can be attributed primarily to the type of tobacco product used rather than confounding differences in baseline demographics.

Oral Hygiene and Periodontal Indices

Mean values ($\pm$ SD) for all clinical indices are presented in the Appendix (*Table 1*). One-way ANOVA revealed statistically significant between-group differences for all five indices ($p<0.05$).

Group 1 (conventional cigarette smokers) demonstrated the highest mean scores across all indices. The OHI-S score in Group 1 (3.47 ± 0.54) was significantly elevated compared to Group 2 (2.90 ± 0.48 ; $p=0.018$) and Group 3 (2.70 ± 0.44 ; $p=0.004$). Similarly, the MGI score in Group 1 (2.21 ± 0.38) was significantly higher than in Group 2 (1.87 ± 0.33 ; $p=0.027$) and Group 3 (1.74 ± 0.30 ; $p=0.006$). DMFT values were also greatest in Group 1 (14.3 ± 2.8) relative to Group 2 (12.6 ± 2.4 ; $p=0.048$) and Group 3 (11.9 ± 2.2 ; $p=0.038$).

Thus, conventional cigarette smoking is associated with the most pronounced impairment of oral hygiene and periodontal status among the three groups studied.

Post-Hoc Pairwise Comparisons

Results of Tukey's HSD post-hoc analysis are presented in Appendix (*Table 2*). Significant differences were consistently identified between Group 1 and both alternative product groups. In contrast, no statistically significant differences were found between Group 2 (HNB) and Group 3 (smokeless tobacco) for any index (all $p>0.05$).

Thus, HNB users and smokeless tobacco users presented with comparable oral health profiles that were significantly better than those of conventional cigarette smokers, yet remained elevated relative to healthy non-tobacco-user reference values reported in the literature.

Discussion

The principal finding of this cross-sectional study is that conventional cigarette smokers exhibit significantly worse oral hygiene status and greater periodontal inflammation compared to users of HNB tobacco systems and smokeless tobacco pouches. These results are consistent with the known pathophysiology of combustion-generated tobacco toxicants on oral tissues and contribute quantitative clinical data to the evolving evidence base on alternative tobacco product effects.

The higher DI-S and CI-S values observed in Group 1 reflect the well-established role of tobacco smoke components in promoting supragingival and subgingival plaque and calculus

accumulation. Combustion products alter salivary composition, reduce salivary flow, and modify the oral microbiome toward a more dysbiotic community, collectively facilitating biofilm development and calcification (*Warnakulasuriya et al., 2010; Johnson & Hill, 2004*). The lower debris and calculus scores in HNB and smokeless tobacco users suggest that the absence of combustion substantially mitigates these effects on oral deposits, although direct mucosal exposure to nicotine and flavoring compounds may still contribute to mild inflammatory responses.

The MGI findings are particularly noteworthy. Conventional cigarette smoking produces a paradoxical reduction in gingival bleeding due to nicotine-induced vasoconstriction, which can mask the true severity of underlying gingival inflammation when using bleeding-on-probing assessments. The MGI, which evaluates visual signs of inflammation without probing, revealed that Group 1 participants had significantly more inflamed gingiva than Groups 2 and 3. This supports the use of non-invasive visual indices in tobacco-using populations and highlights that smoking-associated periodontal disease may be clinically underestimated when standard probing indices are used exclusively.

The absence of a significant difference between Group 2 and Group 3 across all indices is clinically informative. Despite their mechanistically distinct delivery systems, HNB and smokeless tobacco products produced comparable levels of oral hygiene impairment and gingival inflammation in this sample. This finding suggests that the relevant harmful exposures—likely nicotine, flavoring compounds, and tobacco-specific nitrosamines present in both product categories—may produce similar oral tissue effects independent of delivery route. Longer-term prospective studies are needed to determine whether these two product categories diverge in their effects on periodontal attachment, alveolar bone levels, or malignant transformation risk.

Several limitations of this study should be acknowledged. The relatively small sample size ($n=44$) limits statistical power and generalizability. The cross-sectional design precludes causal inference. Duration of tobacco use differed across groups—cigarette smokers had longer use histories than HNB or pouch users, reflecting the more recent market introduction of these products—which may have contributed to the inter-group differences observed. Future research should employ longitudinal designs with matched cohorts and include salivary biomarker assessment and microbiological profiling to elucidate the biological mechanisms underlying the clinical differences identified here.

Conclusion

This cross-sectional study demonstrated that conventional cigarette smokers present with significantly higher plaque accumulation (DI-S), calculus deposition (CI-S), overall oral hygiene impairment (OHI-S), gingival inflammation (MGI), and dental caries experience (DMFT) compared to users of heat-not-burn tobacco systems and smokeless tobacco pouches. Users of HNB products and smokeless tobacco showed comparable oral health profiles that were statistically indistinguishable from each other but significantly worse than healthy non-tobacco-user reference values.

These findings support the clinical rationale for implementing differentiated oral health monitoring and preventive protocols for distinct tobacco product user populations. Dental

clinicians should not assume uniform tobacco-related risk across product categories; rather, product-specific assessment tools and counselling messages are warranted. Conventional cigarette smokers require intensified professional oral hygiene intervention and close periodontal surveillance, while HNB and smokeless tobacco users, though presenting with lower clinical indices, nonetheless require dedicated preventive support. Prospective multicenter studies with larger samples and longitudinal follow-up are recommended to validate and extend these findings.

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Conflict of Interest

The author declares that there is no conflict of interest.

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Appendix

Table 1. Mean values ($\pm$ SD) of oral hygiene and periodontal indices by tobacco product group

Index	Group 1 (Cigarettes) n=15	Group 2 (HNB systems) n=15	Group 3 (Smokeless tobacco) n=14	p-value (ANOVA)
DI-S	1.84 $\pm$ 0.31	1.52 $\pm$ 0.28	1.41 $\pm$ 0.25	0.003*
CI-S	1.63 $\pm$ 0.29	1.38 $\pm$ 0.24	1.29 $\pm$ 0.22	0.008*
OHI-S	3.47 $\pm$ 0.54	2.90 $\pm$ 0.48	2.70 $\pm$ 0.44	0.002*

MGI	2.21 ± 0.38	1.87 ± 0.33	1.74 ± 0.30	0.004*
DMFT	14.3 ± 2.8	12.6 ± 2.4	11.9 ± 2.2	0.041*

Statistically significant ($p < 0.05$, one-way ANOVA). HNB = heat-not-burn system.

Table 2. Post-hoc Tukey's HSD pairwise comparison results

Comparison	DI-S	CI-S	OHI-S	MGI	DMFT
Group 1 vs Group 2	$p=0.021^*$	$p=0.034^*$	$p=0.018^*$	$p=0.027^*$	$p=0.048^*$
Group 1 vs Group 3	$p=0.007^*$	$p=0.009^*$	$p=0.004^*$	$p=0.006^*$	$p=0.038^*$
Group 2 vs Group 3	$p=0.412$	$p=0.487$	$p=0.396$	$p=0.441$	$p=0.519$

Statistically significant ($p < 0.05$). NS = not significant.

Peculiarities and Analysis of Minimally Invasive Elastic Titanium Nail Osteosynthesis for Forearm Bone Fractures in Children ^[12]

Abstract:

This article presents an analysis of the treatment of 365 children with diaphyseal fractures of the forearm bones. The features of treatment, long-term outcomes, and clinical-radiological justification are based on the study of medical histories of children who were treated from 2022 to 2024 in the paediatric trauma department of the Emergency Hospital in Chernivtsi. The aim of the study was to evaluate the outcomes and provide clinical and radiological justification for the treatment of complex forearm bone fractures in children through osteosynthesis of fragments using Titanium Elastic Nails (TEN), ensuring reliable fixation, rapid restoration of limb function, and minimisation of complication risks. Three clinical groups were identified. The first clinical group included 185 children treated with conservative methods. The second group comprised 102 children who underwent osteosynthesis with Titanium Elastic Nails. The third group consisted of 78 children who received other types of osteosynthesis (plating, repositioning, external fixation). The main indication for this functionally stable osteosynthesis was intraoperative fracture instability after primary repositioning, i.e., the inability to achieve a stable and satisfactory alignment of fragments solely with external immobilisation. The minimally invasive nature of the method, combined with functionally stable osteosynthesis, made it applicable for unstable forearm fractures in children at risk of impaired bone healing (older age, diaphyseal location, and associated risk factors). The method of treating forearm fractures in children using TEN is considered one of the most effective and safe approaches in modern paediatric orthopaedics. It provides stable fracture fixation, rapid healing, and a swift return to normal life. Due to its minimally invasive nature, this method significantly improves patients' quality of life and shortens treatment duration.

Keywords: fracture, forearm, diaphysis, functionally stable osteosynthesis, titanium elastic nails.

Introduction

Fractures of the forearm bones are among the most common injuries in paediatric traumatology and occupy one of the leading positions in the general structure of musculoskeletal trauma in children (*Ivanova, 2018; Levytskyi & Oliinyk, 2013; Tarniță et al., 2010*). The most widely used method for treating stable and slightly displaced fractures of the forearm bones in children remains conservative management, which usually includes closed reduction, external immobilisation, and further radiological follow-up (*Levytskyi et al., 2012; Myers et al., 2004*). In stable fractures, residual permissible displacement of bone fragments may be corrected during growth due to the remodelling potential of the child's skeleton.

However, diaphyseal fractures of both forearm bones with complete displacement of fragments are unstable by nature and are associated with a higher probability of secondary displacement during conservative treatment. These fractures are clinically significant because the radius and ulna form a complex functional unit responsible not only for flexion and extension in adjacent joints, but also for pronation and supination of the forearm. Therefore, malalignment, residual rotational deformity, angular displacement, shortening, or delayed consolidation may result in functional impairment, reduced range of motion, prolonged immobilisation, joint contractures, and deterioration in the child's quality of life.

The relevance of this study is determined by the need to optimise the treatment of unstable diaphyseal forearm fractures in children, especially in older age groups, where the remodelling

potential of bone decreases and the risk of unsatisfactory outcomes after conservative treatment increases. Although conservative treatment remains effective for many stable fractures, unstable diaphyseal injuries often require surgical stabilisation. The main surgical options include plate osteosynthesis, Kirschner wire fixation, external fixation in open fractures, and intramedullary osteosynthesis using Titanium Elastic Nails (TEN) (*Fernandez et al., 2010; Flynn et al., 2010; Lascombes, 2010; Patel et al., 2021; Xu et al., 2018*).

Despite the widespread use of these methods, the choice of the optimal surgical stabilisation technique for paediatric forearm fractures remains a matter of discussion in the specialised literature. Plate osteosynthesis provides rigid fixation, but it is more invasive, requires wider surgical access, may be associated with additional soft tissue trauma, and usually requires subsequent implant removal. Kirschner wire fixation is technically simple, but may not provide sufficient stability in some diaphyseal fractures and often requires prolonged external immobilisation. External fixation is usually reserved for open, infected, or combined injuries. In contrast, elastic stable intramedullary osteosynthesis with titanium nails combines relative stability, minimal invasiveness, preservation of growth zones, and the possibility of early functional recovery (*Fernandez et al., 2010; Lascombes, 2010; Patel et al., 2021*).

The technique of osteosynthesis with elastic titanium nails, developed and popularised by Jean Prévot and Jean-Paul Métaizeau, has been widely used since the beginning of the twenty-first century and has gradually established its indications in paediatric orthopaedic trauma practice (*Lascombes, 2010*). Earlier and more recent publications by Ukrainian and international authors confirm the increasing use of intramedullary metal osteosynthesis with TEN for the treatment of children with unstable fracture patterns (*Ivanova, 2018; Lerytskyi et al., 2012; Lerytskyi & Oliynyk, 2013; Patel et al., 2021; Xu et al., 2018*). At the same time, several clinical questions remain insufficiently clarified, including indications for surgery after failed closed reduction, the need and duration of postoperative immobilisation, complication risks, implant removal timing, and long-term functional outcomes.

The research problem of the present article lies in the need to determine the clinical and radiological justification for the use of TEN osteosynthesis in children with unstable diaphyseal forearm fractures. In particular, it is necessary to evaluate whether minimally invasive elastic intramedullary fixation provides reliable fragment stability, allows early mobilisation, reduces the duration of external immobilisation, minimises the risk of complications, and ensures full functional recovery of the injured limb. This issue is especially important for children with complete displacement of fragments, secondary displacement after conservative treatment, recurrent fractures, diaphyseal localisation, and older age, all of which may increase the risk of impaired consolidation under conservative management.

The scientific novelty of this study consists in the clinical and radiological analysis of a large single-centre cohort of paediatric patients with diaphyseal forearm fractures treated during 2022–2024, with particular attention to the comparative clinical characteristics of conservative treatment, TEN osteosynthesis, and other types of surgical fixation. The article systematises indications for functionally stable intramedullary osteosynthesis using titanium elastic nails, evaluates early and long-term outcomes, identifies the main types of complications, and substantiates the role of TEN in restoring anatomical integrity and functional activity of the forearm in children.

The object of the study is the treatment process of children with diaphyseal fractures of the forearm bones.

The subject of the study is the clinical and radiological effectiveness of minimally invasive osteosynthesis with Titanium Elastic Nails in children with unstable diaphyseal forearm fractures.

The aim of the study is to evaluate treatment outcomes and provide clinical and radiological justification for the use of Titanium Elastic Nail osteosynthesis in children with complex diaphyseal forearm fractures, with an emphasis on reliable fragment fixation, rapid restoration of limb function, and minimisation of complication risks.

To achieve this aim, the study addresses the following objectives:

- to analyse the structure of paediatric forearm fractures treated in the paediatric trauma department during 2022–2024;
- to identify the clinical groups of patients treated conservatively, with TEN osteosynthesis, and with other types of osteosynthesis;
- to determine the main indications for minimally invasive elastic titanium nail osteosynthesis in children with unstable diaphyseal forearm fractures;
- to evaluate the clinical and radiological outcomes of TEN osteosynthesis, including fracture consolidation, position of fragments, and restoration of limb function;
- to analyse the frequency and nature of postoperative complications associated with TEN osteosynthesis;
- to determine the role of postoperative immobilisation, rehabilitation, and implant removal timing in the treatment process;
- to assess the advantages and limitations of TEN osteosynthesis in comparison with conservative treatment and other surgical techniques;
- to substantiate practical recommendations for the use of elastic titanium nails in paediatric orthopaedic and traumatological practice.

The theoretical significance of the study lies in deepening the understanding of functionally stable osteosynthesis in paediatric diaphyseal forearm fractures. The research contributes to the development of clinical reasoning regarding the limits of conservative treatment, the indications for surgical fixation, and the biomechanical advantages of elastic intramedullary stabilisation in the growing skeleton. It also clarifies the relationship between fracture localisation, age-related remodelling potential, fixation stability, and functional recovery.

The practical significance of the study lies in the possibility of using its results in the daily practice of paediatric orthopaedic and traumatological departments. The findings may help clinicians determine indications for TEN osteosynthesis, select appropriate nail diameter according to the medullary canal, reduce the risk of secondary displacement, minimise the duration of immobilisation, optimise rehabilitation, and improve functional outcomes. The use of minimally invasive elastic titanium nail osteosynthesis may shorten the period of treatment, reduce the need for prolonged plaster immobilisation, improve cosmetic results, and facilitate a faster return of children to normal daily activity.

Materials and Methods

Study Design and Clinical Setting

This study was designed as a retrospective clinical and radiological analysis of paediatric patients with diaphyseal fractures of the forearm bones. The research was conducted on the basis of medical records of children treated between 2022 and 2024 in the Paediatric Trauma Department of the Emergency Hospital in Chernivtsi. The retrospective design made it possible to evaluate the real clinical practice of treating forearm fractures in children, including conservative management, minimally invasive osteosynthesis with Titanium Elastic Nails, and other surgical fixation techniques.

The study focused on the assessment of treatment outcomes, indications for surgical stabilisation, fracture consolidation, restoration of limb function, postoperative complications, and the clinical-radiological justification for using Titanium Elastic Nails in unstable diaphyseal forearm fractures in children.

Study Population and Eligibility Criteria

The total study population included 365 children with diaphyseal fractures of the forearm bones. All patients were hospitalised and treated in accordance with the accepted clinical principles of paediatric orthopaedic and traumatological care.

The inclusion criteria were as follows:

- paediatric age;
- diaphyseal fracture of one or both forearm bones;
- presence of radiologically confirmed fracture of the radius and/or ulna;
- treatment in the Paediatric Trauma Department of the Emergency Hospital in Chernivtsi during 2022–2024;
- availability of complete medical records and radiological documentation sufficient for retrospective analysis.

The exclusion criteria were distal and proximal meta-epiphyseal fractures, stable greenstick fractures, subperiosteal fractures, incomplete documentation, and cases in which the clinical or radiological data were insufficient for evaluating treatment outcomes.

According to these criteria, 365 medical histories were selected and analysed. Among them, 102 patients underwent minimally invasive osteosynthesis using Titanium Elastic Nails. In this subgroup, the mean age was 11.0 ± 2.2 years. The largest proportion of surgically treated patients belonged to the age group of 11–13 years, which accounted for 57% of all cases treated with TEN osteosynthesis. This age group was of particular clinical interest because the remodelling potential of the forearm decreases with age, while the risk of secondary displacement and unsatisfactory outcomes after conservative treatment increases.

Clinical Groups

For comparative clinical analysis, all patients were divided into three groups according to the treatment method used.

The first clinical group included 185 children treated with conservative methods. Conservative treatment consisted of closed reduction where necessary, plaster immobilisation, radiological follow-up, and rehabilitation after removal of the cast.

The second clinical group included 102 children who underwent osteosynthesis with Titanium Elastic Nails. This group represented the main focus of the study because TEN osteosynthesis was analysed as a minimally invasive and functionally stable method for treating unstable diaphyseal forearm fractures in children.

The third clinical group included 78 children who underwent other types of osteosynthesis, including plate fixation, repositioning fixation, Kirschner wire fixation, or external fixation depending on the fracture type, soft tissue condition, and clinical indications (*Figure 1*).

Indications for TEN Osteosynthesis

The main indication for Titanium Elastic Nail osteosynthesis was instability of the fracture after primary repositioning, that is, the inability to achieve or maintain stable and satisfactory alignment of bone fragments by closed reduction and external immobilisation alone. The method was used in children with unstable diaphyseal fractures characterised by complete displacement of fragments by length and width, pronounced angular displacement, complete rupture of the periosteum, residual unacceptable displacement after closed manual reduction, or secondary displacement during conservative treatment.

Additional indications included recurrent fractures, insufficient stability after plaster immobilisation, and fracture patterns in which prolonged external immobilisation could increase the risk of joint contractures or delayed functional recovery. Surgical stabilisation was also considered in older children with diaphyseal localisation of the fracture, since this group has a reduced potential for spontaneous remodelling and a higher risk of impaired consolidation under conservative treatment.

The choice of TEN osteosynthesis was based on its minimally invasive nature, preservation of growth zones, relative elastic stability, and potential for early functional rehabilitation. These advantages correspond to the general principles of paediatric elastic stable intramedullary nailing described in the specialised literature (*Fernandez et al., 2010; Lascombes, 2010; Patel et al., 2021; Xu et al., 2018*).

Surgical Technique

All children in the TEN group underwent osteosynthesis with Titanium Elastic Nails. The diameter of the nail was selected according to the width of the medullary canal. The preferred diameter of the metal fixator corresponded to approximately 60–70% of the diameter of the medullary canal at its narrowest point. Nails with a diameter of 2.0 to 4.0 mm were used, depending on the child's age, bone size, and anatomical characteristics.

The key biomechanical feature of this technique was relative elastic stability achieved through three-point intramedullary fixation. Before insertion, the nail was pre-bent into an arc so that its apex corresponded to the fracture zone after placement in the medullary canal. The physiological curvature of both the radius and ulna was taken into account during the formation and insertion of the implant. This allowed restoration of the anatomical axis of the forearm bones and provided sufficient stability during fracture consolidation.

In fractures of both forearm bones, elastic nails were inserted into both the radius and ulna. In cases of isolated radial fracture, one nail was inserted into the radius. In cases of ulnar fracture associated with radial head dislocation, corresponding to Monteggia injury, fixation was performed by inserting one nail into the ulna.

Standard surgical access was used according to the anatomical characteristics of the injured bone. Particular attention was paid to minimising soft tissue trauma and avoiding damage to the sensory branch of the radial nerve and the tendon of the extensor pollicis longus during insertion of the nail into the radius. Careful exposure of the bone and atraumatic manipulation were used to prevent these complications.

If closed reduction was unsuccessful, a Kirschner wire with a diameter of 1.5–1.8 mm was introduced percutaneously near the fracture site and used as a “joystick” to reposition the bone fragments. This technique made it possible in most cases to avoid conversion to open osteosynthesis. In cases where closed reduction was impossible because of significant soft tissue interposition, the intramedullary nail was advanced to the fracture area, the interposed tissues were released through a small incision of approximately 3–4 cm, and the fracture was then stabilised by advancing the nail into the proximal bone fragment.

All stages of the surgical procedure were performed under radiological control using an image intensifier, or C-arm. Intraoperative fluoroscopy was used to confirm the quality of reduction, correct positioning of bone fragments, appropriate location of the nails, and sufficient stability of fixation.

Postoperative Management and Rehabilitation

Postoperative management included pain control, monitoring of the surgical wound, assessment of peripheral circulation and sensitivity, and early functional rehabilitation. Plaster immobilisation of the injured limb was performed for 10–14 days until pain subsided. In most cases, immobilisation was performed without including the elbow joint, which allowed earlier restoration of movement and reduced the risk of elbow stiffness.

Although correct nail sizing may theoretically allow treatment without plaster immobilisation, a plaster splint was used in selected cases because TEN provides relative elastic stability rather than absolute rigid fixation. Since micro-mobility of fragments remains and consolidation occurs through callus formation, short-term plaster immobilisation was considered useful for reducing excessive fragment mobility, decreasing pain in the early postoperative period, and preventing the formation of excessive paraosteal callus.

Stable osteosynthesis with elastic titanium nails allowed the duration of plaster immobilisation to be reduced to 2–4 weeks in most patients. This enabled earlier initiation of rehabilitative treatment and restoration of active movements in the elbow and wrist joints. Early mobilisation was considered one of the principal advantages of TEN osteosynthesis in comparison with prolonged conservative immobilisation.

Clinical Outcome Assessment

Clinical assessment was performed during the treatment period and at follow-up visits. The main clinical criteria included patient complaints, pain intensity, external appearance of the operated limb, presence or absence of swelling or deformity, condition of postoperative wounds, peripheral circulation, skin sensitivity, and signs of muscle hypotrophy.

Functional assessment included evaluation of active range of motion in the elbow and wrist joints, as well as pronation and supination of the forearm. Particular attention was paid to restoration of symmetrical function in comparison with the contralateral upper limb. The presence or absence of complications was also assessed, including inflammatory complications, irritation caused by nail protrusion, superficial infection at the nail insertion site, migration of

the nail, nerve injury, tendon injury, delayed consolidation, contracture, angular deformity, rotational deformity, synostosis, limb shortening, or growth disturbance.

Radiological Assessment

Radiological assessment was performed using standard radiographs of the forearm in appropriate projections. Radiographs were analysed to evaluate fracture type, initial displacement, quality of reduction, position of fragments after fixation, location and stability of the nails, restoration of the anatomical axis, and stages of radiopaque callus formation.

Particular attention was paid to the restoration of the physiological curvature of the radius and ulna, since this parameter is important for preserving pronation and supination of the forearm. Radiological evidence of fracture consolidation was used to determine the timing of implant removal. Complete union and satisfactory bone remodelling were considered necessary conditions for safe removal of the metal fixators.

Follow-Up and Implant Removal

Patients who underwent TEN osteosynthesis were followed dynamically after surgery. Follow-up included clinical examination, functional testing, radiological assessment, and evaluation of the quality of recovery. Observations were performed at different postoperative intervals, including 1, 3, and 6 months, and in selected cases later follow-up was conducted at 12 and 18 months after surgery.

The removal of elastic titanium nails was performed after radiological confirmation of fracture union. In most cases, implants were removed between 6 and 14 months after surgery under general anaesthesia in hospital conditions. The timing of removal was determined individually, taking into account fracture consolidation, age of the child, stability of bone remodelling, absence of pain, and restoration of limb function.

Data Processing and Statistical Analysis

The obtained clinical and radiological data were processed using descriptive statistical methods. Quantitative variables were presented as mean values with standard deviation where applicable. Categorical variables were presented as absolute numbers and percentages. The analysis included the distribution of patients by treatment group, age, fracture type, type of fixation, duration of immobilisation, timing of functional recovery, timing of implant removal, and frequency and type of complications.

The study did not involve randomisation or prospective allocation of patients to treatment groups, since the treatment method was determined by clinical indications, fracture stability, fracture localisation, patient age, and the decision of the treating orthopaedic-traumatological team. Therefore, the results were interpreted as retrospective clinical evidence reflecting real practice in paediatric traumatology.

Ethical Considerations

The study was retrospective in nature and was based on the analysis of medical histories and radiological documentation. Personal identifying data were not used in the analysis or presentation of results. The research was conducted in accordance with the principles of confidentiality and ethical handling of medical information.

Literature Review

Forearm bone fractures in children remain one of the most frequently discussed problems in paediatric traumatology and orthopaedics because of their high prevalence, functional significance, and variability of treatment approaches. The radius and ulna form a single biomechanical unit responsible not only for support and flexion-extension movements of the upper limb, but also for pronation and supination of the forearm. Therefore, even a relatively small residual deformity after fracture healing may affect rotational function, especially in diaphyseal fractures where the remodelling capacity is lower than in metaphyseal injuries. Ukrainian and international studies emphasise that the choice of treatment method should take into account the child's age, fracture localisation, degree of displacement, rotational deformity, stability after reduction, and potential for further skeletal growth (*Ivanova, 2018; Levytskyi & Oliinyk, 2013; Levytskyi et al., 2012*).

Conservative treatment remains the traditional and most widely used approach for stable or slightly displaced paediatric forearm fractures. Its main advantage is the absence of surgical trauma and anaesthetic risks. Closed reduction followed by plaster immobilisation may be sufficient in younger children and in cases where the displacement is within acceptable limits. Myers et al. (2004) noted that satisfactory results may be achieved in selected diaphyseal fractures when reduction is stable and further displacement does not occur. At the same time, the effectiveness of conservative treatment depends on accurate reduction, proper cast application, adequate follow-up, and the biological capacity of the growing skeleton to remodel residual angulation.

However, the literature also shows that conservative treatment has important limitations in unstable diaphyseal fractures of both forearm bones. Complete displacement, pronounced angular deformity, rotational malalignment, rupture of the periosteum, and fracture localisation in the diaphysis increase the probability of secondary displacement. This problem becomes more clinically significant in children older than 10 years, since the remodelling potential decreases with age and the risk of persistent functional limitation increases. Levytskyi et al. (2012) emphasised that surgical treatment should be considered when closed reduction is ineffective, when fragment stability cannot be maintained, or when the fracture pattern itself indicates a high risk of unsatisfactory consolidation. Thus, the current literature supports a differentiated approach rather than an unconditional preference for either conservative or surgical treatment.

Surgical stabilisation of paediatric forearm fractures includes several methods: plate osteosynthesis, Kirschner wire fixation, external fixation, and elastic stable intramedullary nailing with titanium elastic nails. Each technique has its own indications, advantages, and limitations. Plate osteosynthesis provides rigid anatomical fixation and is effective in complex fractures, but it requires wider surgical access, greater soft tissue dissection, and subsequent implant removal. In paediatric practice, these features are important disadvantages because they increase surgical trauma, cosmetic defects, and potential risks to the periosteal blood supply. Kirschner wire fixation is less invasive but may provide insufficient stability in some diaphyseal fractures and often requires prolonged immobilisation. External fixation is usually reserved for open fractures, infected injuries, polytrauma, or severe soft tissue damage (*Fernandez et al., 2010; Flynn et al., 2010; Xu et al., 2018*).

Elastic stable intramedullary nailing has become increasingly important in paediatric orthopaedics since the development of the method by Prévot and Métaizeau and its subsequent systematisation in the Nancy school. Lascombes (2010) described flexible intramedullary nailing as a biologically favourable technique that provides relative stability while preserving the fracture haematoma, periosteal blood supply, and growth zones. The principle of three-point fixation allows elastic nails to stabilise bone fragments without rigid compression, creating conditions for callus formation and functional recovery. This method is particularly relevant in children because it corresponds to the biological characteristics of the growing skeleton and minimises iatrogenic damage.

The main advantages of TEN osteosynthesis reported in the literature include minimal invasiveness, small incisions, reduced soft tissue trauma, preservation of the periosteum, stable fragment alignment, shorter immobilisation period, earlier rehabilitation, satisfactory cosmetic results, and easier implant removal. Fernandez et al. (2010) analysed failures and complications associated with intramedullary nailing of children's forearm fractures and showed that most complications are preventable when the correct indications, implant diameter, entry point, and surgical technique are respected. Patel et al. (2021) also reported favourable outcomes in paediatric forearm fractures treated with titanium elastic nails, emphasising the method's ability to provide stable fixation and satisfactory functional recovery.

Comparative studies further support the clinical value of elastic intramedullary fixation. Xu et al. (2018) compared elastic stable intramedullary nailing and plating in paediatric forearm fractures and demonstrated that both methods may provide good union rates, but intramedullary nailing is associated with lower invasiveness and a more favourable soft tissue profile. Flynn et al. (2010), in their long-term operative experience with paediatric forearm fractures, also supported the use of surgical stabilisation in unstable fractures when conservative treatment fails or when there is a high risk of secondary displacement. These findings are consistent with Ukrainian clinical observations that TEN osteosynthesis may be preferable in unstable diaphyseal fractures, especially in older children and adolescents (Ivanova, 2018; Levytskyi & Oliinyk, 2013).

A separate issue in the literature concerns single-bone versus both-bone fixation in fractures of the radius and ulna. Myers et al. (2004) studied Nancy nailing of diaphyseal forearm fractures and discussed the possibility of single-bone fixation in selected cases. This approach may reduce surgical trauma, but it requires careful assessment of fracture stability and restoration of the anatomical relationship between both bones. In fractures of both forearm bones, fixation of both the radius and ulna may provide more reliable restoration of the forearm axis and reduce the risk of rotational limitation. Therefore, the decision should be individualised according to fracture morphology, intraoperative stability, and the surgeon's assessment.

Biomechanical studies provide additional justification for the need to restore the anatomical axis and curvature of the forearm bones. Anderson et al. (2005) developed a three-dimensional finite element model of the radiocarpal joint, demonstrating the importance of load distribution in the forearm-wrist complex. Edwards and Troy (2012) and Troy and Grabiner (2007) showed that bone strength and fracture behaviour depend on loading direction and structural properties. Shefelbine et al. (2005) used micro-CT and finite element analysis to predict mechanical properties of fracture callus, highlighting the relationship between fracture healing and

mechanical stability. These studies support the clinical principle that adequate fixation should provide sufficient stability while preserving biological conditions for callus formation.

The design and material properties of implants are also significant in paediatric fracture treatment. Titanium elastic nails are valued because of their elasticity, biocompatibility, and ability to provide stable intramedullary support without excessive rigidity. Studies of fixation plates and alternative materials, including carbon fibre composites, Nitinol-based plates, and modular orthopaedic plates, show the continuing search for fixation systems that combine mechanical reliability with biological compatibility (*Frydryšek et al., 2014; Saidpour, 2006; Tarniž et al., 2010*). However, in paediatric diaphyseal forearm fractures, TEN remains attractive because it combines sufficient mechanical stability with minimal surgical invasiveness.

The literature also emphasises the importance of complication analysis. Possible complications of TEN osteosynthesis include irritation of soft tissues at the nail entry site, superficial infection, migration or protrusion of the nail, delayed union, refracture after early implant removal, injury to the superficial radial nerve, tendon irritation, and, rarely, synostosis or rotational limitation. Fernandez et al. (2010) stressed that technical errors, incorrect nail diameter, insufficient pre-bending, inadequate fixation, or premature removal may increase the risk of complications. Therefore, successful TEN osteosynthesis requires strict adherence to surgical technique, correct implant sizing, careful protection of neurovascular and tendon structures, and appropriate follow-up.

Timing of implant removal remains a subject of clinical discussion. Lascombes (2010) recommended that removal should be performed only after complete consolidation and adequate remodelling. Premature removal may increase the risk of refracture, whereas excessive delay may cause irritation, discomfort, or technical difficulties during extraction. Clinical practice therefore usually requires radiological confirmation of union before removal. This issue is especially important in children because implant removal should be planned in relation to bone healing, growth, psychological comfort, and the need to minimise repeated surgical trauma.

Another important aspect is early mobilisation and functional recovery. Prolonged plaster immobilisation may lead to stiffness of adjacent joints, muscle hypotrophy, delayed return to activity, and the need for rehabilitation. In this respect, TEN osteosynthesis has a significant functional advantage because it allows a reduction in immobilisation time and supports earlier restoration of movement. The literature suggests that early mobilisation is particularly important for maintaining pronation and supination, which are sensitive to residual angular and rotational deformities of the radius and ulna (*Fernandez et al., 2010; Lascombes, 2010; Patel et al., 2021*).

Despite the growing body of research, several issues remain insufficiently resolved. First, there is still no universal consensus regarding the exact indications for TEN osteosynthesis in paediatric forearm fractures, especially in borderline cases after closed reduction. Secondly, the optimal duration of postoperative immobilisation remains debated because TEN provides relative elastic stability rather than absolute rigid fixation. Thirdly, the timing of implant removal varies across clinical practices. Fourthly, the relationship between patient age, diaphyseal localisation, fracture morphology, and long-term rotational function requires further clinical analysis. Finally, there is a need for more single-centre and multicentre studies based on real clinical practice and long-term follow-up.

Thus, the reviewed literature confirms that minimally invasive elastic titanium nail osteosynthesis is a clinically justified and widely accepted method for the treatment of unstable diaphyseal forearm fractures in children. It provides reliable fixation, preserves biological healing mechanisms, reduces surgical trauma, allows early rehabilitation, and improves functional outcomes. At the same time, the effectiveness of the method depends on correct patient selection, precise surgical technique, adequate postoperative management, and timely implant removal. These considerations define the relevance of the present study, which analyses clinical and radiological outcomes of TEN osteosynthesis in children with diaphyseal forearm fractures treated in a specialised paediatric trauma department.

Results

Certain difficulties in treating forearm fractures in children arise when they are localized in the diaphyseal region. In such fractures, bone fragments are usually displaced laterally (by width) and angularly, which significantly complicates the process of reduction and fixation given the small diameter of the bones. There is no single consensus regarding treatment tactics for patients of different age groups or the choice of treatment strategies, as it is necessary to consider the anatomical features and the potential for growth and development of the forearm in children of various ages. Currently, the conservative method of treating diaphyseal forearm fractures in children remains the primary approach. The prognosis of treatment results is determined by the patient's age, the nature of the fracture, the quality of the reduction and cast application, the duration of fixation, and adequate rehabilitation. It is worth noting that in paediatric traumatology, the concept of permissible displacement is widely used, with the exception of rotational displacement. During a child's growth, spontaneous remodelling occurs at the level of the callus at a rate of approximately 10 degrees per year.

However, this property of the growing organism has its limits, determined by the magnitude of the displacement and the patient's age; therefore, these indicators have limitations for conservative treatment, and the frequency of unfavourable outcomes and complications with the conservative method increases significantly in children over 10 years old. The advantages of this method suggest the absence of surgical risk. However, the conservative method has its drawbacks: high probability of secondary displacement of bone fragments, limitations for use in open fractures, immobilization of adjacent joints leading to the development of joint contractures, inconvenience and potential destruction of the plaster cast itself, the necessity for rehabilitation after its removal. Surgical methods for treating diaphyseal fractures in children were not historically primary and, as a rule, became relevant in cases of ineffective closed manual reduction, the occurrence of secondary displacements, malunited fractures, and refractures. There is an opinion supporting primary indications for surgical treatment in cases of open injuries, unstable fractures, polytrauma, and in children older than 10 years. In our opinion, a certain group of patients faces a risk of impaired fracture consolidation during conservative treatment related to the patient's age (older age group) and fracture localization (diaphyseal).

All this leads to the need for prolonged immobilization, the risk of developing contractures in adjacent joints, or the development of severe complications such as non-union. Due to the above-mentioned factors, the article justifies the use functionally stable osteosynthesis in such patients, which ensures early mobilization of the injured segment and avoids the formation of

contractures. The use of TEN osteosynthesis allows for the avoidance of long-term external immobilization while simultaneously ensuring segment stability throughout the entire consolidation period, regardless of its duration. This type of osteosynthesis was used in patients with diaphyseal forearm fractures with complete displacement of fragments by length and width, pronounced angular displacement, complete rupture of the periosteum, residual unacceptable displacements after closed manual reduction, and secondary displacement of fragments. The minimally invasive TEN technique was used in 82 cases of fractures of both forearm bones; nails were inserted into both the ulna and the radius. In 14 children, one nail was inserted for an isolated radial fracture; in 6 cases of ulnar fractures with associated radial head dislocation (Monteggia injury), one nail was inserted into the ulna. Naturally, there is a risk of damaging the sensory branch of the radial nerve and the tendon of the extensor pollicis longus when passing the nail into the radius. However, careful exposure of the bone without gross tissue damage allows for the avoidance of this complication. Plaster immobilization of the injured limb was performed for 10–14 days until the pain subsided; notably, immobilization was carried out without including the elbow joint. We observed no purulent-inflammatory complications, sensory radial nerve palsies, or injuries to the tendon-ligamentous apparatus. In 14 patients, phenomena of delayed consolidation were noted at 3–5 months post-surgery; however, simply extending the time before removal to 12 months allowed for complete organotypic remodelling.

This group of patients required no special treatment. The size (diameter) of the metal fixator was determined according to the width of the medullary canal, aiming for 60–70% of the diameter of the canal at its narrowest point. Nails from 2.0 to 4 mm were used. A key feature of this osteosynthesis was its relative elastic stability, achieved through three-point intramedullary fixation. For greater stability in the fracture zone, the nail was pre-bent into an arc so that when positioned in the medullary canal, its apex was located at the fracture zone, taking into account the physiological curvature of both the radius and ulna. Satisfactory positioning of the fragments and sufficient stability were confirmed using an Image Intensifier (C-arm). While proper nail sizing could allow for the omission of plaster immobilization, we still utilised a plaster splint (long-leg or short-arm equivalent) for the following reasons. TEN is a method of relative stability (elastic fixation), meaning micro-mobility of fragments remains. Consolidation occurs through callus formation. A plaster splint reduces the micromobility of fragments and prevents the formation of excessive paraosteal callus. Additionally, in the early postoperative period, the plaster splint reduces pain syndrome and decreases the use of non-narcotic analgesics.

Furthermore, stable osteosynthesis of both forearm bones with elastic titanium nails allowed for a reduction in the duration of plaster immobilisation to between 2 and 4 weeks in our patients; this enabled an earlier start to rehabilitative treatment. If closed reduction was unsuccessful, a Kirschner wire (K-wire) with a diameter of 1.5–1.8 mm was inserted percutaneously near the fracture site to reposition the bone fragments using the so-called “joystick” technique, which in most cases allowed us to avoid converting to open osteosynthesis. In instances where closed reduction was impossible due to significant soft tissue interposition, the intramedullary nail was advanced to the fracture area, after which the interposition was cleared through a 3–4 cm incision; the fracture was then synthesized by driving the nail into the proximal bone fragment. All stages of the surgery were strictly monitored using

an Image Intensifier (C-arm). During the treatment analysis, we focused on the following clinical criteria: patient's complaints, external appearance of the operated limb (with the assessment of peripheral circulation and sensitivity), presence or absence of muscle hypotrophy, range of active motion in the wrist and elbow joints, pronation and supination of the forearm, presence of complications. Radiologically, we analyzed the stages of radiopaque callus formation and the positioning of bone fragments and nails. The primary advantages of TEN osteosynthesis, compared to other methods, were earlier mobilization of the forearm and lower invasiveness compared to plate osteosynthesis. The elastically stable intramedullary nail has proven to be a modern tool for treating children with forearm fractures when surgical stabilization is indicated.

On average, sufficient bone callus formation was observed as early as 4 weeks post-intervention, confirmed both clinically and radiologically. In its characteristics, this consolidation was not inferior to the healing processes observed with conservative treatment and, in some cases, surpassed them in terms of timing and stability. The number of postoperative complications was negligible. Out of the total 102 operated patients, 12 (7.8%) experienced temporary complications that did not require significant medical intervention. Six children developed skin irritation in the ulnar region due to nail protrusion, and another six developed a superficial skin infection at the radial nail insertion site. One case required the premature removal of the ulnar nail due to migration. No serious complications leading to functional impairment (such as angular or rotational deformity, growth arrest, synostosis formation, significant restriction of elbow joint mobility, or limb shortening) were detected. All identified complications were reversible, did not affect the duration or outcome of treatment, and did not require repeat surgical interventions.

The best results were observed in children aged 6–13 years, where the ratio between the diameter of the medullary canal, the anatomical features of the growth zones, and the nature of the injury proved to be most favorable for the application of this method.

Most patients began performing active movements in the joints as early as 10–14 days post-surgery, without complaints of pain or restriction. In 90% of cases, full functional recovery was achieved within 4 to 6 weeks. A significant contribution to such results was the possibility of early limb loading and the reduction—or even total absence—of postoperative immobilization. In no case were significant deformations found that would affect the function of the forearm. All patients, including those who experienced minor complications, were discharged with full restoration of movement and symmetrical functionality of both upper limbs. Angular or rotational deformities, synostosis, significant limb length discrepancy, or axial malalignment were not detected. Furthermore, it was noted that the method was well-tolerated by patients and was not accompanied by the psychological discomfort typically associated with, for example, wearing external fixation devices. Parents highly praised the short postoperative period, the absence of noticeable scarring, and the child's rapid return to their usual lifestyle.

Discussion

The study included 365 children with diaphyseal and metadiaphyseal fractures of the forearm bones who were hospitalized over the last three years in the paediatric orthopaedic-traumatology department of the Emergency Hospital; 102 of these children underwent TEN osteosynthesis. The age of the patients ranged from 6 to 16 years, with an average age of

11,0±2,2 years old. In terms of gender distribution: 67 (65.7%) were boys and 35 (34.3%) were girls. From the moment of admission, all patients received full orthopaedic and traumatological care in accordance with the current protocols of the Ministry of Health of Ukraine. All fractures were classified as unstable with fragment displacement. In all cases, the indications for osteosynthesis were: ineffectiveness of closed reduction, secondary displacement following plaster immobilization, recurrent fractures (refractures), combined trauma (2 cases). All patients underwent osteosynthesis with Titanium Elastic Nails (TEN). The choice of this method was justified by its ability to provide stable fixation with minimal soft tissue trauma, preservation of the growth zones (physes), and the possibility of early mobilization. Closed osteosynthesis of both forearm bones was performed in 69 patients (67.65%). In 16 cases (15.69%), only the radius was synthesized, and in 2 cases (1.96%), only the ulna. A combined technique (open-closed) was used in 9 patients, 3 of whom required additional revision due to soft tissue interposition.

In most cases, nails with diameters ranging from 2.0 to 4.0 mm were used, depending on the child's age and the width of the medullary canal. Surgical access followed the standard technique: through the proximal metaphysis of the radius and the distal metaphysis of the ulna. The average duration of surgery was 45±12 minutes. In 56 cases, stable fixation was achieved without the need for additional plaster immobilization. The postoperative period proceeded without complications in the majority of cases. From the first postoperative days, all patients underwent comprehensive rehabilitation, including early mobilization, therapeutic exercise, pain management, and monitoring of the surgical wound. The early restoration of functional activity was made possible by the stability of the fixation and the minimally invasive nature of the intervention.

According to dynamic follow-up at 1-, 3-, and 6-months post-surgery, complete functional recovery of the forearm was recorded in the majority of children. This assessment accounted for the range of rotational and flexion-extension movements in the elbow and wrist joints, as well as the presence of any deformities or complaints. The overall complication rate was 13.2% (14 cases). All of these were of a mild degree and did not require repeat surgical intervention (with the exception of one case). Serious complications, such as angular or rotational deformities, limb shortening, growth impairment, contractures, or ankylosis, were not registered. This indicates the safety and reliability of the technique when the surgical protocol and postoperative care are strictly followed.

Compared to other surgical methods for treating forearm bone fractures in children (plate osteosynthesis, Kirschner wires, external fixation), elastic titanium nails demonstrated a series of indisputable advantages: minimal soft tissue trauma; preservation of growth zones; no requirement for wide surgical access; stable fixation without the need for plaster immobilization; rapid restoration of activity; satisfactory cosmetic results; technical simplicity given a sufficient level of surgical training. Plate osteosynthesis, while providing reliable fixation, is more invasive and requires subsequent hardware removal, which is a significant drawback in paediatric practice. K-wire fixation is accompanied by the need for external immobilization and a higher risk of instability, especially in diaphyseal fractures. External fixation devices are justified only in cases of open, infected, or combined injuries. The results of this study support the assertion

that the minimally invasive elastic titanium nail osteosynthesis technique is a modern and effective approach to treating forearm fractures in children.

Stable results, a low complication rate, rapid functional recovery, and minimal invasiveness attest to the feasibility of broader implementation of this method into the daily practice of paediatric orthopaedic-traumatology departments. The use of this method is particularly justified for children aged 6 to 14 years with diaphyseal and metadiaphyseal fractures of both forearm bones. Thus, the obtained clinical data confirm that intramedullary elastic stabilization of fractures allows not only for the restoration of anatomical integrity but also ensures a high quality of life for patients in both the immediate and long-term postoperative periods. The analysis of long-term treatment results for patients who underwent forearm bone osteosynthesis using elastic titanium nails is crucial for assessing the long-term effectiveness of the method. In children, given the growth and development of the musculoskeletal system, it is especially important not only to achieve union of bone fragments but also to ensure the anatomical and functional integrity of the limb in the long term. Observation of the 102 patients who underwent minimally invasive intramedullary osteosynthesis with elastic titanium nails was carried out at intervals of 3, 6, 12, and 18 months following the surgical intervention. Monitoring included clinical assessment, analysis of radiographic data, functional testing, psychological questioning of patients, and parent surveys regarding the children's quality of life.

Functional assessment was performed by measuring the range of motion in the elbow and radiocarpal (wrist) joints, as well as the rotational movements of the forearm. In 97% of patients, full or nearly full recovery of limb mobility (within a 5–10° deviation) was achieved as early as 6 months after treatment. After 12 months, full recovery was recorded in 100% of the children. Some temporary reduction in the range of motion during the early postoperative period was observed in patients with concomitant muscle contractures or minor residual deformities; however, function was subsequently fully restored. Radiological assessment demonstrated satisfactory results in most cases. A complete bone callus formed on average 3–4 weeks after surgery. All fixators were removed between 8 and 14 months without complications. No signs of pathological remodelling or growth asymmetry were detected. In several children, forearm growth was monitored 18–24 months after the intervention, and no abnormalities were registered. The removal of the metal fixators was primarily performed between 6 and 14 months in a hospital setting under general anaesthesia. The average timeframe for removal is 7.9 months (*Table 1*).

In all operated patients, the alignment of fragments post-surgery and the subsequent union of fractures was observed with a deformity of less than 10%.

Overall, 98% of all patients demonstrated full restoration of the range of flexion and extension in the elbow and wrist joints of the operated limb by the 8-week mark post-surgery. This occurred regardless of the fracture type or the nature of fragment displacement. At the same time, pronation and supination were restricted by more than 25% of the normal range of motion in 52% of patients, which corresponded to a “satisfactory” result. This deficit in movement was fully restored by the time of hardware removal, allowing these patients to transition into the group with “excellent” treatment results. Full restoration of the range of motion in adjacent joints is possible when the anatomical curvature of the ulna and radius is restored following osteosynthesis with elastic titanium nails—a result observed radiographically

in all operated patients. The complications identified in our patients were not irreversible and occurred in a small number of cases (8.8%). The removal of elastic titanium fixators is the final stage of minimally invasive osteosynthesis in children. The procedure requires a balanced approach to the choice of timing, methodology, and type of anesthesia, taking into account both the anatomical and physiological characteristics of the patient and the child's psycho-emotional state; however, it is not traumatic, is time-efficient, and minimizes cosmetic skin defects.

Conclusion

1. Osteosynthesis of unstable complex diaphyseal forearm fractures in children using elastic titanium nails demonstrates a high level of safety and reliability when performed in a specialised paediatric orthopaedic and traumatological department equipped with trained personnel, appropriate surgical instruments, necessary implants, and consumable materials. Under these conditions, Titanium Elastic Nail osteosynthesis can be considered a clinically justified method for stabilising unstable forearm fractures in children.
2. The complication rate associated with this method is low. In the majority of cases, complete restoration of the function of the injured limb can be achieved. The observed complications were generally mild, reversible, and did not lead to persistent functional impairment, angular or rotational deformity, limb shortening, growth disturbance, or the need for repeated reconstructive surgical intervention.
3. Removal of implants at 6–8 months after surgery is advisable when radiological examination confirms complete fracture union. The timing of implant removal should be determined individually, taking into account the degree of bone consolidation, the stability of remodelling, the absence of pain, the restoration of limb function, and the general clinical condition of the child.
4. The technique of osteosynthesis with elastic titanium nails for diaphyseal forearm fractures in children makes it possible to achieve satisfactory fracture stability and early restoration of limb function. This significantly shortens the period of hospitalisation, reduces the need for prolonged external immobilisation, facilitates earlier rehabilitation, and improves the child's quality of life in the postoperative period.

Thus, minimally invasive elastic titanium nail osteosynthesis may be recommended as an effective treatment option for unstable diaphyseal forearm fractures in children, provided that indications are properly determined, surgical technique is strictly followed, and postoperative clinical and radiological monitoring is ensured.

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Conflict of Interest

The author declares that there is no conflict of interest.

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Appendix

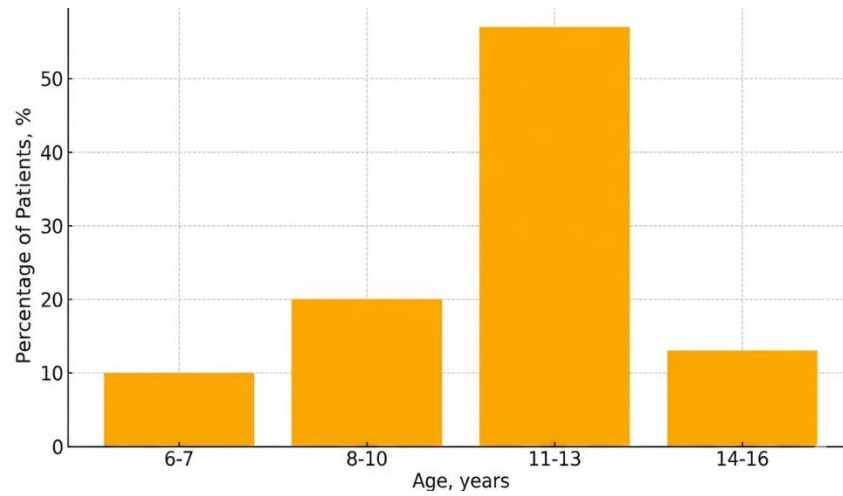


Figure 1. Disposition of operated children by Aige Group

Table 1. Timing of Metal Fixators Removal

Timing of Metal Fixators Removal (months)	Number of Patients	%
5	2	2.04
6	16	16.33
7	16	16.33
8	2	2.04
9	16	16.33
10	16	16.33
11	13	13.27
12	12	12.24
13	4	4.08
14	1	1.02
15	0	0.00

Theoretical and Methodological Aspects of Psychological and Pedagogical Mechanisms of Developing Resilience in Higher Education Students in Conditions of Armed Conflict in Ukraine ^[13]

Abstract:

The article substantiates the relevance of the study in view of the increasing impact of crisis factors on the mental state of young people and the need to ensure their psychological stability as a resource for professional development and restoration of society. The purpose of the work is a theoretical and experimental study of the level of resilience of students, as well as the definition of effective psychological and pedagogical approaches to its development. The article analyzes scientific approaches to understanding the phenomenon of resilience, defines it as a dynamic psychological resource that provides adaptation, restoration and personal growth in conditions of stress. To study the level of resilience and its relationship with psychotraumatic experience, the Connor–Davidson Resilience Scale, standardized methods for assessing the level of anxiety, depression, and symptoms of posttraumatic stress disorder, and the author's questionnaire for identifying the subjective experience of experiencing psychotraumatic events and assessing one's own resources for overcoming stress were used. The results showed an insufficient level of resilience in students, which led to the development and implementation of a psychological and pedagogical program for its development. The implementation of the program contributed to a statistically significant increase in the level of resilience, a decrease in anxiety, and an improvement in the psychological well-being of students in the experimental group. It was established that the effectiveness of organizational and methodological support for the development of resilience in students is a complex activity that should be carried out at the stages and levels of the educational process of a higher education institution. It is recommended to use the possibilities of the variable component of educational programs of the educational institution, optimize the developmental and educational opportunities of academic disciplines of the social and humanitarian cycle in terms of developing the resilience of students; form the readiness of teachers for relevant activities, create a safe environment, pedagogical monitoring of the effectiveness of the process of developing resilience and forecast its promising directions. It is emphasized that the development of resilience is an important condition for the formation of psychologically stable, adaptive and competitive specialists in modern conditions.

Keywords: traumatic events, resilience, psychotraumatic experience, post-traumatic growth.

Introduction

The problem of the psychological resilience of the individual under conditions of stressful and traumatic events is one of the central issues in the contemporary humanities and social sciences. Military conflicts, social crises, disasters and other extreme situations have a significant impact on an individual's mental well-being. Under such conditions, particular importance is attached to the need to study the conditions for maintaining the stability of mental reactions and human behaviour (*Ungar et al., 2008*), as well as the mechanisms involved in the development of personal formations that enable individuals to actively resist the effects of negative lived experience and remain psychologically stable, or resilient (*Yi et al., 2020*).

Given the high probability of traumatic impact on the individual, as well as the known toxic consequences of trauma for health and everyday functioning, the study of the theoretical and methodological foundations of the psychological mechanisms of resilience formation in people who have experienced traumatic events is a critically important area of research. Of particular significance is the need to investigate the development of resilience among students who are

currently receiving education under the conditions of the armed conflict between Russia and Ukraine. The study of this issue is a critically necessary factor in ensuring students' academic success and psychosocial well-being, especially under conditions of prolonged instability.

The relevance of the problem is determined by the fact that young people constitute the basis of society's future professional potential, on which the recovery and development of the country in the post-crisis period will depend. At the same time, a high level of resilience acts as an important resource that enables individuals not only to overcome the consequences of trauma, but also to maintain an active life position, professional motivation and readiness for responsible activity.

The object of the present study is the process of developing resilience among higher education students who have experienced psychotraumatic events under conditions of martial law and forced distance learning.

The aim of the study is to provide a theoretical analysis and experimental investigation of the level of resilience development among students who have experienced traumatic events, as well as to substantiate and identify effective approaches to developing students' resilience as a resource for their psychological stability and academic success.

To achieve this aim, the following objectives have been identified: to analyse scholarly approaches to understanding the phenomenon of resilience; to outline the specific features of students' psychotraumatic experience in the context of military action; to determine the factors influencing the formation of resilience under conditions of distance learning; to investigate the level of resilience formation among students in experimental and control groups; and to substantiate effective ways of developing resilience.

The theoretical framework of the study is based on the works of researchers devoted to the problems of resilience, psychotrauma, stress resistance, post-traumatic growth, personality adaptation under crisis conditions and related issues.

The results of the study are addressed to scholars, lecturers at higher education institutions, practising psychologists, and all specialists working with young people under conditions of increased psycho-emotional stress and wartime challenges.

Methods

The methodological basis of the study is a comprehensive approach that combines theoretical, empirical and statistical methods aimed at exploring the psychological and pedagogical mechanisms of resilience development among students.

At the theoretical level, analysis, synthesis, comparison and generalisation of scholarly sources on the issues of resilience, psychotrauma and post-traumatic growth were applied. This made it possible to define the essence of the concept of "resilience" as an individual's capacity for adaptation, recovery and development after stressful events, as well as to conceptualise it as a dynamic process and psychological resource (*Potapov, 2023; Muzychko, 2024*).

A theoretical and methodological analysis of the psychological and pedagogical mechanisms of resilience development was also conducted, with particular attention to cognitive-behavioural, emotional-regulatory and social-support factors (*Rozova & Khanetska, 2025*).

To assess the level of resilience and its relationship with psychotraumatic experience, the Connor–Davidson Resilience Scale was used (*Connor & Davidson, 2003*). This instrument makes it possible to evaluate an individual's capacity for adaptation under conditions of stress and recovery after traumatic events (*Kolishchak & Filchuk, 2025*). In addition, standardised methods were applied to assess levels of anxiety, depression and symptoms of post-traumatic stress disorder, including the LEC-5, IES-R, PHQ-9 and GAD-7. These instruments enabled a comprehensive investigation of the consequences of psychotraumatic events (*Sodolevska, 2025*).

An author-designed questionnaire was also developed to identify students' subjective experience of psychotraumatic events and to assess their perceived resources for coping with stress. The questionnaire was used to clarify individual features of students' responses to stressful situations and to analyse behavioural strategies for overcoming difficulties. Its development was informed by theoretical and empirical approaches to resilience, coping, adaptation and the consequences of traumatic experience (*Bonanno, 2004; Connor & Davidson, 2003; Folkman & Lazarus, 1980; Luthar et al., 2000; Ungar, 2011*).

The analysis of the obtained results was performed using descriptive statistics, including mean values and standard deviations; correlation analysis, including Pearson's and Spearman's correlation coefficients; Student's t-test for comparing samples; and regression analysis to determine the influence of resilience on psychological state (*Petiak & Melnychuk, 2025*).

These methods made it possible to identify statistically significant relationships between the level of resilience and indicators of the psycho-emotional state of students (*Sodolevska, 2025*).

Literature Review

Contemporary studies on the impact of traumatic events on individuals show that, worldwide, more than 70% of respondents have experienced at least one traumatic event during their lifetime, while almost one-third of survey participants reported exposure to four or more traumatic events (*Benjet et al., 2016*).

An analysis of the scholarly literature indicates that the neurotoxic effects of such experiences have far-reaching consequences. These effects range from impaired neurocompetence (*Teicher et al., 2016*) and psychopathology, including post-traumatic stress disorder (PTSD) and depression (*McLaughlin et al., 2013*), to adverse physical outcomes operating at both molecular (*Esteves et al., 2020*) and systemic levels (*Southwick et al., 2014*).

In contemporary research, there has been a marked increase in scholarly interest in the resilience of students, particularly in the context of experiencing psychotraumatic events and functioning under conditions of martial law. This is determined by the need to identify effective mechanisms for supporting the psychological stability and adaptive potential of student youth.

At the same time, despite the considerable number of studies devoted to this issue, a number of aspects remain insufficiently explored. These include, in particular, the specific features of resilience formation under conditions of prolonged distance learning, the influence of a constant threat to safety on educational motivation, and the effectiveness of psychological and pedagogical interventions in crisis situations.

The psychological mechanisms of resilience formation in individuals who have experienced trauma possess specific features, without the identification and consideration of which it is impossible to determine the effectiveness of particular psychological and pedagogical influences,

to plan effective strategies, or to evaluate their outcomes. One of the key concepts in this regard is “traumatic experience”, which in psychological science and clinical practice is understood as the experience of exposure to events or circumstances perceived by an individual as extremely threatening to their physical safety, life or psychological integrity, and as exceeding their current adaptive and regulatory resources. As a result of such experience, persistent changes may occur in emotional functioning, cognitive processes, behaviour and interpersonal interaction (*Shapar, 2007*).

At the same time, the contemporary scholarly approach emphasises the dual nature of this phenomenon. On the one hand, it includes an objective dimension, namely the characteristics of the event as potentially dangerous, such as actual or threatened death, serious injury or violence. On the other hand, it includes a subjective dimension, namely the individual’s specific appraisal of the event and their capacity to adapt to it (*Esteves et al., 2020*).

With regard to the review of contemporary scholarly literature on the development of resilience among students who have experienced psychotraumatic events, it is appropriate to structure the analysis according to several interrelated areas: theoretical approaches to understanding resilience, the impact of war-related psychotrauma on personality, and psychological and pedagogical mechanisms of resilience development within the educational environment.

The first area is represented by studies that reveal the essence of resilience as a multidimensional and dynamic characteristic of the individual. In contemporary scholarship, resilience is viewed as the capacity for adaptation under conditions of stress and crisis, formed through the interaction of individual, social and environmental factors (*Masten, 2014; Ungar, 2012*). These studies emphasise the multilevel nature of resilience, which encompasses personal, interpersonal and institutional levels (*Windle, 2011*). Particular attention is paid to the phenomenon of educational resilience, understood as the ability of students to achieve academic outcomes despite adverse circumstances (*Martin & Marsh, 2006*).

The second area covers studies of the impact of psychotraumatic events, in particular war, on the mental state and development of the individual. Researchers have shown that prolonged exposure to military conflict increases the risk of developing post-traumatic stress disorder, anxiety and depressive states, and also has a negative effect on cognitive processes and learning capacity (*Betancourt et al., 2013; Charlson et al., 2019*). At the same time, scholars emphasise that social support, access to psychological assistance and a stable educational environment contribute to overcoming the consequences of trauma and to the formation of resilience (*Tol et al., 2013*).

The third area of research is connected with the study of psychological and pedagogical mechanisms for developing resilience within the educational process. Contemporary studies stress the role of educational institutions as environments that can function as resources for support, stabilisation and personal development under crisis conditions (*Theron et al., 2015*). Important mechanisms include the development of self-regulation skills, the formation of adaptive coping strategies, the creation of a safe psychological climate and the implementation of specialised psychosocial support programmes (*Joyce et al., 2018*). In the context of distance learning, the problem of combining academic requirements with psycho-emotional challenges

becomes particularly relevant, requiring the adaptation of pedagogical approaches to conditions of uncertainty.

A separate group of studies is devoted to the factors of resilience among young people who have experienced traumatic events. Key factors include the development of hardiness, the presence of supportive social relationships, involvement in the educational process and the formation of meaning-in-life orientations (*Gilligan, 2000; Luthar et al., 2000*). In this context, the need for a comprehensive approach to supporting students is emphasised.

Thus, the analysis of contemporary sources indicates growing scholarly interest in the problem of resilience under conditions of psychotraumatic events. At the same time, it reveals the insufficient development of issues related to holistic psychological and pedagogical mechanisms for fostering resilience among higher education students under conditions of distance learning and wartime challenges.

Results

For students enrolled at universities located in eastern Ukraine, particularly in Kharkiv, resilience functions not only as an individual psychological characteristic, but also as a complex capacity for adaptation, self-regulation and the maintenance of motivation to learn despite extreme circumstances.

In this context, the study of psychological and pedagogical mechanisms for developing resilience among students who have experienced psychotraumatic events, as well as the development and implementation of effective psychological and pedagogical technologies for fostering resilience in the educational process of higher education institutions through educational practices, psychological and pedagogical support, and the creation of a safe digital educational environment, becomes a necessary condition not only for preserving the student body, but also for restoring students' personal potential and capacity for professional development.

Psychotraumatic experience, particularly under conditions of military action, may significantly affect an individual's capacity for learning, professional formation and social integration. It has been established that psychological trauma is an individual's response to events perceived as threatening to a person's physical or psychological integrity. Such events may lead to the development of mental disorders, including post-traumatic stress disorder, anxiety disorders and depressive states (*American Psychiatric Association, 2013*). However, responses to trauma are not identical for all individuals. Some people demonstrate the capacity to preserve stability and gradually restore psychological equilibrium. This capacity forms the basis of the phenomenon of resilience.

Further theoretical and methodological inquiry made it possible to analyse and substantiate the need for the formation and development of the phenomenon of post-traumatic growth.

In contemporary psychological science, the concept of post-traumatic growth is understood as positive qualitative changes in personality that arise as a result of experiencing severe life crises and psychotraumatic events. Unlike resilience, which implies the preservation of relative functional stability, post-traumatic growth reflects transformational processes that lead to the rethinking of life values, the strengthening of internal resources and the formation of new meanings (*Tedeschi & Calhoun, 2004*).

According to the classical definition, post-traumatic growth is manifested in an increased appreciation of life, improved interpersonal relationships, awareness of one's own strength, the discovery of new possibilities and spiritual development (*Tedeschi & Calhoun, 1996*). Researchers emphasise that this phenomenon is not an automatic consequence of trauma, but is formed through active cognitive processing of the lived experience, in particular through reflection, the search for meaning and the integration of traumatic events into the individual's life narrative (*Calhoun & Tedeschi, 2006*).

Contemporary studies also emphasise the role of the social context in the formation of post-traumatic growth. Support from significant others, a safe environment and access to psychological assistance contribute to a deeper understanding of traumatic experience and to its transformation into a developmental resource (*Zoellner & Maercker, 2006*).

In the educational environment, this is particularly important for students who have experienced wartime events, since the creation of conditions for reflection, support and self-expression may contribute not only to overcoming the negative consequences of trauma, but also to personal growth.

Thus, post-traumatic growth is an important theoretical and practical construct that makes it possible to consider the consequences of psychotraumatic events not only in terms of loss and maladaptation, but also as a potential for personal development, which is of particular significance under contemporary social challenges.

In addition, research demonstrates that the social environment plays a key role in the formation of resilience. The presence of supportive social relationships contributes to reducing stress levels and increasing an individual's psychological safety. Stable interpersonal relationships also enhance the individual's capacity to recover after traumatic events.

The educational environment plays a particularly important role as a space of safety, support and development, in which the lecturer acts as a facilitator of the process of resilience development.

Thus, the theoretical and methodological analysis of the concept of "resilience" has demonstrated the importance of this personal formation as a complex multicomponent system in which cognitive, emotional, meaning-related and social processes mutually complement one another and ensure an individual's capacity not only to adapt to the consequences of crisis, but also to use crisis experience for personal development. Therefore, there is a need to develop and implement effective psychological and pedagogical mechanisms for fostering resilience among students who have experienced psychotraumatic events within the educational process of higher education institutions.

At the initial stage, within the activities of the psychological service of the State Biotechnological University, 50 students aged between 18 and 23 took part in a study of the level of resilience development.

The participants were divided into two groups: an experimental group (EG), consisting of 25 participants, and a control group (CG), also consisting of 25 participants. The groups were equivalent in terms of age, gender and initial indicators.

A number of assessments were conducted in each group, namely:

- determining the level of resilience using a resilience scale, which made it possible to assess the individual's capacity for adaptation under conditions of stress and recovery after traumatic events (*Kolishchak & Filchuk, 2025*);
- assessing levels of anxiety, depression and symptoms of post-traumatic stress disorder using the LEC-5, IES-R, PHQ-9 and GAD-7 instruments, which enabled a comprehensive investigation of the consequences of psychotraumatic events (*Sodolerska, 2026*);
- identifying, through an author-designed questionnaire, the level of subjective experience of psychotraumatic events and assessing students' own resources for coping with stress. The questionnaire was used to clarify individual features of students' responses to stressful situations and to analyse behavioural strategies for overcoming difficulties (*Bonanno, 2004; Connor & Davidson, 2003; Folkman & Lazarus, 1980; Luthar et al., 2000; Ungar, 2011*).

The obtained results confirmed that the level of resilience development in both the control and experimental groups was insufficient, indicating the need to develop a programme for fostering resilience among students who had experienced traumatic events. Therefore, as a pilot project, a Programme for the Development of Students' Resilience was designed and implemented within the activities of a permanent psychological and pedagogical seminar organised by the university's psychological service. The programme consisted of two blocks: a theoretical block and a practical block, which included sessions with elements of training. Meetings were held once a week in a distance format. The control group did not participate in the programme. After completion of the programme, repeated diagnostics were conducted and the results were compared.

As a result of the conducted experiment, statistically significant changes were identified in the level of resilience among students in the experimental group.

The comparative analysis showed that, after the implementation of the psychological and pedagogical programme, the mean resilience score in the experimental group increased from $M = 52.3$ to $M = 68.3$ ($p < .01$).

No significant changes were found in the control group ($M = 53.0 \rightarrow 54.2$; $p > .05$).

A decrease in the level of anxiety was also recorded among students in the experimental group ($\Delta = -5.4$), whereas changes in the control group were minimal ($\Delta = -0.9$). Indicators of psychological well-being in the experimental group increased by 21.6 points, indicating positive dynamics in adaptive processes. Correlation analysis revealed an inverse relationship between resilience and anxiety ($r < 0$), as well as a direct relationship between resilience and psychological well-being ($r > 0$).

The obtained data indicated an increase in the level of resilience in the experimental group, a decrease in anxiety and an improvement in psychological well-being. In the control group, the changes were not statistically significant. This confirmed the need for activities aimed at developing and implementing psychological and pedagogical technology for fostering resilience among higher education students within the educational process, as well as for providing organisational and methodological support for this process.

The development of resilience is an important task of contemporary education not only in the context of overcoming the consequences of psychotraumatic events, but also as a universal condition for the harmonious personal and professional formation of students.

Under conditions of rapid social change, growing uncertainty and increased requirements for the adaptability of specialists, resilience functions as a key competence that ensures the capacity for self-regulation, effective stress management, the preservation of learning motivation and the achievement of long-term goals. Its development contributes to the formation of flexible thinking, responsibility, the capacity for lifelong learning and constructive interaction with others.

Thus, the integration of psychological and pedagogical mechanisms for developing resilience into the educational process is strategically important not only for supporting vulnerable categories of students, but also for training competitive, psychologically stable and socially active specialists capable of acting effectively under the constant challenges of the modern world.

In the course of the study, it was established that the effectiveness of organisational and methodological support for the development of students' resilience depends on comprehensive activity carried out at different stages and levels of the educational process of a higher education institution. This includes the use of the opportunities provided by the variable component of educational programmes; the optimisation of the developmental and educational potential of disciplines within the social and humanitarian cycle for fostering students' resilience; the formation of lecturers' readiness and preparedness for such activity; the creation of a safe environment; pedagogical monitoring of the effectiveness of the resilience development process; and forecasting its prospective directions.

Thus, investing in the development of the psychological stability of student youth is a strategically important task, since it is directly related to the training of competitive, adaptive and socially responsible specialists.

Discussion

The obtained data are consistent with contemporary theoretical approaches that consider resilience as a dynamic system of an individual's adaptive resources.

The increase in the level of resilience in the experimental group indicates the effectiveness and necessity of the relevant psychological and pedagogical activity. The identified patterns demonstrate that psychotraumatic experience not only reduces adaptability, but may also activate processes of post-traumatic growth, provided that appropriate psychological support is available.

The main research problem remains the insufficient development of long-term psychological and pedagogical technologies for fostering resilience within the educational environment of higher education institutions.

A limitation of the present study is also the relatively small sample size and the short duration of the intervention, which do not allow the stability of the observed effects to be fully assessed in the long term.

Further research on this problem may focus on studying the mechanisms of resilience development in different social and cultural contexts, as well as on a more in-depth examination of individual differences in the manifestation of these phenomena, the mechanisms of their formation, and the factors that facilitate or hinder personal adaptation.

It is also relevant to investigate the role of cognitive strategies, emotional regulation, social and spiritual resources in different age and professional groups, as well as to study the long-term effects of post-traumatic growth on quality of life and psychological health.

In addition, the development of psychological support programmes aimed at strengthening personal resilience and stimulating positive changes after crisis events is of considerable interest.

Particular importance should be attached to the integration of resilience development programmes into the higher education system as a component of psychological and pedagogical support for students within the activities of psychological services at educational institutions, as well as within the variable component of educational and professional programmes in different specialities.

A promising direction is also the study of digital interventions, including online training courses, mobile applications and related tools, aimed at increasing students' psychological resilience. Further research should also test the effectiveness of psychological and pedagogical mechanisms for developing resilience, including the implementation of psychological interventions such as cognitive-behavioural techniques, mindfulness practices, elements of positive psychotherapy, and group psychological support training.

Conclusion

Thus, the conducted study confirmed the relevance of the problem of developing resilience among students who have experienced psychotraumatic events under the conditions of contemporary social and wartime challenges. Resilience is considered as a dynamic multidimensional construct that includes the capacity for adaptation, recovery after stress, emotional self-regulation, cognitive reappraisal of experience, and the use of personal and social resources.

It was established that the initial level of resilience among students was insufficient, which substantiates the need to introduce targeted psychological and pedagogical programmes. The implemented resilience development programme under conditions of distance learning demonstrated its effectiveness and ensured positive dynamics in the indicators of the experimental group.

After the implementation of the programme, a statistically significant increase in the level of resilience was recorded ($p < .01$), along with a decrease in anxiety levels and an increase in indicators of psychological well-being. No significant changes were identified in the control group. An inverse relationship was established between resilience and anxiety, as well as a direct relationship between resilience and psychological well-being.

The obtained results indicate the effectiveness of a comprehensive psychological and pedagogical approach that combines educational, training-based and supportive components, and also provides for the creation of a safe educational environment and the preparation of academic staff to work with students who have experienced psychotrauma.

The prospects for further research are associated with improving the organisational and methodological support for resilience development and expanding psychological and pedagogical support programmes in higher education institutions.

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Conflict of Interest

The author declares that there is no conflict of interest.

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Professional Training of Future Ecologists: The Experience of Ukraine and the Czech Republic ^[14]

Abstract:

The article focuses on the problem of ecological education and, in particular, on the professional training of future ecologists in the Czech Republic and Ukraine. The relevance of the study is determined by the growing urgency of environmental issues in the twenty-first century, including climate change, biodiversity loss, pollution, ecosystem degradation, and the need for sustainable development. In this context, ecologists are essential professionals for the modern world, as they study the interaction between living organisms and their physical environments and contribute to the protection of natural systems that support human life, public health, and the economy. The object of the study is the process of professional training of future ecologists in higher education institutions in Ukraine and the Czech Republic. The aim of the article is to analyse the conceptual foundations of the environmental sphere, clarify the role of ecologists in contemporary society, and compare the specific features of professional training in ecology in the two countries. The scientific novelty of the study lies in the comparative analysis of Ukrainian and Czech approaches to ecological education, with particular attention to curriculum structure, fieldwork, laboratory and data-based training, internationalisation, EU policy alignment, and the response of educational programmes to national environmental challenges. Training environmental professionals typically includes degrees in environmental science, ecology, or sustainability, complemented by international certifications and specialised professional courses. These qualifications allow graduates to engage in academic research, fieldwork, environmental management, conservation, or corporate sustainability in global and local contexts. The article shows that the professional training of ecologists in the Czech Republic is thorough and combines intensive fieldwork, data analysis, laboratory research, applied landscape ecology, conservation biology, and ecological monitoring. In Ukraine, the training of ecologists focuses on green recovery, European integration, sustainable development, environmental protection, and the restoration of territories affected by contemporary socio-ecological challenges. The article compares and summarises the common and distinctive features of professional training of ecologists in the Czech Republic and Ukraine, emphasising the specific needs, priorities, and educational strategies of each country.

Keywords: ecological education, environment, environmental professionals, ecologists, international certification, international certification, professional training.

Introduction

The 21st century is characterised by the rapid development of information and communication technologies, which are widely used in various areas of modern society. At the same time, the twenty-first century is also marked by a number of global problems and challenges. One of the most widely discussed problems of contemporary global society is the environment and the growing complexity of ecological issues. Human activities have significantly transformed natural landscapes, climate systems and the balance of ecosystems. These disturbances threaten not only wildlife, but also human health, food security and economic stability throughout the world. Understanding the causes and consequences of environmental problems is therefore the first step towards finding effective and sustainable solutions (*Academia Brasileira do Sono, 2026*).

If ecology is considered as a concept or term, it refers to the scientific study of the relationships between living organisms and their environment, as well as to broader applied

concepts related to environmental protection and human interaction with nature (*Encyclopaedia Britannica, n.d.*). Ecology is also regarded as a scientific discipline, namely as a branch of biology that studies how living organisms, or biotic factors, interact with one another and with their physical environment, or abiotic factors. These interactions are examined at different levels and scales, from individual organisms and populations to communities, ecosystems and the biosphere (Maurya, 2024). Ecology may also be considered in its applied dimension, where scientific principles are used to solve real-world environmental problems and to support the sustainable management of natural resources. In public discourse, the concepts of human ecology and environmental ecology are often closely connected with environmental protection and the environmental movement (*Michigan Technological University, n.d.*).

Thus, at the present stage of social development, ecology is understood as a complex interdisciplinary science concerned with the relationships between organisms, society and the environment. It studies the laws governing the life of organisms in their natural habitat and analyses the changes occurring in this environment as a result of human activity. In recent years, ecology and environmental problems caused by anthropogenic activity have become constant subjects of academic, public and media discussion (*Vasileva-Tcankova, 2022*). This has strengthened the social demand for specialists capable of analysing environmental risks, interpreting ecological data, participating in conservation activities, and designing strategies for sustainable development.

Accordingly, professionals engaged in this field, namely ecologists, study the relationships between living organisms and their environment. They investigate ecosystems, biodiversity and environmental change in order to understand how plants, animals and natural systems interact. Ecologists collect and analyse data, conduct field and laboratory research, and contribute to studies that support conservation, land management and environmental policy. A career as an ecologist may involve work in natural environments, as well as in offices, laboratories, research institutions, universities, government agencies, environmental consulting firms and conservation organisations (*University of Southern Queensland, 2026*).

Considering the challenges of the twenty-first century, ecologists are essential professionals for the modern world because they protect the natural systems that support human life and the economy. They act as important specialists in addressing urgent environmental crises such as climate change, pollution, deforestation and biodiversity loss. Their professional activity is closely connected with shaping public policy, promoting sustainable development, supporting corporate responsibility and informing society about the consequences of environmental degradation (*Foley, 2026*).

The training of environmental professionals and ecologists typically includes degrees in environmental science, ecology or sustainable development, complemented by international certifications and specialised professional courses. These qualifications allow specialists to engage in academic research, fieldwork, environmental monitoring, conservation, ecological consulting, public administration or corporate sustainability in both global and local contexts (*Bouchrika, 2026*). Environmental scientists apply scientific principles to protect the environment and human health. They investigate environmental problems by collecting and analysing data from various sources, including soil, water and air. Their work includes assessing pollution levels, studying ecosystems and developing strategies for sustainable development. They also

disseminate their findings to inform policy decisions, guide business practices and educate the public. By specialising in areas such as climate change, waste management or ecosystem restoration, they contribute to building a healthier and more sustainable future (*Bouchrika, 2026*).

The training of ecologists differs across countries and is shaped by regional environmental challenges, cultural values, educational traditions and economic priorities. Some countries place greater emphasis on fundamental scientific research, ecological modelling and environmental policy, whereas others focus on community-based conservation, environmental education, applied fieldwork or grassroots environmental activism. These differences demonstrate that professional training in ecology cannot be considered as a universal and identical process in all national contexts; rather, it reflects the interaction between global environmental priorities and the specific needs of each country (*Springer Nature Link, 2023*).

The relevance of the present study is determined by the growing importance of environmental problems for contemporary society, the need to train highly qualified specialists in ecology, and the necessity of comparing environmental education programmes and their specific features in higher education. This issue is especially important in the context of European integration, sustainable development, climate policy, biodiversity protection, green recovery and the increasing demand for specialists who are able to combine theoretical knowledge with field practice, laboratory research, data analysis and environmental management.

The research problem lies in the fact that, despite the global relevance of ecological education, the professional training of future ecologists remains strongly dependent on national educational systems, institutional traditions and regional environmental priorities. In this regard, the experience of Ukraine and the Czech Republic is particularly significant. The Czech Republic has developed a structured and internationally oriented system of ecological education, closely connected with European environmental policy, field research, ecological monitoring and specialised academic institutions. Ukraine, in turn, is modernising its ecological education in the context of European integration, sustainable development, environmental protection, green recovery and the need to restore ecosystems affected by contemporary socio-ecological challenges. Therefore, a comparative analysis of these two systems makes it possible to identify both common tendencies and nationally specific features of professional training in ecology.

The scientific novelty of the study lies in the comparative analysis of the professional training of future ecologists in Ukraine and the Czech Republic, with attention to curriculum structure, educational levels, practical training, fieldwork methodologies, internationalisation, EU policy integration, institutional experience and the adaptability of educational programmes to contemporary environmental challenges. The study also clarifies how national priorities influence the content and organisation of ecological education and how higher education institutions prepare future specialists for work in research, environmental management, conservation, public administration and sustainable development.

The object of the study is the process of professional training of future ecologists in higher education institutions in Ukraine and the Czech Republic.

The subject of the study is the common and distinctive features of educational programmes, curricula, practical training and institutional approaches to the professional preparation of ecologists in the two countries.

The study aims to analyse the conceptual foundations of the environmental sphere, clarify the role of ecology and ecologists in the modern world, examine the peculiarities of professional training in ecology, and compare the features of educational programmes in ecology in Ukraine and the Czech Republic.

To achieve this aim, the following objectives have been identified:

- to analyse scholarly and informational sources defining ecology as a scientific and applied field;
- to clarify the role of ecologists and environmental professionals in addressing contemporary environmental challenges;
- to characterise the main components of professional training in ecology, including theoretical, practical, field, laboratory and research-oriented elements;
- to examine the specific features of professional training of future ecologists in the Czech Republic;
- to analyse the main characteristics of ecological education and professional training of ecologists in Ukraine;
- to compare Ukrainian and Czech educational programmes in ecology according to their curriculum structure, flexibility, practical orientation, internationalisation and relation to national environmental priorities;
- to identify common and distinctive features in the training of future ecologists in the two countries;
- to determine the theoretical and practical significance of comparative analysis for improving ecological education in higher education institutions.

The theoretical significance of the study lies in expanding the understanding of ecological education as an interdisciplinary and comparative research field. The article contributes to the analysis of how professional training in ecology is shaped by environmental challenges, higher education policy, European integration, institutional traditions and labour market demands. It also provides a basis for further comparative studies of environmental education in different national contexts.

The practical significance of the study lies in the possibility of using its results to improve educational programmes in ecology, strengthen the practical component of professional training, develop flexible learning trajectories, enhance international cooperation and adapt curricula to current environmental challenges. The findings may be useful for higher education institutions, curriculum developers, lecturers, educational policymakers and specialists involved in the training of future ecologists. They may also support the modernisation of ecological education in Ukraine by taking into account relevant European experience, including the Czech model of combining fieldwork, laboratory research, data analysis, conservation biology and environmental policy training.

Thus, the professional training of future ecologists is a strategically important task for higher education in the 21st century. It determines the capacity of societies to respond to environmental crises, implement sustainable development strategies, protect ecosystems and train specialists who are able to operate effectively in scientific, applied, administrative and international contexts.

Methods

The methodological framework of this study is based on a qualitative comparative research design combined with structural-functional analysis and content analysis of higher education programmes in ecology. This approach was selected because the professional training of future ecologists cannot be adequately examined through a single institutional case or a purely descriptive overview. It requires a comparative analysis of educational aims, curriculum structure, practical training, research orientation, internationalisation, and the capacity of higher education systems to respond to contemporary environmental challenges.

The study was conducted within the framework of comparative education, with a focus on identifying common and distinctive features in the professional training of future ecologists in Ukraine and the Czech Republic. The comparison was based on the assumption that ecological education is shaped by both global environmental priorities and nationally specific factors, including environmental policy, labour market needs, institutional traditions, European integration processes, and regional socio-ecological challenges.

The primary data sources included official educational programmes, university curricula, publicly available descriptions of academic departments, state and institutional regulations, and academic profiles of leading higher education institutions that provide training in ecology, environmental science, environmental protection, and related fields. The study also used informational and analytical sources concerning ecology as a scientific discipline, the professional role of ecologists, environmental education, and sustainability-oriented training.

The Czech case was represented by leading academic centres that provide ecology-related education and research, including Charles University, the Czech University of Life Sciences in Prague, Palacký University Olomouc, Masaryk University, and other institutions involved in ecological and environmental training. Particular attention was paid to programmes associated with applied and landscape ecology, conservation biology, ecological monitoring, hydrobiology, environmental protection, and environmental education. The analysis also considered the role of international cooperation, European environmental policy, field-based learning, laboratory research, and research infrastructure in the Czech model of ecological education (*Czech Universities, 2020; Czech Society for Ecology, n.d.; Palacký University Olomouc, n.d.*).

The Ukrainian case was analysed through the professional training of ecologists in higher education institutions offering the “Ecology” speciality and related educational programmes. The study considered the general structure of ecology education in Ukraine, where training is provided at bachelor’s, master’s and doctoral levels in more than 90 higher education institutions. Particular attention was paid to universities that play an important role in environmental education, including Taras Shevchenko National University of Kyiv, the National University of Life and Environmental Sciences of Ukraine, the National University of Kyiv-Mohyla Academy, Ivan Franko National University of Lviv, the Ukrainian National Forestry University, V. N. Karazin Kharkiv National University, Odesa State Environmental University, and Bohdan Khmelnytsky National University of Cherkasy. The analysis focused on the integration of classical ecology, environmental protection, sustainable development, ecological audit, ecomanagement, green recovery, and restoration of ecosystems affected by

contemporary environmental and socio-political challenges (*Cherkasy National University, n.d.*; *National University of Kyiv-Mohyla Academy, n.d.*; *National University of Food Technologies, 2026*).

The units of analysis were educational programmes, curriculum components, forms of practical training, institutional profiles, and declared learning outcomes. At the bachelor's level, attention was paid to the formation of basic ecological, biological, environmental, and methodological competencies. At the master's level, the analysis focused on specialisation, applied research, professional orientation, field practice, and the ability to solve complex environmental problems. At the doctoral level, the study considered the development of research competence, participation in scientific projects, and integration into national and international academic networks.

The criteria for comparison included:

- the structure of educational programmes at bachelor's, master's and doctoral levels;
- the balance between theoretical, practical, field, laboratory and research components;
- the degree of curriculum flexibility and the possibility of forming individual learning trajectories;
- the presence of specialised subjects and professional modules;
- the integration of European and international environmental policy;
- the role of fieldwork, ecological monitoring and laboratory training;
- the use of data analysis, modelling and modern research methods;
- the connection between educational programmes and labour market needs;
- the adaptability of training to national environmental priorities;
- the orientation of programmes towards sustainable development, green recovery, conservation and environmental management.

The structural-functional method was used to determine how different components of professional training function within each national educational system. This method made it possible to analyse how theoretical disciplines, fieldwork, laboratory classes, internships, research projects and professional practice are connected with the declared aim of training future ecologists. It also helped identify the role of universities as institutions that combine academic education, applied ecological training, environmental research and preparation for professional activity.

Content analysis was applied to educational programme descriptions, curricula, departmental materials and institutional information. This method made it possible to identify repeated thematic components, including ecology, environmental protection, landscape ecology, conservation biology, sustainable development, environmental monitoring, ecological audit, climate policy, ecosystem restoration, and environmental education. The analysis also allowed the study to determine the extent to which these components are integrated into the training of future ecologists in both countries.

The comparative method was used to identify similarities and differences between the Ukrainian and Czech systems of ecological education. The comparison was not limited to listing educational programmes, but focused on the logic of professional training, including institutional priorities, curriculum flexibility, practical orientation, research opportunities,

international cooperation and responsiveness to environmental challenges. This made it possible to distinguish both shared European tendencies and nationally specific approaches.

The generalisation method was used to summarise the obtained results and formulate conclusions concerning the common and distinctive features of professional training of future ecologists in Ukraine and the Czech Republic. The study also used elements of interpretative analysis in order to explain why certain features of ecological education are more pronounced in one national context than in another. For example, the Czech system demonstrates stronger integration with EU environmental policy, international research cooperation and flexible specialisation, whereas the Ukrainian system places increasing emphasis on green recovery, environmental protection, ecological audit, sustainable development and the restoration of territories affected by contemporary socio-ecological challenges.

The research procedure consisted of several stages. At the first stage, scholarly and informational sources concerning ecology, ecological education, the role of ecologists, and environmental challenges were analysed. At the second stage, official and publicly available materials on ecology-related educational programmes in Ukraine and the Czech Republic were collected and systematised. At the third stage, the selected programmes and institutional profiles were examined according to the defined comparison criteria. At the fourth stage, the common and distinctive features of professional training in the two countries were identified. At the fifth stage, the results were interpreted in relation to the needs of modern environmental education, sustainable development, European integration and the professional preparation of future ecologists.

The validity of the study was supported by the use of multiple types of sources, including university programme descriptions, institutional materials, professional information resources and academic literature. Cross-comparison of several institutions in both countries made it possible to avoid reducing the analysis to a single university case. At the same time, the study is limited by its reliance on publicly available documents and programme descriptions. It does not include interviews with lecturers, students or employers, nor does it provide statistical measurement of learning outcomes. Therefore, the findings should be interpreted as a qualitative comparative analysis of educational models and institutional approaches rather than as an empirical assessment of programme effectiveness.

Despite these limitations, the selected methodology makes it possible to provide a structured and academically grounded comparison of professional training of future ecologists in Ukraine and the Czech Republic. The combination of comparative, structural-functional, content and interpretative analysis allows the study to reveal how ecological education is organised in different national contexts and how it responds to contemporary environmental, educational and socio-economic challenges.

Literature Review

Contemporary research on ecological education is developing in the context of increasing global environmental instability. Climate change, biodiversity loss, pollution, degradation of ecosystems, depletion of natural resources and the growing anthropogenic pressure on landscapes require not only technological and political responses, but also a transformation of professional training in higher education. Environmental problems in the modern world are

increasingly interpreted as complex interdisciplinary challenges that connect natural sciences, social sciences, public policy, economics, public health and sustainable development (*Academia Brasileira do Sono, 2026; Vasileva-Tcankova, 2022*). Therefore, the training of future ecologists is no longer limited to the acquisition of biological or environmental knowledge. It must also include practical research skills, fieldwork, data analysis, laboratory methods, ecological monitoring, environmental management, communication with stakeholders and the ability to operate within national and international policy frameworks.

The concept of ecology itself has undergone considerable expansion. In its classical scientific meaning, ecology is understood as the study of interactions between organisms and their environment (*Encyclopaedia Britannica, n.d.*). At the same time, contemporary ecological knowledge is increasingly applied to the solution of real-world environmental problems, including conservation, sustainable resource use, climate adaptation, pollution control and ecosystem restoration. Maurya (2024) emphasises that ecology examines the dynamics of life and the environment at different levels, from organisms and populations to ecosystems and global ecological systems. In this regard, ecological education must combine fundamental theoretical knowledge with applied competencies that allow future specialists to assess, predict and manage environmental change.

The applied dimension of ecology is particularly important for higher education because it determines the practical orientation of professional training. Educational programmes in ecology should prepare graduates not only for academic research, but also for work in environmental consulting, public administration, conservation organisations, research laboratories, national parks, industrial enterprises, environmental monitoring agencies and international projects. This corresponds to the broader understanding of ecology as a science that uses biological, geographical, chemical, technological and socio-economic knowledge to support environmental protection and sustainable development (*Michigan Technological University, n.d.; University of Southern Queensland, 2026*).

A significant part of the literature focuses on the professional role of ecologists in contemporary society. Ecologists study ecosystems, biodiversity, species interactions, environmental change and the consequences of human activity. Their work includes the collection and interpretation of field and laboratory data, ecological modelling, assessment of pollution levels, monitoring of natural systems, participation in environmental impact assessment, and development of recommendations for policy and practice. In this sense, ecologists act as specialists who connect science, public administration and practical environmental protection. Foley (2026) stresses that ecologists and environmental professionals are essential in responding to urgent environmental crises such as climate change, deforestation, pollution and biodiversity loss. Thus, the training of ecologists is directly linked to the capacity of societies to protect natural systems and maintain long-term ecological security.

Studies on professional pathways in environmental science indicate that ecological training usually includes university degrees in ecology, environmental science, sustainability or related fields, supplemented by specialised courses, certifications, field experience and professional practice. Bouchrika (2026) notes that environmental scientists apply scientific principles to protect ecosystems and human health, investigate environmental problems by analysing soil, water and air, and develop strategies for sustainable development. This implies that professional

ecological education must be interdisciplinary, practice-oriented and responsive to labour market needs. Graduates should be able to combine scientific analysis with practical decision-making in complex and uncertain environmental contexts.

The literature also demonstrates that the training of ecologists varies significantly between countries. These differences are shaped by environmental priorities, cultural values, economic conditions, educational traditions, national legislation and international commitments. Some countries place greater emphasis on fundamental research, ecological modelling and environmental policy, whereas others prioritise community-based conservation, environmental education, regional monitoring or grassroots environmental activity. Studies devoted to sustainability education also show that barriers to learning for sustainability may arise from insufficient institutional support, limited curriculum flexibility, lack of teacher preparedness, weak integration between theory and practice, or the absence of a coherent educational strategy (*Springer Nature Link, 2023*). Consequently, the comparative study of national models of ecological education is necessary for identifying effective approaches to curriculum design and professional training.

Within the field of comparative education, the analysis of ecological training programmes makes it possible to identify how higher education systems respond to shared global challenges through nationally specific educational models. Comparative research is particularly relevant when educational programmes operate under different socio-economic and environmental conditions but aim to prepare specialists for similar professional tasks. In this context, the comparison between Ukraine and the Czech Republic is methodologically justified because both countries are located within the broader European educational and environmental space, yet their ecological education systems have developed under different historical, institutional and socio-political conditions.

The Czech model of ecological education is frequently characterised by strong integration of fundamental ecological theory, applied environmental training, field practice and international cooperation. According to Czech Universities (*2020*), ecology-related programmes in the Czech Republic often combine theoretical preparation with field research, laboratory work, conservation biology, applied landscape ecology and environmental monitoring. Czech higher education institutions benefit from close links with European environmental policy, international research projects and protected natural areas, including Natura 2000 sites and biosphere reserves. This creates favourable conditions for combining academic training with real field-based ecological research.

A number of Czech institutions play a central role in the training of future ecologists. The Czech University of Life Sciences in Prague, Charles University, Masaryk University and Palacký University Olomouc provide ecology-related programmes at different levels of higher education and offer specialised courses in areas such as landscape ecology, conservation biology, hydrobiology, environmental protection, biodiversity research, ecological monitoring and environmental education. The Czech Society for Ecology (*n.d.*) also contributes to the professional and academic development of ecology as a scientific field by supporting ecological research and cooperation among specialists.

Particular attention in the Czech context is given to Palacký University Olomouc, whose Department of Ecology and Environmental Sciences is one of the oldest ecological departments

in the country. Its educational and research profile demonstrates the connection between fundamental ecology and applied environmental problem-solving. The department offers bachelor's, master's and doctoral programmes in ecology, environmental protection, landscape conservation, hydrobiology and environmental education. Its curriculum combines biological disciplines, Earth sciences, theoretical ecology, field excursions, practical training and courses related to nature and landscape conservation. Such a structure illustrates the Czech tendency to integrate research, field practice, interdisciplinary training and public engagement in ecological education (*Palacký University Olomouc, n.d.*).

The literature and institutional sources indicate that Czech ecological education is strongly aligned with European environmental policy. This alignment influences curriculum content, learning outcomes, research priorities and graduate employability. Students are prepared for participation in international research grants, cross-border conservation projects, EU-level environmental programmes and professional activity in environmental protection agencies, research institutions, state administration, non-governmental organisations and private environmental consulting. The flexibility of Czech study programmes is also important. Students may often shape individual learning trajectories by choosing specialised subjects and focusing on areas such as tropical ecology, behavioural ecology, ecogeography, microbial ecology or ecosystem services. This flexibility supports the formation of differentiated professional profiles.

The Ukrainian model of ecological education has its own specific features. Training in the speciality “Ecology” is offered by a large number of higher education institutions across the country. Ukrainian educational programmes traditionally combine classical ecology, environmental protection, nature management, ecological audit, environmental safety and sustainable development. At the same time, recent socio-political and environmental challenges have strengthened the relevance of green recovery, ecosystem restoration, military ecology, environmental consequences of war, environmental epidemiology and European integration. The National University of Kyiv-Mohyla Academy, for example, presents environmental studies as an area connected with natural sciences, environmental policy and sustainable development (*National University of Kyiv-Mohyla Academy, n.d.*).

Ukrainian ecological education is influenced by the Bologna Process and the broader movement towards integration into the European Higher Education Area. However, it also retains strong national regulatory features and a relatively standardised structure of educational programmes. Compared with the Czech model, Ukrainian programmes are often less flexible in terms of individual learning trajectories, although they provide broad interdisciplinary training in ecology and environmental protection. A typical Ukrainian programme prepares students for work in environmental departments of enterprises, state authorities, research institutions, laboratories, environmental inspections, protected areas and educational institutions. This reflects the practical orientation of Ukrainian ecological education and its connection with national environmental governance.

The experience of Bohdan Khmelnytsky National University of Cherkasy is illustrative in this regard. Its “Ecology” educational programme at bachelor's and master's levels is aimed at forming general and professional competencies for practical, scientific, innovative and educational activity in the field of ecology, environmental protection and balanced nature

management. The programme combines theoretical learning, practical training, internships and scientific project work. It is designed to prepare graduates for professional tasks in institutions, organisations, higher education establishments, public authorities and civil associations. According to institutional materials, the programme emphasises the ability to assess the state of natural systems, apply scientific methods to solve complex environmental problems and operate under conditions of uncertainty (*Cherkasy National University, n.d.*).

Another important direction in Ukrainian ecological education is the orientation towards sustainable development and green recovery. The National University of Food Technologies (2026), for instance, represents environmental safety and health as areas connected with sustainable development, environmental protection and applied ecological competencies. In the current Ukrainian context, such an orientation has particular importance because environmental training must respond not only to general global challenges, but also to the consequences of war-related damage, industrial risks, contamination, destruction of infrastructure and the need for post-war restoration of ecosystems and territories.

The review of institutional and academic sources shows that both Ukraine and the Czech Republic train ecologists at bachelor's, master's and doctoral levels and recognise ecology as an interdisciplinary field. In both countries, educational programmes include theoretical training, practical work, field studies, laboratory components and preparation for professional activity in environmental protection. Both systems also recognise the need to train specialists capable of working in public administration, research institutions, environmental organisations and private companies. These common features reflect broader European and global tendencies in ecological education.

At the same time, the comparison reveals important differences. Czech programmes are more strongly associated with flexible specialisation, internationalisation, EU environmental policy, research mobility and the integration of advanced field and laboratory infrastructure. Ukrainian programmes, while also interdisciplinary, are more closely connected with national environmental regulation, ecological audit, environmental protection, sustainable development, green recovery and restoration of territories affected by contemporary socio-ecological challenges. These differences do not indicate the superiority of one system over the other, but rather reflect different environmental priorities, institutional capacities and socio-historical conditions.

The reviewed literature also points to several unresolved issues. First, there is a need for deeper analysis of how ecological education can respond to rapidly changing environmental and geopolitical conditions. Fixed educational trajectories may be insufficient when ecological risks develop dynamically and require new competencies. Secondly, more attention should be paid to the balance between fundamental ecological theory and applied professional training. Thirdly, there is a need to strengthen individual learning pathways and modular curriculum design, especially in contexts where students must prepare for diverse professional roles. Fourthly, the integration of digital technologies, ecological data analysis, environmental modelling and interdisciplinary project-based learning remains an important direction for the development of ecological education.

Thus, the literature review confirms that the professional training of future ecologists is a complex interdisciplinary problem that requires comparative analysis. Existing studies and

institutional sources provide a basis for understanding ecological education as a field shaped by global environmental challenges and national educational priorities. However, the comparative dimension of Ukrainian and Czech experience remains insufficiently systematised. This creates a research gap that the present study addresses by analysing the common and distinctive features of professional training of ecologists in Ukraine and the Czech Republic, with particular attention to curriculum structure, practical training, fieldwork, internationalisation, European policy alignment and responsiveness to contemporary environmental challenges.

Results

The professional training of ecologists in the Czech Republic is very thorough and combines intensive fieldwork, data analysis and laboratory research. Programs often integrate applied landscape ecology, conservation biology and ecological monitoring. Key academic centers have strong international partnerships, EU policy training and unique specialized institutes (*Czech Universities, 2020*). Practical training emphasizes modern computational biology, data interpretation, and statistical modeling. Students have direct access to well-funded state and EU-backed research centers, allowing for extensive hands-on experience with advanced analytical chemistry and bioinformatics. Researchers state the Czech system offers highly modular, flexible study tracks and students can shape their learning paths, choosing specialized subjects like tropical ecology, ecogeography, or behavioral ecology starting from the master's level.

Professional training for environmentalists in Ukraine focuses on green recovery, European integration, and sustainable development. The curriculum, delivered by universities and research institutes, covers bachelor's, master's, and doctoral levels, integrating programs in ecomanagement, ecological audit, and climate decarbonization (*National University of Food Technologies, 2026*).

The training of ecologists in the Czech Republic is focused around interdisciplinary study programs (Bachelor, Master, PhD) and specialized field practice. The country is home to several world-class research and academic centers, whose programs often use European Natura 2000 protected areas and local biosphere reserves to conduct large-scale practical field research (Czech Society for Ecology). Leading institutions in this field are the Czech University of Life Sciences in Prague (CZU), which offers highly regarded programs such as the Applied and Landscape Ecology Program at Mendel University, and specialized degrees (e.g., Nature Conservation) at the CZU Faculty of Environmental Sciences; Charles University (Prague), which offers internationally recognized master's and doctoral programs in ecology, closely affiliated with the Czech Academy of Sciences; Masaryk University (Brno), known for its strong emphasis on aquatic and theoretical ecology; Palacký University in Olomouc, which has the specialized department of ecology, focusing on ecosystem services and public engagement (Palacký University Olomouc: Department of Ecology and Environmental Sciences). The researchers note that curricula at Czech universities largely focus on fundamental ecological theory, evolutionary biology, and empirical research. Universities such as Charles University and the Czech University of Life Sciences (ČZU) focus on specialized fields such as macroecology, invasion ecology, and microbial ecology. Concerning EU policy, the Czech programs are strictly aligned with EU environmental policies and the degrees naturally prepare students for

international research grants, cross-border conservation projects, and EU-level environmental law.

In Ukraine, training of specialists in the “Ecology” specialty is carried out in more than 90 higher educational institutions. Educational programs focus on both classical ecology and green restoration of territories. Leading universities involving high-quality environmental education are concentrated throughout the country. Among the leading higher education institutions are Taras Shevchenko National University of Kyiv, National University of Life Resources and Environmental Sciences of Ukraine, National University “Kyiv-Mohyla Academy”, Ivan Franko Lviv National University, National Forestry University of Ukraine, V. N. Karazin Kharkiv National University, Odesa State Ecological University and others.

The curriculum for the “Ecology” specialty in Ukraine has traditionally been interdisciplinary. Due to recent events, the curriculum now places a strong emphasis on military ecology, restoration of ecosystems damaged by war, and environmental epidemiology (National University of Kyiv Mohyla Academy: Environmental Studies). Fieldwork is foundational, but programs often rely more heavily on classical monitoring methods. The researchers state that the educational framework is adapting to comply with the European Higher Education Area (Bologna Process) but retains its own distinct national standards, placing strong emphasis on state regulations and environmental auditing. Concerning specialization and flexibility in Ukraine, students typically choose a broad, designated educational program (e.g., Ecology and Environmental Protection) with less room to customize individual course trajectories.

Discussion

It should be noted that the Department of Ecology and Environmental Sciences in the Palacký University in Olomouc is the oldest department of ecology in the Czech Republic. With over 30 years of tradition, the department provides education and conducts research in the field of ecology and environmental sciences. It is a modern and dynamically growing academic department with experts in various fields, which supports strong international cooperation. The goal of the department is to promote and disseminate fundamental discoveries in ecology and apply them to key environmental problems facing our society today. Whether scientists study the dynamics of species populations, microbial activity in water, soil quality or ecosystem services on agricultural lands, they use ecological approaches and encourage public involvement in solving local and global environmental problems. Working at the intersection of fundamental and applied science, the members of the department educate students and inspire professionals and the public to better understand the living world around them and to adopt a more sustainable approach to the environment (Palacký University Olomouc: Department of Ecology and Environmental Sciences).

The department offers the opportunity to obtain a bachelor’s degree in ecology and environmental protection, as well as a study program in biology and environmental education. As part of further study in the master’s program, the program “Ecology and Environmental Protection” is offered, as well as the program “Protection and Creation of Landscapes”, “Hydrobiology” or “Teaching Biology and Environmental Education for Secondary Schools”. The department is also the guarantor of a doctoral program (PhD) in ecology (Palacký University Olomouc: Department of Ecology and Environmental Sciences). The curriculum consists of

basic lectures focused on biology, supplemented by courses from the Earth Sciences portfolio, and also includes subjects in theoretical ecology, after which ecology is applied in the form of practical courses on nature and landscape conservation, management, etc. An integral part of the curriculum is a series of field trips and exercises that complement the topics discussed in the lectures. During their studies, students can participate in selected exchange internships abroad. In addition to the department's staff, a number of external staff from other universities, scientific institutions and practices participate in the teaching (Palacký University Olomouc: Department of Ecology and Environmental Sciences). It should be noted that graduates of the educational program find employment in various organizations, such as state administration (e.g., Department of Environmental Protection), Department of Protected Landscape Areas, Nature Conservation Agency and National Parks (NP). Some find employment in science and research (academic institutions, museums, universities), private companies working in the field of environmental protection (expert opinions, planning, consulting, revitalization, tourism), as well as in school and extracurricular pedagogy (primary, secondary, university, Centers for Environmental Education, etc.) (Palacký University Olomouc: Department of Ecology and Environmental Sciences). Therefore, the training of specialists in the field of biology has a long tradition and is based on the needs of society in these specialists.

In Ukraine, Bohdan Khmelnytsky National University of Cherkasy offers training for bachelor's and master's degrees in the "Ecology" educational program, the purpose of which is to form general and professional competencies in higher education applicants to perform professional tasks and duties of a practical, innovative, scientific and educational nature in the field of ecology, environmental protection and balanced nature management in institutions, organizations, higher education institutions, state and executive authorities, public associations (Cherkasy National University). The educational and professional program of the master's degree is both fundamental and applied in nature; the structure of the program provides for dynamic, integrative and interactive learning. The program offers a comprehensive approach to performing activities in the field of ecology and implements this through teaching and practical training. The disciplines and modules included in the program are focused on relevant areas within which the applicant's further professional career is possible (Cherkasy National University). The main focuses of the educational and professional program are: acquiring skills and knowledge in ecology and environmental protection, developing in graduates the abilities of practical research and assessment of the state of natural systems at various levels of organization, applying theories and scientific methods to solve complex tasks and address real environmental problems that are characterized by complexity and uncertainty of conditions. The program provides for mandatory internships in environmental departments of enterprises, research institutions, laboratories and state authorities, writing and defending a scientific project (Cherkasy National University).

It should be noted that graduates of the "Ecology" educational program can work in such institutions, enterprises and organizations as scientific and research institutions in technical and natural sciences; state and corporate institutions of environmental management; laboratories of industrial enterprises, sanitary and epidemiological stations; environmental and customs inspections; inspections for control over the use and protection of land, plant protection, civil

protection and technogenic safety; objects of the nature reserve fund (reserves, national natural parks, zoos, botanical gardens, etc.) (Cherkasy National University).

Conclusion

Thus, the modern world faces a number of ecological problems. The concept of ecology is considered as a complex, interdisciplinary science of the relationships between organisms, society and the environment. Considering the challenges of the 21st century, ecologists are essential professionals for the modern world. The training of ecology experts varies around the world and is shaped by a region's unique environmental challenges, cultural values, and economic priorities.

The "Ecology" educational program, which is offered by universities and research institutes in the Czech Republic and Ukraine, covers the bachelor's, master's and doctoral levels. At the same time, educational programs in the Czech Republic often integrate applied landscape ecology, conservation biology and ecological monitoring. Educational programs in Ukraine focus on both classical ecology and green restoration of territories. Professional training of ecologists in the Czech Republic combines intensive fieldwork, data analysis and laboratory research. Professional training of ecologists in Ukraine applies a comprehensive approach to carrying out activities in the field of ecology and implements this also through training and practical training. The individual path and specialization of the educational program is more flexible in Czech universities, and their programs are strictly aligned with EU environmental policies. The educational path in Ukraine is largely preset. It should be noted that graduates of the educational program in both the Czech Republic and Ukraine find work in various organizations, such as state and corporate institutions in the field of environmental protection, as well as in academic institutions, universities, other scientific and educational institutions.

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Conflict of Interest

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Ukrainian Phonetic Shibboleths: Articulatory Specificity and Linguodidactic Ways of Overcoming Interference ^[13]

Abstract:

The relevance of this study is determined by the growing importance of phonetic shibboleths in contemporary Ukrainian sociolinguistic, linguodidactic and security contexts. Under the conditions of globalisation, mass language learning and intensified bilingual communication, phonetic interference has become one of the central problems of applied phonetics. At the same time, since the full-scale Russian invasion of Ukraine, Ukrainian phonetic shibboleths have acquired not only linguistic, but also national, regional, cultural and identification significance. The research problem lies in the need for a comprehensive scientific and methodological description of Ukrainian sounds that are difficult for non-native speakers and bilinguals to reproduce because of subconscious articulatory habits and differences between phonological systems. The object of the study is Ukrainian phonetic shibboleths, namely sounds and pronunciation features that function as ethnic, national or regional indicators of a speaker. The study aims to conduct a scientific and methodological analysis of Ukrainian phonetic phenomena that create pronunciation difficulties for speakers of other languages or dialects and to identify effective linguodidactic ways of overcoming phonetic interference. The scientific novelty of the article lies in interpreting Ukrainian phonetic shibboleths not only as linguistic markers, but also as instruments of identity recognition, regional localisation and applied phonetic training. The study employs descriptive and scientific-methodological analysis. The theoretical framework is based on the works of Ukrainian phoneticians and linguists, including N. Totska, V. Brakhnov, Z. Dudnyk, O. Ishchenko, O. Bas-Kononenko, V. Bondarenko, I. Savchenko and other scholars. The article analyses vowel and consonant shibboleths of Ukrainian, including the pronunciation of [ɪ], [o], [ɘ], [r], [ɾ] and related phonetic phenomena. Particular attention is paid to the preservation of full vowel pronunciation in unstressed positions, the absence of strong vowel reduction, regional articulatory variants, the pronunciation of the Ukrainian pharyngeal fricative [ɣ], the non-syllabic [ɘ], soft affricates, and the word *paliamytsia* as a complex phonetic test. The study demonstrates that the main obstacle to accurate pronunciation is not only insufficient knowledge of orthoepic norms, but also the stability of the native articulatory base, which operates at the level of subconscious neuromotor programmes. The article concludes that effective correction of phonetic interference requires targeted linguodidactic and speech-therapy strategies, including work with quasi-homonyms, contrastive pronunciation pairs, visual control of articulation, video recording, tongue-twisters and specific mechanical exercises. Ukrainian phonetic shibboleths are therefore considered both reliable tools of linguistic identification and important objects of applied phonetic and linguodidactic research.

Keywords: shibboleth, phonetics, sound, articulation, linguistic identity, interference, linguodidactics.

Introduction

In the context of globalisation and the mass study of foreign languages, the problem of phonetic interference has become one of the central issues in contemporary applied phonetics. Interference may be understood as the transfer of pronunciation skills from the native language to another language, which results in an accent and, in some cases, distortion of meaning. Researchers identify several causes of this phenomenon. The first is subconscious resistance, namely a psychological barrier to accepting articulatory movements that are not characteristic of the speaker's native language. The second is the influence of the first language, which is manifested in the automatic use of already established articulatory patterns. For example, Ukrainian students often do not distinguish between long and short vowels in English because

this contrast is absent in Ukrainian. The third cause is the lack of language contact, that is, the absence of perceptual experience in listening to authentic speech (*Nesterenko & Lysenko, 2024*).

The relevance of the study is determined by the fact that, after Russia's full-scale invasion of Ukraine, clear transformational processes have been observed in relation to self-identification, language policy, and the language codes used in everyday communication (*Kuznietsova, 2025, p. 23*). Applied phonetics is therefore acquiring a broader social significance: it becomes not only a field of linguistic description, but also an instrument of sociolinguistic analysis that helps to understand processes of integration, differentiation or marginalisation of certain groups through language.

Although the problem of phonetic interference is one of the key issues in applied phonetics, the mechanisms for overcoming subconscious articulatory barriers and the stability of the native-language articulatory matrix in adult speakers require deeper scholarly investigation. In the context of Russia's full-scale invasion, phonetic shibboleths have acquired not only linguistic, but also security-related and identification significance. Accordingly, there is a need for a comprehensive scientific and methodological description of specific Ukrainian sounds, in particular [ɪ], [ʏ], [r], [ɪʀ] and others, as markers of national and regional identity. There is also a need to develop effective linguodidactic approaches to their acquisition by non-native speakers and bilinguals.

The research problem lies in the insufficiently developed scientific and methodological explanation of Ukrainian phonetic shibboleths as articulatory, acoustic, sociolinguistic and linguodidactic phenomena. On the one hand, such sounds function as stable identifiers of a speaker's linguistic, ethnic or regional background. On the other hand, they represent pronunciation difficulties for speakers whose native articulatory base does not contain the relevant phonological or phonetic patterns. This creates a methodological challenge: it is not enough to explain the orthoepic norm theoretically; it is necessary to determine how subconscious articulatory habits can be modified through targeted phonetic, speech-therapy and linguodidactic training.

The scientific novelty of the study lies in interpreting Ukrainian phonetic shibboleths as complex linguistic units that combine articulatory-acoustic specificity, sociolinguistic identification value and practical linguodidactic potential. The article considers shibboleths not merely as isolated pronunciation difficulties, but as markers of national and regional belonging, as indicators of phonetic interference, and as objects of applied phonetic correction. Particular attention is paid to the sounds and sound combinations that reveal the influence of another language or dialectal background and therefore require systematic methodological description.

The object of the study is phonetic shibboleths, namely the sounds of the Ukrainian language that most often function as ethnic or regional indicators of a speaker.

The subject of the analysis is the articulatory-acoustic and linguodidactic parameters of Ukrainian phonetic shibboleths.

The study aims to provide a scientific and methodological analysis of Ukrainian phonetic phenomena that constitute pronunciation difficulties for speakers of another language or dialect.

To achieve this aim, the following objectives have been set:

- to clarify the scholarly definition of the concept of “shibboleth” in linguistics and its role as an instrument of linguistic identification of the individual;

- to analyse key Ukrainian phonetic shibboleths, including the pronunciation of [u], [o], [ŷ], [r], [r'] and other sounds, and to provide their linguodidactic justification;
- to describe the articulatory-acoustic features of selected Ukrainian phonetic shibboleths;
- to identify typical deviations from the Ukrainian literary pronunciation norm caused by phonetic interference;
- to examine the role of subconscious articulatory habits in the reproduction of Ukrainian sounds by non-native speakers and bilinguals;
- to consider scientific and methodological approaches to the use of shibboleths in applied linguistics, dialectology and linguodidactics;
- to outline effective ways of overcoming phonetic interference through targeted pronunciation training, work with contrastive pairs, visual control and specific mechanical exercises.

The theoretical significance of the study lies in deepening the understanding of phonetic shibboleths as phenomena situated at the intersection of phonetics, sociolinguistics, psycholinguistics, dialectology and linguodidactics. The research contributes to the theoretical description of Ukrainian phonetics by showing that individual sounds may function not only as elements of the phonological system, but also as markers of identity, regional origin and language competence. It also clarifies the role of articulatory habits as stable cultural and ethnic identifiers of the speaker.

The practical significance of the study lies in the possibility of using its results in Ukrainian language teaching, pronunciation correction, speech training, work with bilingual speakers, and Ukrainian as a foreign or second language instruction. The proposed linguodidactic approaches may be useful for teachers, speech therapists, lecturers, language instructors, dialectologists and specialists in applied linguistics. They may also contribute to the development of methodological materials aimed at overcoming pronunciation interference and forming a stable Ukrainian articulatory base in adult learners.

Thus, the study of Ukrainian phonetic shibboleths is important not only for the description of the sound system of the Ukrainian language, but also for understanding broader processes of linguistic identity, regional differentiation, language adaptation and phonetic integration. In contemporary Ukrainian realities, phonetic shibboleths are becoming a significant object of linguistic research because they reveal how pronunciation connects language, identity, social belonging and communicative security.

Methods

The methodological framework of the study is based on a qualitative linguistic and scientific-methodological approach combining descriptive phonetic analysis, articulatory-acoustic interpretation, elements of sociolinguistic observation, and linguodidactic modelling. This methodological combination was selected because Ukrainian phonetic shibboleths are not only units of the sound system, but also markers of national, regional and sociolinguistic identification, as well as practical objects of pronunciation training for non-native speakers and bilinguals.

The study focuses on Ukrainian phonetic phenomena that create pronunciation difficulties for speakers of another language or dialect, in particular for adult bilinguals whose established articulatory base differs from that of Ukrainian literary pronunciation. The empirical material of the study includes Ukrainian vowel and consonant sounds that most frequently function as phonetic shibboleths, namely [ɪ], [o], [ʃ], [r], [ɪ'] and related pronunciation patterns. Particular attention is paid to those sounds whose incorrect reproduction reveals phonetic interference, regional origin, or the influence of another phonological system.

The descriptive method was used to record, classify and systematically explain the articulatory properties of Ukrainian phonetic shibboleths and typical deviations from the literary pronunciation norm. This method made it possible to describe the position of the speech organs, the degree of openness of the oral cavity, labialisation, tongue position, palatalisation, pharyngeal articulation, and the interaction between vowels and consonants in different phonetic contexts. It was also used to identify recurrent pronunciation substitutions, such as the replacement of Ukrainian [ɪ] by sounds closer to [i] or [ɪ], the replacement of unstressed [o] by [a], the incorrect pronunciation of non-syllabic [ʃ], the substitution of the Ukrainian pharyngeal [r] by [r] or [x]-like variants, and the insufficiently soft articulation of [ɪ'].

The scientific-methodological analysis was applied in order to examine Ukrainian phonetic phenomena that constitute pronunciation difficulties for speakers of another language or dialect. This analysis was aimed not only at describing the relevant sounds, but also at determining their linguodidactic justification. In this respect, each phonetic shibboleth was analysed according to several parameters: its place in the Ukrainian phonetic system, its articulatory and acoustic specificity, its potential role as a national or regional identifier, the most frequent types of interference, and the most effective methodological techniques for overcoming pronunciation difficulties.

The theoretical basis of the study is formed by the works of Ukrainian phoneticians and linguists, including N. Totska, V. Brakhnov, Z. Dudnyk, O. Ishchenko, O. Bas-Kononenko, V. Bondarenko, I. Savchenko and other scholars. Their studies provide the foundation for analysing Ukrainian vocalism and consonantism, orthoepic norms, articulatory habits, sound modifications in speech flow, assimilation processes, vowel quality, speech tempo, and the relationship between phonetic norm and actual pronunciation practice. The study also relies on the methodological understanding that articulatory habit is a stable cultural and ethnic identifier of a speaker and that theoretical knowledge of orthoepic rules is insufficient without systematic articulatory training.

The research procedure consisted of several stages. At the first stage, the concept of “shibboleth” was examined in its linguistic, historical and sociolinguistic dimensions. Particular attention was paid to its transformation from a historical marker of group identification into a contemporary instrument of linguistic, national, regional and security-related recognition. At the second stage, the most significant Ukrainian phonetic shibboleths were selected for analysis. The selection was based on their phonetic specificity, frequency of pronunciation errors among bilinguals and non-native speakers, and relevance for identifying national or regional pronunciation features.

At the third stage, the selected sounds were described in terms of their articulatory features and their position within the Ukrainian phonological system. Ukrainian vocalism was analysed

with attention to the preservation of full vowel pronunciation in both stressed and unstressed positions, the absence of strong vowel reduction, the quality of [ɪ] and [o], and regional deviations from the literary norm. Ukrainian consonantism was analysed with attention to the pronunciation of non-syllabic [j̥], soft affricates such as [ɲ'], the Ukrainian pharyngeal fricative [r], and the articulatory complexity of words such as *paliamytsia*, which function as complex phonetic tests.

At the fourth stage, typical cases of phonetic interference were identified and interpreted. The study considered interference as the transfer of pronunciation habits from the native or dominant language into Ukrainian. Particular attention was paid to subconscious articulatory resistance, that is, the difficulty adult speakers experience when they attempt to reproduce movements of the speech organs that are absent from their native phonetic system. This approach made it possible to explain why pronunciation errors persist even when speakers consciously know the relevant orthoepic rules.

At the fifth stage, linguodidactic strategies for overcoming pronunciation difficulties were systematised. These strategies include contrastive work with quasi-homonyms and minimal or near-minimal pairs, slow controlled reading, visual monitoring of lip and tongue position, video recording of one's own speech, gradual acceleration of pronunciation tempo, work with tongue-twisters, and specific mechanical exercises aimed at activating speech organs that are not normally involved in the speaker's native language. For example, exercises for the Ukrainian pharyngeal [r] require attention to the movement of the root of the tongue and the narrowing of the pharyngeal cavity, while the pronunciation of [ɲ'] requires the gradual development of soft affricate articulation.

The analysis of vowel shibboleths was conducted with regard to both national and regional pronunciation markers. The Ukrainian [ɪ] was examined as one of the most salient indicators of phonetic competence, especially in the speech of Ukrainian-Russian bilinguals. The sound [o] was analysed in relation to the preservation of labialisation and the avoidance of "akannia", that is, the replacement of [o] by [a] in unstressed positions. Regional variants, such as the narrowed [ô] in Transcarpathian speech or the expanded articulation of [ɪ] in the Galician-Bukovynian dialectal area, were interpreted as markers of regional phonetic identity.

The analysis of consonant shibboleths focused on sounds that are particularly difficult for bilinguals and non-native speakers. The non-syllabic [j̥] was examined as a positional allophone of /ʲ/ that is often incorrectly replaced by [ɸ] under the influence of another phonetic system. The soft affricate [ɲ'] was analysed as a complex sound requiring the coordinated articulation of a stop and a fricative component. The Ukrainian [r] was examined as a pharyngeal voiced fricative whose correct pronunciation requires specific articulatory training of the throat muscles. These sounds were treated as linguodidactic priorities because their incorrect pronunciation immediately reveals phonetic interference.

The study also used elements of comparative phonetic analysis. Ukrainian pronunciation features were considered in relation to other phonological systems, primarily Russian, but also English, Belarusian, Romanian, French and other languages where relevant. This comparison made it possible to explain why certain Ukrainian sounds are replaced by more familiar sounds from another phonetic system. It also helped to identify the articulatory basis of pronunciation

errors and to determine which correction strategies may be most effective for particular groups of learners.

The linguodidactic component of the methodology is based on the principle that pronunciation correction must combine conscious explanation with repeated articulatory practice. Therefore, the study does not limit itself to describing phonetic errors, but proposes practical ways of overcoming them. Particular emphasis is placed on exercises that transform theoretical knowledge of pronunciation into stable neuromotor skills. This is especially important for adult learners, whose native articulatory base has already been consolidated through many years of speech practice.

The validity of the analysis is supported by the integration of theoretical phonetic sources, description of actual pronunciation difficulties, comparison of literary and non-literary pronunciation patterns, and the formulation of practical methodological recommendations. The study is qualitative in nature and does not involve instrumental acoustic measurement or experimental testing of learners. Therefore, its findings should be interpreted as a scientific-methodological and linguodidactic analysis rather than as an experimental phonetic study. At the same time, the proposed approach provides a basis for further empirical research, including acoustic analysis, perception experiments, and testing the effectiveness of specific pronunciation correction techniques.

Thus, the selected methods make it possible to examine Ukrainian phonetic shibboleths as complex phenomena situated at the intersection of phonetics, sociolinguistics, psycholinguistics and linguodidactics. The combination of descriptive analysis, scientific-methodological interpretation and linguodidactic modelling allows the study to explain both the articulatory specificity of Ukrainian shibboleths and the practical ways of overcoming interference in their acquisition by bilinguals and non-native speakers.

Literature Review

The concept of a “shibboleth” — from the Hebrew words meaning “ear of grain” or “stream” — historically denotes a linguistic feature by which the ethnic or regional origin of a speaker can be recognised. The term originates from the biblical story of the conflict between the Gileadites and the Ephraimites: the Gileadites blocked the crossing over the River Jordan and forced everyone who attempted to pass to pronounce the word *shibboleth*. If a person pronounced it as *sibboleth*, they were killed, since this confirmed that they belonged to the hostile Ephraimite tribe (*Judges 12:5–6*).

In the twenty-first century, the shibboleth has acquired new significance in the Ukrainian context. Since the beginning of Russia’s full-scale invasion in 2022, Ukrainian shibboleths, such as *palianytsia*, *polunytsia* and *Ukrzaliznytsia*, have been transformed from linguistic curiosities into real security instruments and markers of national identity. In the contemporary context, shibboleths perform several main functions: first, a recognitional function, namely the rapid verification of belonging to the “us–them” group, which is relevant for identifying spies and Russian-speaking Ukrainians, including internally displaced persons; secondly, a protective function, namely the detection of saboteurs, since the articulatory habits of an adult are difficult to change instantly even with excellent knowledge of another language; and thirdly, a unifying function, since the memefication of the word *palianytsia* has created a powerful cultural code

that consolidates Ukrainians through humour and awareness of the uniqueness of their own language.

The ethnic self-awareness of any person is based primarily on their native language. The production of sounds is the result of the coordinated work of the respiratory, nervous and muscular systems. In the process of communication, the speaker does not think each time about how to adapt one sound to another, since human consciousness immediately sets the pronunciation of the whole word in accordance with the laws of the articulatory base of the native language, which has been formed through regular training over many years. This property of linguistic consciousness is nothing other than an articulatory habit, which, according to Z. Dudnyk, acts as a specific cultural and ethnic identifier of the individual. Therefore, “the speaker who masters the articulatory base of another type of speech, even knowing the orthoepic rules, may incorrectly apply the acquired knowledge of pronunciation both because another system of skills predominates in their experience and because they do not understand the action of subtle but regular factors for a given speech community that have not entered the field of systematic scholarly consideration” (*Dudnyk, 2010, p. 4*).

From the methodological experience of developing perfect Ukrainian pronunciation, it is known that what hinders it is not so much the learner’s or student’s inability to pronounce correctly, but rather the “nets” of established intentions transferred from native speech to another language (*Dudnyk, 2010, p. 5*). Understanding and eliminating phonetic obstacles become key elements in the pedagogical landscape, since they form the basis of successful attempts at language learning (*Nesterenko & Lysenko, 2024, p. 187*).

In the modern Ukrainian literary language, the vowel system consists of six vowel phonemes: /a/, /o/, /y/, /e/, /u/, /i/. The main feature of Ukrainian vocalism is that unstressed vowels do not differ significantly in their pronunciation from stressed ones, and all syllabic vowels of the Ukrainian language retain full pronunciation in all positions, as well as, with relatively few exceptions, their quality in unstressed syllables. Sharp reduction, weakening or indistinct pronunciation of a vowel is a rare and atypical phenomenon for the Ukrainian language, which in this respect brings it closer to Italian or Spanish. By contrast, English and Russian, for example, are characterised by strong reduction. The absence of full vowel reduction is caused by the nature of Ukrainian word stress, the strength of which in Ukrainian is greater than in Polish and Czech, but significantly weaker than in Russian or English. For this reason, the stressed syllable in Ukrainian is not as sharply distinguished from unstressed syllables (*Kiuntzli & Pyskach, 2010, p. 161*). L. Skalozub also noted that synthetic factors of the segmental and suprasegmental levels of the phonetic system are always manifested in a sentence (*Skalozub, 2001, pp. 51–52*).

In the monograph *Vowel Sounds of the Ukrainian Language Depending on Speech Tempo*, O. Ishchenko experimentally traced the specific characteristics—duration, spectrum and intensity—of vowel sounds in different word positions against the background of speech tempo variation. According to the researcher, as tempo increases, the duration of the vowel sound decreases. Tempo changes the sounding time of a sound in all positions of the word—initial, medial and final—and in all syllables regardless of their consonantal composition. Thus, tempo change is observed through the shortening or lengthening of vowel sounds (*Ishchenko, 2012, p. 185*).

O. Bas-Kononenko noted that “the quality of a vowel is influenced by its position in the word, its consonantal-vocalic environment, and the rhythm of the word” (*Bas-Kononenko, 2019*). Having analysed three major orthoepic dictionaries of the Ukrainian language—*Ukrainian Literary Pronunciation and Stress. Dictionary-Reference Book* (1973), M. I. Pohribnyi’s *Orthoepic Dictionary* (1984), and the two-volume *Orthoepic Dictionary of the Ukrainian Language* (2001–2003)—the researcher drew attention to differences and scholarly inaccuracies in the most recent of them.

The system of Ukrainian literary consonantism comprises thirty-two consonant phonemes: /б/, /п/, /м/, /в/, /ф/, /л/, /л'/, /т/, /т'/, /з/, /з'/, /ц/, /ц'/, /и/, /и'/, /а3/, /а3'/, /ж/, /ч/, /ш/, /аж/, /л/, /л'/, /н/, /н'/, /р/, /р'/, /й/, /г/, /к/, /х/, /г/. Pronunciation difficulties for bilinguals are posed by the sounds [и'], [а3], [а3'], [ч], [аж], [р], [р'], [г] and [х]. In oral literary speech, many cases of double and even triple phonetic interactions, overlapping phonetic phenomena and the emergence of one combinatory change as a result of another have been identified, which is clearly illustrated by modern orthoepic dictionaries (*Peshchak et al., 2001–2003*). Various modifications of consonants, including assimilation, dissimilation, dieresis and others, have been examined in the scholarly works of V. Brakhnov, N. Totska, V. Bondarenko, I. Savchenko and other researchers (*Bondarenko, 2010; Brakhnov, 1970; Savchenko, 2012; Totska, 1981*).

Vowel Sounds as Phonetic Shibboleths

In the modern Carpathian dialects of Ukraine, the ancient Slavic back vowel phoneme /ы/ has been preserved (*Berżenko, 1980, p. 52*), and it functions as a regional marker of Ukrainian speech. We have often observed the speech of highly educated people who had long since left

their dialectal environment, but who had not managed to get rid of their articulatory habit and, when communicating in the literary language, continued to pronounce [ɨ] instead of [и], which developed from the back Indo-European long *ī*: *мы, проблеми, син*. This phenomenon has a clear historical, articulatory and psycholinguistic basis and indicates the deep preservation of an archaic Proto-Slavic phonetic matrix operating at the level of subconscious neuromotor programmes.

Another specific feature in the system of dialectal Ukrainian vocalism of the Galician-Bukovynian group is the expanded articulation of the stressed sound [и], with full or partial approximation to [e]: *родѐна* instead of *родина*, *сѐла* instead of *сила*, *нѐти* instead of *нуми* (*Matviias, 1990, p. 73*). This feature often marks a person originating from these territories, who, while speaking the literary language, pronounces *сѐнтаксис* instead of *синтаксис* or *прѐисудок* instead of *присудок*.

The sound [o] may also be regarded as both a regional and national shibboleth. It is a broad, labialised, back vowel of mid aperture. The replacement of the rounded unstressed [o] by the unrounded [a], a phenomenon known as *akannia*, which is characteristic of northern Ukrainian, especially Polissian, dialects, as well as Belarusian and Russian, serves as an identifier of a Russian-speaking person. Such a speaker may pronounce *мості́ти* as *масці́ти*, *на́раду* as *нара́ду*, *голо́сува́ти* as *галасува́ти*, *ра́бі* as *рабі́*, and so on. This feature is also used to identify many people originating from northern, southern and eastern Ukraine.

The speech of Transcarpathians is distinguished by the narrowed [ô], which occurs in both stressed and unstressed positions before a soft consonant, before a syllable containing [і], [y], [ô], and before the non-syllabic sounds [ʏ] and [ĩ]: *кѣ́ѣ, хѣ́м'іти*. In order to develop the technique of broad articulation of [o], it is necessary to monitor the correct shape of the lips and the degree of opening of the oral cavity, and to practise constantly distinguishing the pronunciation of [o] and [y], for example in quasi-homonyms: *сам* — with the mouth widened on [o] while looking in the mirror — *сѣм, бор – бѣр, бот – бут, копа – куна, копити – купити, лоб – луб, мор – мур, роки – руки, ток – тук, топати – тупати*, and so on. One should begin with slow reading, fixing the articulation, and then gradually increase the tempo. The reading should be recorded on video, with constant correction and improvement of one's own pronunciation.

Conversely, people originating from eastern and central Ukraine are often identified by a broad [o]. Moreover, the articulation of [a] with a noticeable tendency towards [o] may frequently serve as a phonetic shibboleth for identifying them: [їа жиела́о ѣ Ха́оркові саома́ о]. Such pronunciation is immediately noticed by residents of south-western Ukraine, where, because of the war, there are now many internally displaced persons.

Consonant Sounds as Phonetic Shibboleths

In Ukrainian, most consonants are produced by the approximation of the anterior parts of the speech organs: the lips, the front part of the tongue, and the upper teeth. In addition, as a result of coarticulation, sounds change their qualitative and quantitative characteristics. The modifications of Ukrainian consonants that depend on their position within the word and the syllable include the changes of [в] and [і] into [ʋ] and [ĩ]. The following dependence is observed: at the beginning of a syllable before a vowel, the sounds [в] and [і] occur, whereas at the end of a syllable after a vowel, or at the beginning of a syllable before the following consonant, the

non-syllabic vowels [ʃ] and [ʃ̥] occur as positional allophones of the phonemes /в/ and /й/. Compare: [йáблукo], [пйтáйу], [гул'áʃ], [вaм], [бувáʃ], [мáʃ], [стáʃтe], and others. However, Russian-Ukrainian bilinguals often incorrectly pronounce [ф] instead of [ʃ]: [знaф], [л'убóф], [слухач'íф], [жóфтí].

Ukrainian has a developed system of consonant softness, which covers a significant part of its consonant system: /Δ'/, /т'/, /з'/, /с'/, /Δз'/, /ц'/, /л'/, /н'/, /р'/, /й'/. The well-known shibboleth *palianytsia* [пaл'aниц'а] functions as a complex phonetic test that checks several levels of speech competence simultaneously. Its pronunciation requires precise coordination of the movements of the speech organs, which is natural for Ukrainians but a serious challenge for foreigners. The sound [ц'] is an affricate formed through the instantaneous fusion of the plosive [т'] and the fricative [с']. Foreigners whose languages do not contain such a sound will replace it with their own equivalents. An example of such substitution is the transliteration of the Ukrainian surname *Лисича* as *Lissitsa*, as a result of which, for instance, the well-known Ukrainian agricultural expert Oleksii Lysytsia became Alex Lissitsa. However, the modern transliteration of this surname as *Lysytsia* is also unable to convey the exact sound of the affricate [ц'].

Russian-speaking individuals find it particularly difficult to reproduce the soft [ц'], since their native language has only its hard counterpart. To correct pronunciation, it is advisable first to practise two-sound combinations such as [ц'a], [ц'o], [ц'y], [ц'i], and then to articulate two- and multi-syllabic words: *цяця, киця, праця, вулиця, криниця, столиця, крамниця, залізниця*, and others; *цього, цьому, лицьовий, кільцьовий, працьовитий, кицю, пацюк, цюкати, танцюю; ціна, цілий, цікаво, руці, таниці*. Tongue-twisters containing this sound may also be suggested: *Ця киця-цяця у спідниці / Танцює танець у крамниці; Вранці наші іноземці / Принесли смачні гостинці; / Тут рум'яна паляниця / І солодка полуниця!*

A vivid indicator of Ukrainian euphony is the tendency to avoid hiatus, that is, the meeting of two vowels. For this purpose, an intervocalic [j] often appears, for example in the words *проскт, діста, траєкторія, егойст*, and others. This sound must not be omitted during articulation. Therefore, the incorrect pronunciation of the words *лінія* as [л'ін'ia] instead of [л'ін'ija], *пам'ять* as [пáм'at'] instead of [пáмjat'], and *нумає* as [пнeтáє] instead of [пнeтáje] immediately identifies Russian-speaking bilinguals.

Ukrainian orthoepy allows the pronunciation of the consonants [т] and [т'] with an approximation to [ц] and [ц'] if they occur after [с'] or before the sibilants [ц], [с], [ц'], [с']: *стіна* [с'т'п'інá], *радість* [рáд'іс'т'п'], *у місті* [у м'іс'т'п'], *воріття* [воур'іц':a], *дивиться* [дівнeц':a]. By contrast, in the words *життя* [житт':á] and *тіло* [т'іло], the approximation of [т'] to [ц']—[житт'п':á], [т'п'іло]—is a violation of the pronunciation norm. Similarly, [Δ] and [Δ'] may be pronounced as [Δз] and [Δз'] only before the sibilant sounds [з], [ц], [с], [Δз], [з'], [ц'], [с'], [Δз']: *радься* [рáдз'c'a], *на грядці* [на гр'áдз'п'і]. In other cases, such affricatisation is erroneous: *діти* [дз'іти], *ходять* [хóдз'ат'п'], and others.

The pronunciation of the Ukrainian voiced pharyngeal fricative [ɣ] is problematic for foreigners, including Russians, Romanians, French speakers and others. This sound is produced as a result of a narrowing that occurs in the pharyngeal cavity owing to the backward movement of the root of the tongue and its approximation to the posterior wall of the pharynx, as well as through the contraction of the muscles of the posterior pharyngeal wall. Speakers who do not

have the articulatory skills required for correct pronunciation often pronounce it before back vowels as [ɣx]: [ɣxárho], [ɣxolová], [ɣxýcto]. Since the vowels [a], [o], [y] require the lowering of the lower jaw and the retraction of the tongue, it is difficult for a foreigner in this position to maintain a “pure” vibration of the vocal cords. The root of the tongue involuntarily rises towards the soft palate, creating excessive friction, which results in a sound resembling a hoarse, “unclean” [x] with an admixture of voicing.

Another incorrect pronunciation, [ɦípkɔ], [ɦíɦɪɫ], [ɦréɦzer], is explained by the fact that the vowels [e], [i] and [ɪ] are front vowels, during the production of which the back of the tongue rises high towards the palate. For a foreigner, especially a speaker of Romance languages or Russian, this tense tongue position provokes a reflex closure, as a result of which the plosive sound [ɾ] (g) is produced. Thus, [ɾ] is a genuine phonetic exclusivity that requires training of the throat muscles, which are usually not involved in other languages. For this purpose, the “gargling” exercise may be recommended: one should take a little water into the mouth, tilt the head back and begin to “gargle” while producing the sound [x-x-x] or [ɾ-ɾ-ɾ], and then try to perform the same procedure without water, monitoring the movement of the tongue. Articulation drills and tongue-twisters combining the sounds [ɾ] – [ɾ] – [x] are also effective. For example: *Григорій гнав гусей на гору; Гліб горланить, а Хома ховається; Годувала гава гавенят на ганку. Готувала в горщику гарну запіканку.*

Discussion

The general research problem addressed in this study lies at the intersection of sociolinguistics, applied phonetics and linguodidactics. The results confirm and expand previous findings in Ukrainian phonetic studies by demonstrating that phonetic shibboleths are not merely isolated pronunciation features, but complex linguistic phenomena connected with articulation, identity, regional belonging, social perception and language acquisition. In contemporary Ukrainian conditions, especially after the beginning of Russia’s full-scale invasion, these phenomena have acquired particular relevance because they function simultaneously as markers of linguistic competence, national identity, regional localisation and communicative security.

The analysis of the pronunciation of the vowels [ɪ] and [o] as reliable shibboleths corresponds to O. Bas-Kononenko’s observations concerning the preservation of full vowel pronunciation in Ukrainian, including in unstressed positions. Unlike Russian or English, where strong reduction is typical, the Ukrainian articulatory base requires a comparatively clear and full realisation of vowels. This feature makes processes such as *akannia*, that is, the replacement of [o] by [a], or the approximation of [ɪ] to [i] or [y], especially noticeable identifiers of phonetic interference. Such deviations are not accidental pronunciation errors; they reveal the influence of another phonological system and demonstrate the stability of previously formed articulatory habits.

The findings also show that Ukrainian vocalism can function as both a national and regional marker. The Ukrainian [ɪ] is particularly important because it occupies a specific position in the vowel system and is difficult for Ukrainian-Russian bilinguals to reproduce accurately. The tendency to replace it with [y] or [i] demonstrates the mechanism of phonetic substitution, when a speaker uses the closest available sound from the dominant language. At the same time,

regional variants, such as the preservation of the archaic back vowel [ɤ] in Carpathian dialects or the approximation of stressed [ɪ] to [e] in the Galician-Bukovynian area, indicate that shibboleths do not operate only according to the binary opposition “native speaker—non-native speaker”. They may also identify a speaker’s regional background within the Ukrainian-speaking continuum.

The sound [o] provides another important example of the interaction between the national literary norm, regional variation and interference. The preservation of rounded [o] in unstressed positions is an important feature of Ukrainian pronunciation, whereas its replacement by [a] may indicate the influence of Russian, Belarusian or certain northern Ukrainian dialectal patterns. Conversely, a narrowed [ô] in Transcarpathian speech or a broadened [o] characteristic of some speakers from central and eastern Ukraine may function as regional phonetic markers. Thus, vowel shibboleths demonstrate that phonetic identification is multidimensional: it can reveal not only whether a speaker has mastered the literary norm, but also which regional or bilingual articulatory background influences their speech.

From the perspective of psycholinguistics, the difficulties recorded in mastering Ukrainian consonants such as [ɲ], [r] and [ʎ] by adult speakers illustrate Z. Dudnyk’s concept of articulatory habit as a stable cultural and ethnic identifier of the individual. The present study confirms that theoretical knowledge of orthoepic rules is insufficient for achieving correct pronunciation. Articulatory matrices formed in the native or dominant language operate at the level of subconscious neuromotor programmes. As a result, adult bilinguals and non-native speakers often encounter a powerful psychological and muscular barrier when attempting to produce movements that are not characteristic of their established phonetic system.

This is particularly evident in the pronunciation of the Ukrainian non-syllabic [ʎ]. The replacement of [ʎ] by [ɸ] among Russian-Ukrainian bilinguals demonstrates the influence of another phonetic system on the realisation of Ukrainian positional allophones. Such errors reveal not only the speaker’s lack of automatic control over Ukrainian phonetic alternation, but also the deeper problem of transferring native-language articulation into Ukrainian. Therefore, the acquisition of [ʎ] requires not only knowledge of its positional distribution, but also systematic auditory and articulatory training aimed at developing automatic pronunciation skills.

The soft affricate [ɲ] represents another significant case of phonetic interference. The Ukrainian word *paliannytsia* functions as a complex phonetic test because it requires the coordinated realisation of several features: palatalisation, affrication, vowel quality and rhythmic organisation. For Russian-speaking individuals, the reproduction of [ɲ] is especially difficult because their native language has a hard counterpart but lacks the same soft affricate in the relevant phonetic function. The inability to pronounce [ɲ] accurately therefore becomes a reliable indicator of articulatory interference. At the same time, this case demonstrates that shibboleths are not only diagnostic tools, but also useful didactic units: they concentrate several pronunciation difficulties in one lexical form and can be used as material for systematic correction.

The Ukrainian pharyngeal voiced fricative [r] is one of the most distinctive consonantal shibboleths. Its correct pronunciation requires a specific configuration of the pharyngeal cavity, the root of the tongue and the posterior pharyngeal wall. Speakers whose native languages lack such articulation tend to replace it with sounds that are closer to their own phonetic system,

including [r] or a voiced [x]-like variant. This confirms that phonetic interference depends not only on auditory perception, but also on the physical readiness of the articulatory apparatus. The production of [r] requires activation of muscular mechanisms that may be unfamiliar to speakers of Russian, Romance languages and other linguistic systems. Consequently, the correction of this sound must include not only explanation, but also mechanical and speech-therapy exercises.

The results require a reconsideration of traditional linguodidactic approaches to pronunciation training. Overcoming phonetic interference cannot be achieved through conscious control alone. Learners may know the rule, understand the difference between sounds and even recognise the correct pronunciation in another speaker's speech, but still fail to reproduce the sound accurately because the native articulatory matrix remains dominant. Therefore, effective correction must include repeated speech-therapy training, auditory differentiation, articulatory automatisisation and multimodal feedback.

The proposed exercises with quasi-homonyms and contrastive pairs are particularly important because they combine auditory discrimination with articulatory practice. Pairs such as *діл – дім*, *сік – сів*, *кім – кум*, *сом – сям*, *бод – бод* and similar examples enable learners to distinguish between sounds that are close in perception but different in the Ukrainian phonetic system. Such exercises help transform abstract knowledge of pronunciation norms into practical phonetic competence. They also allow teachers to detect whether a learner's error is primarily auditory, articulatory or both.

Visual control is another important strategy for overcoming interference. Monitoring the shape of the lips, the opening of the oral cavity and the position of the tongue, including through mirrors or video recording, makes articulatory movements more conscious and controllable. This is especially useful for sounds whose correct pronunciation depends on visible articulatory parameters, such as labialisation in [o] or the opening of the mouth during vowel production. Video recording also provides learners with delayed feedback and allows them to compare their pronunciation over time, which is important for forming stable neuromotor skills.

Mechanical exercises, such as the “gargling” exercise for the Ukrainian [r], are justified by the fact that some sounds require the activation of articulatory mechanisms that are not normally used in the learner's native language. In such cases, purely verbal explanation is insufficient. The learner must first develop physical awareness of the relevant articulatory zone and only then integrate the movement into actual speech. This approach brings linguodidactics closer to speech therapy and supports the view that adult pronunciation training should include not only phonological explanation, but also targeted motor practice.

The study also has broader sociolinguistic implications. Ukrainian shibboleths operate in the space between language, identity and social evaluation. They can mark a speaker as belonging to a particular national, regional or linguistic group. In wartime conditions, they may also acquire a security-related function, as in the case of *palianytsia*, which has become a cultural symbol of resistance and unity. However, the social function of shibboleths should be interpreted carefully. On the one hand, they may consolidate a community and reinforce linguistic awareness. On the other hand, they may also become instruments of exclusion or stigmatisation, especially in relation to bilinguals, internally displaced persons or speakers who are actively transitioning to Ukrainian. This ambivalence requires further sociolinguistic and ethical reflection.

The theoretical contribution of the study lies in the interpretation of phonetic shibboleths as complex markers located at the intersection of phonetic structure, articulatory habit and identity. Traditional phonetic description usually focuses on the classification of sounds and pronunciation norms. The present study shows that certain sounds become socially meaningful because they are difficult to imitate without long-term articulatory training. In this sense, shibboleths reveal the embodied nature of language: identity is not expressed only through lexical choice or grammar, but also through deeply automatised movements of the speech organs.

The practical contribution of the study lies in the development of linguodidactic approaches to overcoming interference. The findings suggest that pronunciation teaching should be organised around specific articulatory difficulties rather than around abstract rules alone. For bilinguals and non-native speakers, the correction of Ukrainian pronunciation should include work with minimal or quasi-minimal pairs, controlled repetition, slow reading, gradual tempo increase, tongue-twisters, visual feedback, video analysis and mechanical exercises. Such strategies are particularly important for adult learners because their native articulatory base is already stabilised and cannot be restructured through passive exposure alone.

At the same time, the study has several limitations. First, it is primarily qualitative and scientific-methodological in nature; it does not include instrumental acoustic measurements or experimental testing of learners before and after pronunciation training. Secondly, the analysis focuses on selected Ukrainian shibboleths, while other potentially significant sounds and prosodic features remain outside the central scope of the article. Thirdly, the discussion of regional variation is based on selected phonetic markers and does not aim to provide a complete dialectological description of all Ukrainian regions. Fourthly, the sociolinguistic role of shibboleths in wartime communication requires additional empirical research involving speakers from different regions, age groups and linguistic backgrounds.

Future research may develop this topic in several directions. One promising direction is the experimental acoustic study of Ukrainian phonetic shibboleths in the speech of bilinguals and non-native speakers. Such research could measure vowel formants, duration, intensity, degree of labialisation, palatalisation and pharyngeal articulation. Another important direction is the psycholinguistic study of articulatory resistance in adult learners, including the role of auditory perception, motor control and emotional attitudes towards pronunciation correction. It would also be useful to test the effectiveness of specific linguodidactic techniques, such as quasi-homonym drills, video feedback and mechanical exercises, through controlled pedagogical experiments.

A further perspective concerns the long-term stability of lexical shibboleths as social and security markers. Human speech is adaptive, and speakers can gradually learn even difficult pronunciation patterns if they have sufficient motivation, exposure and training. Therefore, the effectiveness of particular shibboleths may change over time. Words that once functioned as reliable markers may lose part of their diagnostic value when they become widely known and deliberately practised. This makes it necessary to examine shibboleths dynamically, as phenomena that evolve together with social conditions, language policy and communicative practice.

Overall, the discussion confirms that Ukrainian phonetic shibboleths are significant not only for theoretical phonetics, but also for applied linguistics, language teaching, sociolinguistics and identity studies. They reveal how deeply pronunciation is connected with the speaker's linguistic biography, regional background and cultural affiliation. The main obstacle to accurate pronunciation is not the absence of knowledge, but the stability of subconscious articulatory habits and the difference between phonological systems. Therefore, the successful acquisition of Ukrainian phonetic shibboleths requires systematic, multimodal and practice-oriented training aimed at transforming conscious knowledge into stable articulatory skill.

Conclusion

In the twenty-first century, the phonetic shibboleth is being transformed from a biblical password into a high-precision instrument of applied linguistics that enables reliable identification of an individual in a globalised world. However, shibboleths do not merely identify speakers; they also shape social attitudes towards them. In Ukraine, the word *palianytsia* has become a symbol of unity and cultural resistance.

In addition to functioning as a marker of national identification and as a means of distinguishing between “us” and “them”, phonetic shibboleths serve as an accurate instrument for the regional localisation of a speaker. Specific articulatory habits, such as the preservation of the archaic Proto-Slavic phoneme /ɫ/ or the narrowed [ô] in Transcarpathia, the expanded articulation of [ɪ] in Galicia and Bukovyna, and the replacement of unstressed [o] by [a] among speakers originating from southern, northern and eastern Ukraine, make it possible to identify the geographical origin of a speaker even when they communicate in standard Ukrainian.

Phonetic phenomena are reliable instruments of linguistic identification because they are rooted in deep articulatory and phonological structures. The main reason why foreigners or Russian-speaking Ukrainians are unable to reproduce certain Ukrainian sounds correctly lies primarily in the divergence between articulatory bases, that is, the set of habitual movements of the speech organs. This difficulty is further reinforced by the absence of practical pronunciation skills and by a psychological barrier to unfamiliar articulatory movements.

An important feature of Ukrainian, which distinguishes it from Russian and English, is the preservation of full vowel pronunciation in unstressed positions. This is determined by the specific character of Ukrainian word stress, which makes sharp reduction or indistinct pronunciation of vowels atypical for the Ukrainian phonetic system.

Successful elimination of accent and correction of sound substitution by foreigners or bilingual speakers cannot be achieved through knowledge of orthoepic norms alone. The formation of an accurate Ukrainian articulatory base requires the purposeful use of speech-therapy and phonetic practices, including work with quasi-homonyms and contrastive word pairs, visual control of lip and tongue position, video recording of speech, and the use of specific techniques such as the “gargling” exercise for practising the pharyngeal [r].

In view of the above, a promising direction for the development of applied phonetics lies in the integration of linguodidactic approaches with new technologies and sociolinguistic monitoring. The development of innovative psycholinguistic methods for rapidly overcoming articulatory barriers in adult speakers, as well as further research into the evolution of shibboleths as security-related instruments, remains a key task for future scholarly studies.

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Conflict of Interest

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Verbal Negation in the Context of Power: The Theme of Identity in a Colonial Society ^[16]

Abstract:

The relevance of this study is determined by the growing importance of linguistic, literary and postcolonial approaches to the analysis of identity formation in societies shaped by colonial domination and its long-term consequences. In postcolonial literature, language functions not only as a means of representation, but also as an instrument of resistance, self-definition and cultural reconstruction. Within this framework, verbal negation acquires particular significance because it allows characters and narrators to reject imposed colonial meanings, question dominant power structures, and articulate alternative forms of individual and collective identity. The research problem lies in the insufficiently explored pragmatic and narrative role of verbal negation in representing identity conflicts, uncertainty, social constraints and the search for autonomy in colonial and postcolonial discourse. The object of the study is verbal negation in English-language colonial and postcolonial novels. The subject of the research is the pragmatic function of verbal negation in shaping the theme of identity within literary discourse. The aim of the study is to reveal how verbal negation reflects conflicts, limitations, resistance and self-identification in societies marked by colonial and postcolonial power relations. The scientific novelty of the article lies in combining quantitative analysis of recurrent negation forms with pragmatic interpretation of literary fragments in order to demonstrate the role of negation as both a linguistic marker and a narrative strategy of identity construction. The study analyses verbal negation forms such as *did not*, *was not*, *could not* and the full verb *stop*, focusing on their frequency, distribution and contextual functions in selected postcolonial novels, including *Efuru*, *The River Between*, *No Longer at Ease*, *Things Fall Apart*, and *Girl, Woman, Other*. The results show that verbal negation is not limited to grammatical denial. It functions as a means of expressing refusal, psychological tension, social restriction, resistance to colonial narratives, and the desire to preserve or restore indigenous cultural identity. The study concludes that verbal negation in postcolonial novels is a multifaceted linguistic and pragmatic phenomenon that reveals the complexity of identity formation under conditions of colonial influence, neocolonial pressure and cultural transition.

Keywords: verbal negation, postcolonial literature, identity formation, colonial discourse, narrative resistance, pragmatics of negation, indigenous identity, social constraints.

Introduction

The phenomenon of verbal negation occupies a central place in linguistic, literary and cultural studies, as it reflects not only grammatical structures, but also pragmatic strategies of meaning-making. Negation is one of the fundamental mechanisms through which language expresses rejection, absence, contradiction, limitation, prohibition, opposition and alternative interpretation. In literary discourse, it becomes particularly significant because it participates in the construction of character psychology, narrative conflict, social evaluation and ideological positioning. Therefore, the analysis of verbal negation makes it possible to examine not only the formal organisation of language, but also the ways in which linguistic structures convey cultural, psychological and political meanings.

In postcolonial literature, negation becomes a powerful narrative device through which authors challenge colonial ideologies, resist imposed identities and articulate the search for autonomy. Colonial discourse historically functioned through the production of hierarchies, oppositions and exclusions, defining colonised subjects through categories imposed by imperial power. In this context, verbal negation may function as a linguistic form of refusal, a pragmatic

act of resistance and a means of reconstructing identity. By denying, rejecting, interrupting or limiting imposed meanings, postcolonial texts create space for the revaluation of indigenous experience, collective memory and cultural self-definition.

The relevance of this study lies in the increasing scholarly interest in how language functions as a tool of resistance and identity reconstruction in societies marked by colonial domination and its aftermath. Postcolonial identity is often formed under conditions of cultural displacement, historical trauma, social constraint, linguistic hybridity and the conflict between inherited traditions and imposed colonial norms. In such conditions, negation is not merely a grammatical category. It becomes a means of expressing uncertainty, disagreement, resistance, psychological pressure, social limitation and the desire for autonomy. By focusing on verbal negation, the present research contributes to the broader discourse on postcolonial identity formation and the pragmatics of literary communication.

The research problem is determined by the fact that, although negation has been widely examined in syntax, semantics, logic and discourse studies, its role as a pragmatic and narrative mechanism of identity formation in postcolonial literary discourse remains insufficiently systematised. Existing studies provide important theoretical foundations for understanding the structure and functions of negation (*Payne, 1985; Rowlett, 1986; van der Wouden, 1997*), as well as its pragmatic, sociocultural and discursive dimensions (*Roitman, 2017; Roitman, 2023; Widdowson, 2004*). However, less attention has been paid to the way recurrent verbal negation forms operate in literary texts as markers of colonial pressure, personal limitation, resistance to imposed identities and the search for cultural continuity.

This problem is particularly important for postcolonial novels, where identity is often represented as a process of negotiation between the self and the dominant structures of power. Characters may experience internal conflict, uncertainty, alienation or an inability to act freely because of colonial and neocolonial constraints. In such contexts, forms such as *did not*, *was not*, *could not* and the verb *stop* may acquire meanings that exceed their grammatical function. They can mark refusal, impossibility, psychological restraint, social prohibition, rupture with imposed norms or an attempt to interrupt oppressive processes. Therefore, the pragmatic interpretation of verbal negation allows researchers to reveal deeper layers of identity conflict in postcolonial literature.

The scientific novelty of the study lies in the combination of quantitative analysis of recurrent verbal negation forms with qualitative pragmatic interpretation of literary fragments in selected colonial and postcolonial novels. This approach makes it possible to show that verbal negation functions simultaneously as a linguistic marker, a pragmatic strategy and a narrative device. The study does not reduce negation to a formal grammatical phenomenon, but interprets it as a meaningful element of literary discourse that participates in the representation of power relations, social constraints, identity reconstruction and resistance to colonial narratives.

The object of the study is verbal negation in English-language colonial and postcolonial novels.

The subject of the study is the pragmatic and narrative functions of verbal negation in shaping the theme of identity within colonial and postcolonial literary discourse.

The purpose of the research is to demonstrate how verbal negation functions as a strategy of resistance, identity reclamation and critique of colonial and neocolonial practices, as well as

to reveal how negation reflects conflicts, uncertainty and self-identification in societies marked by colonial domination.

To achieve this purpose, the following tasks are set:

- to analyse the frequency and distribution of verbal negation forms in selected colonial and postcolonial novels;
- to identify the most recurrent verbal negation patterns, including forms with *BE*, *DO*, *HAVE*, modal verbs and full verbs;
- to interpret the pragmatic functions of negation in literary discourse;
- to examine how verbal negation reflects internal conflicts, social constraints, psychological pressure and processes of self-identification;
- to determine how negation contributes to the representation of resistance to colonial and neocolonial power structures;
- to reveal the role of verbal negation in reclaiming indigenous identity, collective memory and cultural autonomy;
- to contextualise the findings within broader theoretical frameworks of negation, discourse analysis and postcolonial studies.

The theoretical significance of the study lies in deepening the understanding of verbal negation as a pragmatic and culturally embedded phenomenon. The research contributes to the development of linguistic and literary studies by demonstrating that negation in postcolonial novels should be understood not only as a grammatical or semantic category, but also as a discourse strategy connected with power, resistance and identity formation. It also expands the theoretical interpretation of negation in literary discourse by integrating quantitative corpus-oriented observation with pragmatic and postcolonial analysis.

The practical significance of the study lies in the possibility of using its results in courses on English philology, pragmatics, discourse analysis, stylistics, postcolonial literature and literary linguistics. The findings may be useful for scholars, lecturers, postgraduate students and researchers interested in the linguistic mechanisms through which literary texts represent cultural conflict, social pressure and identity transformation. The proposed approach may also be applied to the analysis of other linguistic categories in literary discourse, especially where language functions as an instrument of ideological resistance and cultural self-representation.

In brief, the study demonstrates that verbal negation in postcolonial novels is not only a linguistic marker, but also a narrative strategy that reveals the complexity of identity formation. By resisting colonial narratives, reclaiming indigenous heritage and exposing social constraints, negation becomes a means of articulating both conflict and hope in the postcolonial condition. It enables literary texts to express not only what is denied or rejected, but also what is being sought: autonomy, dignity, cultural continuity and a renewed sense of self.

Methods

The methodological framework of the study is based on a mixed linguistic and literary approach that combines quantitative analysis of verbal negation forms with qualitative pragmatic interpretation of selected literary fragments. This combination of methods was chosen because verbal negation in postcolonial novels functions simultaneously as a formal

linguistic structure, a pragmatic device, and a narrative strategy connected with the representation of power, resistance, social constraint, and identity formation.

The study is corpus-oriented in nature. The empirical material consists of selected English-language colonial and postcolonial novels in which the themes of identity, colonial domination, cultural displacement, indigenous self-definition, and resistance to imposed social norms are represented through narrative discourse. Particular attention is paid to novels such as *Efuru*, *The River Between*, *No Longer at Ease*, *Things Fall Apart*, and *Girl, Woman, Other*, which are analysed as literary texts reflecting different dimensions of colonial and postcolonial experience. These works were selected because they contain narrative situations in which identity conflict, social pressure, cultural opposition, and the search for autonomy are expressed through recurrent verbal negation.

The main unit of linguistic analysis is the verbal negation construction. In the study, verbal negation is understood as a grammatical and pragmatic structure that expresses denial, refusal, absence, impossibility, prohibition, interruption, exclusion, resistance, or limitation through verbal forms. The analysis includes negative forms with auxiliary and modal verbs, as well as full verbs that carry negative or restrictive semantics. The following groups of verbal negation were considered:

- negative forms with the verb *BE*: *is not*, *are not*, *was not*, *were not*, *isn't*, *aren't*, *wasn't*, *weren't*, *ain't*;
- negative forms with the auxiliary verb *DO*: *do not*, *does not*, *did not*, *don't*, *doesn't*, *didn't*;
- negative forms with the verb *HAVE*: *have not*, *has not*, *had not*, *haven't*, *hasn't*, *hadn't*;
- negative modal constructions: *cannot*, *can't*, *could not*, *couldn't*, *may not*, *might not*, *should not*, *shouldn't*, *shall not*, *shan't*, *must not*, *mustn't*, *need not*, *needn't*, *dare not*;
- full verbs and lexical units with negative or restrictive meaning, including *absent*, *fail*, *forget*, *exclude*, *stop*, *avoid*, *prohibit*, *forbid*, *doubt*, *refuse*, *deny*, *ignore*, and *refrain*.

At the first stage of the research, the selected texts were examined in order to identify and extract verbal negation forms. The identified units were grouped according to their grammatical type and lexical-semantic function. This classification made it possible to distinguish between auxiliary negation, modal negation, and lexical negation. Such grouping was necessary because different types of negation may perform different pragmatic and narrative functions in postcolonial discourse. For example, forms such as *did not* and *was not* often indicate refusal, contradiction, or the denial of imposed meanings, whereas *could not* frequently marks limitation, impossibility, or the pressure of external circumstances. The verb *stop* may function as a marker of interruption, resistance, or an attempt to terminate an oppressive psychological or social process.

At the second stage, a quantitative analysis was carried out. The frequency and distribution of verbal negation forms were calculated across the selected corpus. Both absolute and relative frequencies were considered. Absolute frequency made it possible to determine which forms occur most often in the analysed texts, while relative frequency helped to compare the use of negation across works of different length. Special attention was paid to the most frequent forms identified in the study, namely *did not*, *was not*, *could not*, and *stop*. These forms were selected for

further pragmatic interpretation because their statistical prominence indicates their potential relevance to the representation of identity conflicts and postcolonial resistance.

At the third stage, the quantitative results were visualised and interpreted. Frequency distribution was represented through figures showing the occurrence of selected verbal negation forms in the analysed literary corpus. This made it possible to identify dominant patterns of negation and to determine which forms were most strongly associated with particular novels. The visual analysis supported the interpretation of *did not* and *was not* as recurrent forms in novels such as *Efuru*, *The River Between*, *No Longer at Ease*, and *Things Fall Apart*. It also made it possible to highlight the significance of *could not* in *The River Between* and the role of *stop* in texts such as *Girl*, *Woman*, *Other*, *No Longer at Ease*, and *Efuru*.

At the fourth stage, qualitative pragmatic interpretation was applied to selected literary fragments. This method was used to determine how verbal negation functions in specific narrative contexts. The interpretation focused on the relationship between negation and the representation of identity, autonomy, cultural belonging, psychological tension, social constraint, and resistance to colonial or neocolonial power structures. Each selected fragment was analysed not only in terms of the grammatical structure of negation, but also in relation to the broader narrative situation, character motivation, social context, and ideological meaning.

The pragmatic analysis was guided by the assumption that negation in literary discourse does not simply deny a proposition, but also produces meaning through contrast, opposition, implication, and contextual inference. In postcolonial novels, negation may reveal the tension between individual desire and collective expectations, between indigenous cultural memory and colonial domination, or between personal autonomy and social restriction. Therefore, the study examined how negation contributes to the construction of implicit meanings, emotional intensity, ideological resistance, and narrative perspective.

The interpretation of literary fragments was performed according to several analytical criteria:

- the grammatical form of verbal negation used in the fragment;
- the immediate syntactic and semantic context of the negative construction;
- the character or narrator associated with the negation;
- the social, cultural, or psychological conflict represented in the fragment;
- the pragmatic function of negation, such as refusal, limitation, impossibility, prohibition, self-defence, resistance, or rejection of imposed identity;
- the role of negation in revealing the broader theme of identity formation in colonial or postcolonial society.

The theoretical basis of the methodology is formed by studies of negation in syntax, semantics, pragmatics, discourse analysis, and postcolonial literary studies. The research draws on approaches that consider negation as a linguistic category with grammatical, semantic, pragmatic, and sociocultural dimensions. The works of Payne, Rowlett, Roitman, Widdowson, van der Wouden, Vernay and other scholars provide the conceptual foundation for interpreting negation not merely as a formal marker of denial, but as a socially and culturally embedded discourse phenomenon.

The study also applies elements of discourse analysis. This made it possible to consider verbal negation as part of broader narrative and ideological structures. In postcolonial discourse, language often reflects asymmetrical power relations, cultural conflict, and the struggle for self-representation. Therefore, verbal negation was analysed as a discourse mechanism through which literary texts express disagreement with colonial narratives, expose social constraints, and construct alternative forms of identity.

The method of contextual interpretation was used to connect individual verbal negation forms with broader literary and cultural meanings. For example, the form *did not* may indicate a character's refusal to obey social or familial expectations; *was not* may signal the rejection of an imposed interpretation of identity; *could not* may reveal the impossibility of acting freely under external pressure; and *stop* may mark a desire to interrupt psychological self-blame, social control, or oppressive circumstances. Such interpretation makes it possible to demonstrate that negation participates in the representation of both internal and external conflict.

The research procedure consisted of several consecutive stages. First, the theoretical literature on negation, pragmatics, discourse analysis, and postcolonial identity was examined. Secondly, the literary corpus was selected and prepared for analysis. Thirdly, verbal negation forms were identified, classified, and counted. Fourthly, the most frequent and pragmatically significant forms were selected for closer examination. Fifthly, literary fragments containing these forms were analysed in relation to narrative context, character identity, social pressure, and postcolonial meaning. Finally, the quantitative findings and qualitative interpretations were synthesised in order to determine the role of verbal negation in representing identity in colonial and postcolonial societies.

The validity of the study is supported by the combination of quantitative and qualitative methods. Quantitative analysis provides measurable evidence of the frequency and distribution of verbal negation forms, while pragmatic interpretation reveals their contextual and narrative significance. This dual approach reduces the risk of relying only on subjective literary interpretation and allows linguistic patterns to be connected with broader thematic and ideological meanings.

At the same time, the study has certain limitations. The analysis focuses on selected colonial and postcolonial novels and therefore does not claim to represent the entire field of postcolonial literature. The interpretation of negation is also context-dependent, since the same grammatical form may perform different functions in different narrative situations. In addition, the study concentrates primarily on verbal negation and does not fully examine other forms of negative meaning, such as lexical opposition, irony, silence, rhetorical questioning, or metaphorical denial. These limitations may serve as directions for further research.

Despite these limitations, the selected methodology makes it possible to analyse verbal negation as a complex linguistic and narrative phenomenon. The combination of corpus-oriented frequency analysis, classification of negation forms, pragmatic interpretation of fragments, and postcolonial discourse analysis enables the study to demonstrate how negation contributes to the representation of resistance, limitation, uncertainty, self-identification, and the reconstruction of identity in colonial and postcolonial literary discourse.

Literature Review

The study of negation has a long intellectual history and occupies an important place in logic, semantics, syntax, pragmatics and discourse analysis. In linguistic theory, negation is usually understood as a fundamental category that enables speakers and writers to deny propositions, reject assumptions, mark contradiction, express absence, indicate impossibility or establish contrast between alternative meanings. At the same time, in literary discourse, negation performs functions that go beyond its formal grammatical role. It participates in the construction of narrative conflict, character psychology, ideological opposition and the representation of social relations. Therefore, the analysis of verbal negation in postcolonial fiction requires an interdisciplinary theoretical framework that combines linguistic, pragmatic and literary approaches.

Early approaches to negation were closely connected with logic and the problem of meaning. Partridge (1971) examined negation as a problem in logic and semantics, emphasising that negative meaning cannot be reduced to a simple reversal of affirmative meaning. This position is important for the present study because verbal negation in literary texts often produces complex interpretative effects. A negative construction may deny a factual statement, but it may also imply resistance, hesitation, conflict, social constraint or emotional tension. Thus, the semantic meaning of negation must be interpreted together with its pragmatic and narrative context.

The syntactic and typological study of negation provides another important theoretical basis. Payne (1985) analysed negation within the framework of language typology and clause structure, showing that negative constructions vary across languages and grammatical systems. Rowlett (1986) further developed the analysis of negation by examining its syntactic, semantic and pragmatic dimensions. These works are significant because they demonstrate that negation is not a marginal grammatical element, but a central component of linguistic organisation. For the present research, this means that verbal negation in postcolonial novels should be examined not only as isolated word forms, but as part of broader syntactic and discourse structures.

The bibliographic and systematising work of Seifert and Welte (1987) also indicates the breadth of scholarly interest in negation as a linguistic phenomenon. Their bibliography demonstrates that negation has been studied from multiple perspectives, including logic, grammar, semantics, pragmatics and natural language analysis. This plurality of approaches is methodologically important because it supports the need for a combined analysis of negation in literary discourse. In the context of postcolonial novels, negation cannot be fully explained by grammar alone; it must also be interpreted in relation to discourse, power and identity.

The historical foundations of the study of negation may be traced back to classical logic. Aristotle's treatment of categories and interpretation established early principles for understanding affirmation, denial and propositional opposition (Aristotle, 1963). Although contemporary linguistic analysis has moved far beyond classical logical models, the opposition between affirmation and negation remains essential for understanding how language structures reality and meaning. In postcolonial discourse, however, negation is not only logical opposition. It is also a rhetorical and ideological act through which colonised or postcolonial subjects may reject imposed representations and assert alternative forms of self-understanding.

An important contribution to the study of negation is made by research on collocation, polarity and multiple negation. van der Wouden (1997) examined negative contexts, polarity

phenomena and collocational patterns, showing that negation often functions within wider lexical and grammatical environments. This approach is relevant to corpus-oriented literary analysis because recurrent patterns of negation may reveal not only grammatical frequency, but also typical semantic and pragmatic associations. In the present study, forms such as *did not*, *was not*, *could not* and *stop* are significant not only because they occur frequently, but also because they appear in contexts of refusal, limitation, pressure and identity conflict.

The cognitive and usage-based perspective is also relevant to the analysis of negation in literary discourse. Taylor (2012) argues that language is represented in the mind through experience, usage and recurrent patterns. From this perspective, frequent verbal forms may be understood as part of a mental and textual corpus that shapes interpretation. In literary texts, repeated negative constructions can create a recognisable pattern of meaning and contribute to the reader's perception of characters, social constraints and ideological tensions. Therefore, frequency is not merely a quantitative indicator; it may also point to cognitive and narrative salience.

The pragmatic study of negation is particularly important for the present article. Roitman (2017) examines negation as a pragmatic phenomenon, emphasising that negative forms are shaped by context, speaker intention, communicative situation and social meaning. In later work, Roitman (2023) further develops this approach by analysing the relationship between negative form, negative meaning and the sociocultural context. These studies are central to the present research because postcolonial literary discourse is deeply embedded in relations of power, cultural hierarchy and social conflict. In such discourse, negation may perform the pragmatic function of rejecting imposed identities, resisting colonial assumptions, expressing internal conflict or challenging dominant narratives.

The discourse-analytic dimension of negation is also supported by Widdowson's work on text, context and pretext. Widdowson (2004) emphasises that meaning is produced not only by linguistic form, but also by the interaction between text and context. This idea is especially relevant for literary analysis, where negation must be interpreted in relation to the narrative situation, character position, ideological background and cultural conflict. A form such as *could not*, for instance, may express grammatical impossibility, but in a postcolonial novel it may also reveal social limitation, psychological pressure or the boundaries imposed by colonial and neocolonial structures.

Recent research has also drawn attention to contrastive and constructional variation in negation. Silvennoinen (2019) analyses contrastive negation and constructional variation within and across languages, demonstrating that negation may function as a means of producing contrast, differentiation and interpretative tension. This is relevant for postcolonial literary discourse because identity is often constructed through contrast: between coloniser and colonised, tradition and modernity, imposed identity and self-definition, collective memory and cultural erasure. In this context, verbal negation contributes to the articulation of difference and conflict.

The relationship between negation, emotion and postcolonial experience is addressed by Vernay (2024), who examines the productivity of negative emotions in postcolonial literature. This approach is important because negation in postcolonial novels is often connected with emotional states such as fear, shame, anger, alienation, disappointment, resistance and hope.

Negative emotions do not merely indicate psychological damage; they may also become productive forces that enable critique, reflection and identity reconstruction. Therefore, verbal negation may be interpreted as a linguistic form through which emotional and ideological resistance becomes narratively visible.

The postcolonial dimension of verbal negation is especially significant because colonial discourse historically relied on the denial, marginalisation or distortion of indigenous identities. Postcolonial literature often responds to such discursive violence by rejecting colonial categories and rearticulating cultural memory. In this sense, negation functions as a strategy of narrative resistance. It allows authors to expose the limitations imposed by colonial power, challenge inherited stereotypes and create space for alternative identities. Negation may therefore be read as both a destructive and constructive mechanism: it denies imposed meanings while simultaneously opening the possibility of self-definition.

The theme of identity formation in postcolonial society is closely connected with the pragmatics of negation. Characters in postcolonial novels frequently exist in situations of conflict between inherited cultural traditions and colonial or neocolonial expectations. Their speech and narrative representation often contain markers of refusal, impossibility, hesitation and interruption. These markers are not accidental. They reflect the instability of identity under conditions of cultural displacement and power asymmetry. Verbal negation may indicate a character's refusal to accept external control, inability to act freely, rejection of social pressure or attempt to preserve cultural continuity.

Previous quantitative research on negation in colonial and postcolonial English novels has demonstrated that negative words and constructions occupy a significant place in such literary texts. Tatarovska et al. (2023) analysed the quantitative status of negation words in colonial and postcolonial English novels, showing that negative linguistic units may be studied as measurable indicators of thematic and pragmatic tendencies. This research provides an important empirical foundation for the present article. However, the present study seeks to deepen the analysis by combining quantitative observation with pragmatic interpretation, thereby connecting frequency patterns with the narrative representation of identity, resistance and social constraint.

The analysis of verbal negation in selected novels such as *Efuru*, *The River Between*, *No Longer at Ease*, *Things Fall Apart* and *Girl, Woman, Other* demonstrates that recurrent forms of negation are closely connected with the themes of autonomy, collective identity, cultural conflict and psychological struggle. Forms such as *did not* and *was not* often mark conscious refusal, denial of imposed interpretations or the rejection of socially prescribed roles. The modal form *could not* frequently signals limitation, impossibility and the pressure of external circumstances. The verb *stop* may mark interruption, resistance or the desire to end a process of self-blame, social domination or emotional dependence. These forms show that negation operates simultaneously at grammatical, pragmatic and narrative levels.

Despite the substantial body of scholarship on negation, several issues remain insufficiently explored. First, the relationship between the frequency of verbal negation forms and their pragmatic functions in postcolonial novels requires further systematisation. Secondly, the role of negation in the construction of identity within colonial and postcolonial societies has not been sufficiently examined through combined quantitative and interpretative methods. Thirdly, existing studies often analyse negation as a linguistic category, whereas its function as a narrative

strategy of resistance and self-identification requires deeper attention. Finally, the connection between negation, power, social constraint and indigenous identity remains a productive area for literary-linguistic research.

Thus, the literature review shows that negation is a complex and multidimensional phenomenon. It has been studied as a logical relation, a semantic category, a syntactic structure, a pragmatic act, a discourse mechanism and a literary device. For the purposes of the present study, the most productive approach is one that integrates these perspectives. Verbal negation in postcolonial novels should be understood not only as a grammatical form, but also as a pragmatic and narrative strategy through which texts represent conflict, uncertainty, resistance, limitation and the search for identity. This theoretical basis justifies the need for a mixed analysis combining quantitative corpus-oriented methods with pragmatic interpretation of literary fragments.

Results

Verbal negation in postcolonial novels is an important narrative strategy that authors use to challenge and deconstruct colonial ideologies. This section examines how verbal negation functions in postcolonial literature, exploring its role in confronting colonial narratives, affirming indigenous identity, and critiquing neocolonial practices.

Verbal negation involves using language to deny, reject, or dispute statements, ideas, or conditions. In postcolonial literature, this often manifests as characters or narrators who explicitly refute colonial ideologies, histories and identities. This form of negation is not merely a linguistic device, but a powerful act of resistance and reclamation.

Verbal negation serves as a form of resistance against colonial and neocolonial power structures. By rejecting imposed identities and narratives, postcolonial characters assert their freedom of action and autonomy. Through verbal negation, postcolonial writers reclaim the history, culture and identity of indigenous peoples who were suppressed or distorted by colonial discourse. Verbal negation allows both colonial and postcolonial societies to be criticised. It highlights the contradictions and injustices inherent in these systems, prompting readers to question and challenge them.

Verbal negation in postcolonial novels is a multifaceted and powerful narrative strategy. It allows writers to resist colonial narratives, reclaim indigenous identity, and critique existing forms of oppression. Examining the use of verbal negation in postcolonial literature deepens understanding of the complexity and nuances of postcolonial resistance and identity formation.

Verbal negation explores the theme of identity in postcolonial society by reflecting on conflicts, uncertainty, and the search for self-identification among people who have experienced colonial domination and its consequences. Through refusal or a sense of alienation from accepting certain norms, values, or cultural traditions, individuals in postcolonial society feel oppressed and influenced by colonisers. The pragmatics of verbal negation reflect the search for a new sense of identity, opposition to or rejection of the dominant colonial culture, and the desire to preserve or restore one's own cultural and historical heritage.

Thus, verbal negation in the context of literary colonial discourse quantitatively reveals the theme of identity in postcolonial society through verb forms- *BE: is not (712), are not (231), was not (1227), isn't (64), aren't (29), ain't (1), were not (260), weren't (20); DO: do not (432), did not (1543),*

don't (507), *doesn't* (37), *didn't* (196), HAVE: *have not* (204), *has not* (104), *had not* (521), *haven't* (31), *hasn't* (52), *hadn't* (37); modal verbs – CAN: *cannot* (10), *can't* (159); COULD: *could not* (695), *couldn't* (77); MAY: *may not* (35), *mayn't* (-); MIGHT: *might not* (31), *mightn't* (-); SHOULD: *should not* (76), *shouldn't* (13); SHALL: *shall not* (37), *shan't* (1); MUST: *must not* (74), *mustn't* (11); DARE: *dare not* (6), *daren't* (-); NEED: *need not* (18), *needn't* (4); full verbs – *absent* (37), *fail* (238), *forget* (220), *exclude* (26), *stop* (880), *avoid* (126), *prohibit* (19), *forbid* (89), *doubt* (276), *refuse* (356), *deny* (69), *ignore* (99), *refrain* (25).

The most common verbal negations are the verb forms *did not*, *was not*, the modal verb *could not*, and the full verb *stop*. The verb form *did not* most often appears in the novels *Efuru*, *The River Between*, *was not* – in the novels *No Longer at Ease*, *Efuru*, *The River Between*, *Things Fall Apart* (Figure 1).

He has sent some young men to fetch his daughter, but she *did not go* with them. And since then he has done nothing about it. If it were in his youthful days, Nwashike would have taught that fool a lesson. Things are changing fast these days. These white people have imposed so much strain on our people (*Efuru*, p. 7)—in this fragment of text, we see that the daughter did not go with those who were sent for her, which indicates her independence and self-awareness; about the struggle for identity and self-determination under colonial influence, as the white community excessively abused their rights over the local population: *These white people have imposed so much strain on our people*.

The old man who broke the kola nuts in Lagos and called Obi Okonkwo an only palmfruit *was not*, however, thinking of Okonkwo's family. He was thinking of the ancient and war-like village of Umuofia. Six or seven years ago Umuofians abroad had formed their Union with the aim of collecting money to send some of their brighter young men to study in England (*No Longer at Ease*, p. 6)—the author-narrator notes that post-colonial society preserves its collective identity and traditions, which are connected to the native village or tribe. The use of *was not* indicates that the action was not aimed at individual interests or needs, but at the preservation and support of shared, identical experiences and hereditary values within the collective.

The modal negation *could not* is significant in the novel *The River Between* with a relative frequency of 0.0015 (Figure 2).

Hence, the verbal negation *could not* in the given text fragment reveals the theme of identity in a post-colonial society by emphasising limitations and the desire for more than what the traditional environment can offer. In this case, the character born in Kamenno, like Mugo, was not satisfied with the limited life on the hills and sought to break free from his native land. This indicates that in a post-colonial society, there is a tension between traditional constraints and new opportunities, which creates a new dimension of identity. The negation *could not* highlight the character's inability or unwillingness to remain within narrow social confines, symbolising the search for oneself beyond traditional boundaries and established norms: Or there was that great witch, Kamiri, whose witchery bewildered even the white men at Muranga. His witchery and magic, before he was overcome by the white men with smiles and gifts, had won him resounding fame. He too, it was said, had been born at Kamenno. Like Mugo before him, he had *disappeared* from the hills to the country beyond. He *could not* be contained by the narrow life of the ridges (*The River Between*, p. 18).

The full verb *stop* shows the highest absolute frequency in the novels *Girl, Woman, Other*, *No Longer at Ease*, and *Efuru*, with a relative frequency of 0.0004 (Figure 3).

Since in a postcolonial society people face internal conflicts resulting from the colonial past, Dominique's self-blame can be seen as a metaphor for the broader process where people stop blaming themselves for circumstances caused by external forces or colonial influence: It took years for Dominique to stop beating herself up for staying with Nzinga for as long as she did—nearly three years, three years how could she have been so weak when she'd been so strong, and was again after she left her? grateful to go back to the self she had lost... (*Girl, Woman, Other*, p. 57). *It took years for Dominique to stop beating herself up* indicates a long process of inner struggle and self-recrimination that prevented Dominique from restoring her identity. This emphasises that her journey towards self-discovery and self-acceptance was difficult and prolonged.

Therefore, the verbal negation *stop* in the following text fragment plays a key role in highlighting the conflict between personal desires and social constraints characteristic of a post-colonial society. It emphasises the character's internal struggle for identity and autonomy. The negation *stop* symbolises Obi's desire to halt all external influences and obstacles in order to make his personal choice: The doctor must have said something about him because Clara looked in his direction once and immediately took her eyes away. Obi wanted to rush out of his car and shout: 'Stop. Let's go and get married now,' but he *couldn't* and *didn't*. The doctor's car drove away (*No Longer at Ease*, p. 108). Obi wants to shout *Stop. Let's go and get married now*, which reflects his strong desire to immediately resolve the issue and find personal happiness. However, he cannot do this due to an internal conflict related to his identity and role in society. It should be noted that the verbal negations *couldn't* and *didn't* in this excerpt not only describe the impossibility and absence of actions but also add depth to the understanding of Obi's internal conflict and his struggle with social constraints and expectations in a postcolonial society. They emphasise the complexity of choosing identity and autonomy under the pressure of tradition and modernity.

As a result, in postcolonial artistic discourse the verbal negations *did not*, *was not*, *could not* are significant in revealing the theme of identity. They are essential elements for depicting characters' internal conflicts, their social constraints, and the psychological pressure they experience in postcolonial society. The negations *did not*, *was not* indicate the conscious refusal of characters to act, driven by fear of social reproach or lack of confidence in their abilities. The negations *could not* and *stop* point to the limitations of characters' possibilities due to external or internal factors. Thus, the author-narrator portrays the complexity and diversity of the process of identity restoration through profound social and personal conflicts that arise along the path to self-discovery and self-acceptance in postcolonial society.

The pragmatics of verbal negation emphasises themes of conflict, uncertainty, and the obstacles faced by individual characters and social groups in a post-colonial society, regarding colonial stereotypes, power structures, and cultural norms. At the same time, they reflect hope for change, improvement and integration into new social, political and cultural contexts.

Discussion

The results of the study confirm that verbal negation in colonial and postcolonial novels should not be interpreted only as a grammatical marker of denial. In the analysed literary texts,

negation functions as a complex pragmatic and narrative mechanism through which the themes of identity, resistance, social constraint and psychological conflict are articulated. The quantitative predominance of forms such as *did not*, *was not*, *could not* and the full verb *stop* demonstrates that negation occupies a structurally significant place in the linguistic organisation of postcolonial narrative. At the same time, the pragmatic interpretation of literary fragments shows that these forms acquire specific ideological and identity-related meanings in the context of colonial domination and its consequences.

The frequency of the form *did not* is particularly important because it often marks a refusal to perform an expected action or to submit to an imposed order. In postcolonial literary discourse, such refusal cannot be reduced to a neutral statement of non-action. It may indicate a character's attempt to preserve autonomy, resist external pressure or reject a socially prescribed role. In this sense, *did not* becomes a linguistic form through which the narrative represents the conflict between individual self-determination and collective or colonial expectations. The example from *Efuru*, where the daughter "did not go" with those sent for her, illustrates that negation may signal agency, independence and the emergence of self-awareness under conditions of social and colonial pressure.

The form *was not* performs a related but distinct function. It frequently marks the rejection of an imposed interpretation or the denial of an expected identity position. In postcolonial novels, identity is often constructed through the tension between what a character or community is assumed to be and what they refuse to be. Therefore, *was not* may function as a narrative device for correcting, challenging or destabilising externally imposed meanings. In the fragment from *No Longer at Ease*, the use of *was not* redirects attention from the individual family context to the collective identity of Umuofia. This demonstrates that negation can serve not only as a denial, but also as a means of reorienting the reader towards collective memory, communal belonging and inherited cultural values.

The modal negation *could not* is especially significant for the representation of limitation. Unlike *did not*, which may suggest refusal or conscious non-compliance, *could not* often foregrounds impossibility, constraint or the pressure of circumstances. In postcolonial discourse, such impossibility is rarely purely personal. It is frequently produced by social hierarchy, colonial restriction, inherited trauma or the conflict between traditional norms and new historical conditions. In *The River Between*, the statement that a character "could not be contained by the narrow life of the ridges" reflects both the limitations of the traditional environment and the desire to exceed them. Thus, *could not* articulates the tension between belonging and departure, rootedness and mobility, cultural continuity and the search for new identity.

The full verb *stop* occupies a special place because it expresses interruption, cessation and the desire to terminate a process. In postcolonial novels, this process may be external, such as social control or colonial domination, or internal, such as self-blame, fear, dependency or psychological fragmentation. The example from *Girl, Woman, Other*, where Dominique needs years to "stop beating herself up", demonstrates that negation may participate in the representation of trauma recovery and self-restoration. Here, the verb *stop* does not simply indicate the end of an action; it marks a long and difficult process of regaining selfhood after

emotional and psychological damage. In this case, negation is connected with healing, self-acceptance and the reconstruction of identity.

The analysis also shows that several forms of negation may operate together within a single fragment, intensifying the representation of internal conflict. In the example from *No Longer at Ease*, Obi wants to shout “Stop. Let’s go and get married now,” but “he couldn’t and didn’t”. The combination of *stop*, *couldn’t* and *didn’t* creates a layered pragmatic effect. *Stop* expresses the desire to interrupt the current situation and assert personal will; *couldn’t* indicates the impossibility of acting freely; *didn’t* confirms the absence of realised action. Together, these forms reveal the character’s psychological paralysis under the pressure of social expectations, tradition and modernity. This confirms that verbal negation may convey not only what is absent, but also what remains desired, suppressed or unrealised.

These findings are consistent with pragmatic approaches to negation, according to which negative forms must be interpreted in relation to communicative context, speaker position and sociocultural meaning (Roitman, 2017; Roitman, 2023). In the analysed texts, negation produces meaning through implication, contrast and contextual inference. It does not merely deny propositions, but opens a space for the interpretation of power relations. A negative construction may signal that a character resists an imposed narrative, cannot act because of social constraint, or attempts to interrupt an oppressive psychological process. Therefore, the pragmatic meaning of negation depends on the relationship between linguistic form, narrative context and cultural background.

The results also correspond to discourse-analytic approaches that emphasise the role of context in meaning production (Widdowson, 2004). In postcolonial fiction, the same grammatical form may perform different functions depending on the narrative situation. For example, *did not* may express simple non-occurrence in one context, but in another it may reveal refusal, resistance or identity assertion. Similarly, *could not* may refer to physical impossibility, psychological inability or social prohibition. This confirms the need to analyse verbal negation not only at the level of grammar, but also within the broader textual and ideological environment.

From the perspective of postcolonial literary studies, the findings demonstrate that negation is closely connected with the reconstruction of identity. Colonial discourse historically imposed categories of identity on colonised peoples, often denying the legitimacy of indigenous cultures, languages, histories and social systems. Postcolonial literature responds to this by using language to reject, reinterpret and transform these imposed meanings. Negation becomes one of the linguistic means through which such rejection is articulated. It allows characters and narrators to say not only what they are not, but also what they refuse to become and what they seek to recover.

The connection between negation and identity formation is especially visible in the relationship between individual and collective experience. In some fragments, negation expresses personal refusal or psychological limitation. In others, it points to collective memory, communal identity and resistance to colonial erasure. This duality is important because postcolonial identity is rarely purely individual. It is shaped by family, community, ethnicity, colonial history, language, education and social hierarchy. Therefore, verbal negation in

postcolonial novels often functions at several levels simultaneously: personal, interpersonal, communal and ideological.

The study also demonstrates that negation may be both destructive and constructive. On the one hand, it reveals limitation, absence, impossibility, prohibition and psychological suffering. On the other hand, it may create the conditions for resistance, autonomy and self-definition. This ambivalence is central to postcolonial discourse. Identity formation in colonial and postcolonial societies often begins with refusal: refusal of imposed inferiority, refusal of colonial categories, refusal of silence, and refusal of cultural erasure. However, such refusal is not an end in itself. It becomes a step towards the reconstruction of selfhood, community and cultural continuity.

The quantitative results strengthen this interpretation by showing that negation is not occasional or marginal in the analysed corpus. The high frequency of forms such as *did not*, *was not*, *could not* and *stop* indicates that negative constructions participate systematically in the textual representation of postcolonial experience. Their repetition creates a linguistic pattern of conflict, resistance and limitation. This supports the view that frequency analysis can reveal significant tendencies in literary discourse when it is combined with contextual interpretation. Quantitative data alone cannot explain the meaning of negation, but it helps identify the forms that require closer pragmatic and narrative analysis.

The findings contribute to the theoretical understanding of negation as a socially and culturally embedded phenomenon. Traditional approaches to negation have often focused on its logical, syntactic or semantic properties (Partridge, 1971; Payne, 1985; Rowlett, 1986). These approaches remain important, but the present study shows that in literary discourse negation must also be understood as a pragmatic and ideological strategy. In postcolonial novels, verbal negation reflects not only the structure of language, but also the structure of power. It reveals how characters are positioned within systems of domination and how they attempt to resist or reinterpret those systems.

The study also develops previous quantitative research on negation in colonial and postcolonial English novels (Tatarovska et al., 2023). While quantitative analysis identifies the frequency and distribution of negative forms, the present discussion shows that these forms acquire meaning through their interaction with narrative context. The integration of quantitative and pragmatic methods therefore provides a more complete understanding of how negation functions in literary discourse. This methodological combination is especially productive for postcolonial studies, where linguistic patterns are deeply connected with historical, cultural and ideological processes.

The practical implications of the study are relevant for literary linguistics, discourse analysis and the teaching of postcolonial literature. The findings suggest that verbal negation can be used as an analytical entry point for examining identity conflict, resistance and narrative positioning. In teaching contexts, attention to negation may help students understand how grammar participates in the construction of literary meaning. In research contexts, the proposed approach may be applied to other linguistic categories, such as modality, deixis, evaluation, silence, reported speech or rhetorical questions, in order to reveal their role in postcolonial discourse.

At the same time, several limitations should be acknowledged. First, the study focuses on selected colonial and postcolonial novels and therefore cannot represent the entire diversity of

postcolonial literature. Secondly, the interpretation of negation is context-dependent, and the same form may perform different functions in different literary, cultural or historical settings. Thirdly, the study concentrates mainly on verbal negation, while other forms of negative meaning, such as irony, silence, metaphorical denial, lexical opposition and narrative omission, remain outside the central scope of analysis. Fourthly, the corpus could be expanded in future research to include a larger number of texts from different postcolonial regions and historical periods.

Further research may develop this approach in several directions. One promising direction is a comparative analysis of verbal negation across different postcolonial literary traditions, including African, Caribbean, South Asian and diasporic writing. Another direction is the study of how negation interacts with gender, class, race, ethnicity and collective memory. It would also be productive to examine the relationship between negation and narrative voice, especially in texts where the narrator's position is unstable, hybrid or ideologically contested. In addition, computational corpus methods may be used to analyse larger collections of postcolonial texts and identify broader patterns of negative constructions.

Overall, the discussion confirms that verbal negation in postcolonial novels is a multifaceted phenomenon. It functions as a grammatical structure, a pragmatic act, a discourse mechanism and a narrative strategy. Its significance lies in the fact that it expresses not only denial, but also resistance, limitation, psychological conflict and the search for identity. Through negation, postcolonial literature represents the painful complexity of societies shaped by colonial domination, while also articulating the possibility of autonomy, cultural restoration and self-definition.

Conclusion

The analysis of verbal negation in postcolonial novels has demonstrated its significance as both a linguistic device and a narrative strategy. In the first part of the study, the relevance of negation was established by situating it within the broader discourse of colonial and postcolonial identity. Negation was shown to function not merely as a grammatical category but as a pragmatic tool of resistance, enabling characters and narrators to reject imposed ideologies and reclaim indigenous perspectives.

The second section, devoted to the quantitative analysis, revealed the frequency and distribution of negation forms such as *did not*, *was not*, *could not*, and *stop*. These forms emerged as the most recurrent markers of opposition, reflecting both conscious refusals and structural limitations imposed on characters. Their statistical prominence underscores the centrality of negation in the linguistic representation of identity conflicts.

The third section, focused on pragmatic interpretation, illustrated how negation operates in literary fragments to highlight themes of autonomy, collective memory, and psychological struggle. Examples from novels such as *Efuru*, *The River Between*, *No Longer at Ease*, *Things Fall Apart*, and *Girl, Woman, Other* demonstrated that negation conveys both resistance to colonial power and the search for self-definition. The pragmatic dimension revealed how negation embodies inner conflicts, social constraints, and the tension between tradition and modernity.

The fourth section emphasized the interplay between negation and identity formation, showing that negation is not only a refusal but also a constructive act of self-assertion. By

rejecting colonial narratives, characters articulate new possibilities for identity, autonomy, and cultural continuity. The forms *did not* and *was not* often signal conscious refusals shaped by fear of social judgment, while *could not* and *stop* highlight external and internal limitations, symbolizing the struggle for self-realization.

Interim results across the manuscript confirm that verbal negation functions on multiple levels:

- As a quantitative marker, it reveals recurring linguistic patterns of resistance.
- As a pragmatic strategy, it conveys psychological depth and social tension.
- As a narrative device, it enables authors to critique colonial and neocolonial structures while reclaiming indigenous identity.

The study's overall results demonstrate that verbal negation is a multifaceted phenomenon in postcolonial literature. It simultaneously expresses opposition, limitation, and hope, reflecting the complexity of identity formation in societies marked by colonial domination. Negation emerges as a linguistic embodiment of conflict and uncertainty, but also as a pathway toward autonomy and cultural restoration. By integrating quantitative and pragmatic approaches, the research underscores the central role of negation in shaping postcolonial discourse and highlights its enduring relevance for literary and linguistic studies.

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Conflict of Interest

The author declares that there is no conflict of interest.

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Appendix

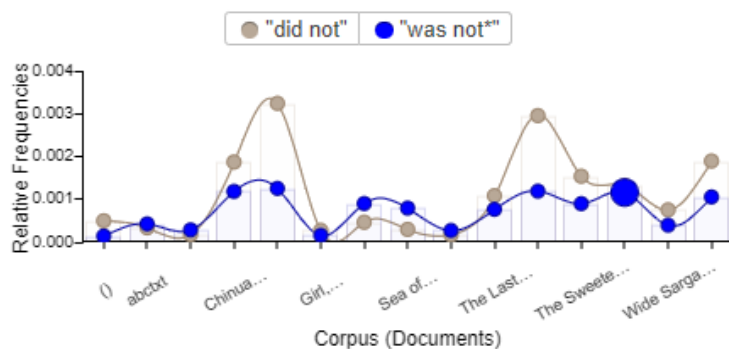


Figure 1. The pragmatics of verbal negation presented in fragments of literary texts

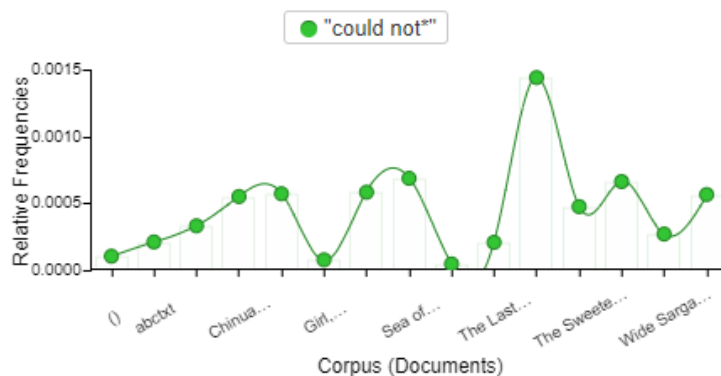


Figure 2. Modal negation could not in the novel The River Between

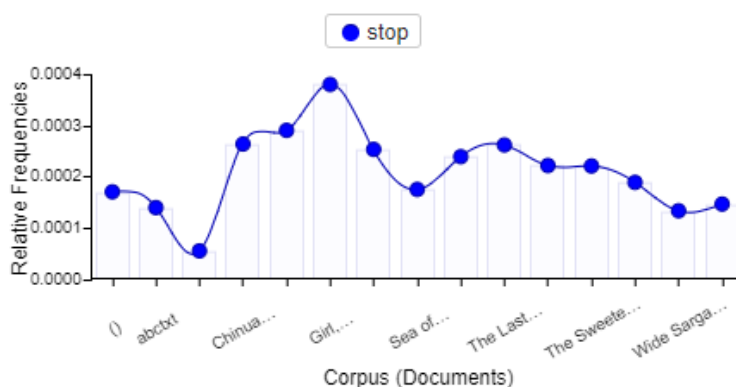


Figure 3. Verb stop in postcolonial novels Girl, Woman, Other, No Longer at Ease, Efuru

Improved Hurst Fractal Dimension Estimation with the Corrective Function Method Application ^[17]

Abstract:

The relevance of this study is determined by the increasing importance of accurate mono-fractal and multi-fractal analysis methods for investigating complex natural and artificial processes. The Hurst fractal dimension is one of the key numerical characteristics used to describe self-affine properties, persistence, anti-persistence and memory effects in physical signals. However, when the rescaled range analysis method, or R/S method, is applied to finite stochastic signals, the accuracy of Hurst fractal dimension estimation may be significantly reduced. The research problem lies in the existence of an undesirable non-linear dependence between the estimated and true values of the Hurst fractal dimension obtained by the R/S method. The scientific novelty of the article consists in constructing and applying a corrective function that compensates for this distortion and improves estimation accuracy. The object of the study is Hurst fractal dimension estimation by means of rescaled range analysis. The aim is to investigate the specific features of this estimation procedure, improve its accuracy using the corrective function method, and test the proposed approach on model stochastic mono-fractal signals and the sunspot number time series. The methodological framework includes the R/S method, the corrective function method, the wavelet transforms modulus maxima method, and multifractal detrended fluctuation analysis. The corrective function was built using stochastic mono-fractal signals based on the modified cosine Weierstrass–Mandelbrot function. The empirical part of the study uses daily total sunspot numbers from 1 January 1818 to 31 July 2024. The theoretical basis includes works on fractal geometry, chaos theory, multifractals, Hurst analysis, wavelet analysis and solar activity by B. Mandelbrot, K. Falconer, J. Feder, H. Hurst, S. Mallat, J. Kantelhardt and co-authors, L. Chernogor, O. Lazorenko, A. Onishchenko and other researchers. The results demonstrate that the R/S method produces systematic non-linear distortions: depending on signal length, Hurst fractal dimension estimates may be overestimated in one range and underestimated in another. The corrective function method reduces this distortion by inverting the empirically obtained dependence between estimated and true fractal dimensions. Its application to the sunspot number time series reveals several scale ranges with mono-fractal properties, confirms the multifractal and non-stationary character of the process, and supports its interpretation as a second-order fractal process. The study concludes that the corrective function method is an effective tool for improving the reliability of Hurst fractal dimension estimation when using the R/S method. The proposed approach may be useful for analysing finite stochastic signals and complex natural processes, including solar activity, geospace phenomena and non-linear dynamical systems.

Keywords: signal processing, mono-fractal analysis, corrective function, rescaled range analysis, Hurst fractal dimension, sunspot numbers time series.

Abbreviations:

CWT is Continuous Wavelet Transform,

FGN is Fractional Gaussian Noise,

GBM is Generalized Brownian Motion,

LRD is Long-Range Dependence,

MFDFA is Multi-Fractal Detrended Fluctuation Analysis,

SDF is Spectral Density Function,

SRD is Short-Range Dependence,

WTMM is Wavelet Transform Module Maxima.

Introduction

The term *fractal*, derived from the Latin *fractus*, meaning “broken”, was introduced into scientific circulation by the American physicist and mathematician Benoit Mandelbrot. After several decades of intensive scientific discussion involving both supporters and opponents of the new approach, fractal ideas became firmly established in modern science and acquired the status of an important methodological basis for the analysis of complex natural and artificial processes (Mandelbrot, 1982; Falconer, 1990; Feder, 1988; Feldman, 2012; Mandelbrot, 2005; Schroeder, 1991).

According to the so-called fractal paradigm proposed by V. V. Yanovsky, fractality, like nonlinearity before it, may be regarded as one of the fundamental properties of the world around us (Yanovsky, 2003, 2006). In the nonlinear and system paradigms formulated by L. F. Chernogor, open, complex, nonlinear and dynamical systems are considered as systems in which many natural and artificial processes, especially those caused by powerful non-stationary sources of energy release, may be classified as short-time, ultra-wideband, nonlinear and fractal processes (Chernogor, 2008). Thus, fractality is not an abstract mathematical construction only; it is increasingly interpreted as a universal property of physical reality and as an effective tool for describing complex processes in nature and technology.

To discover, investigate, describe and explain the fractal properties of natural and artificial processes, various methods of mono-fractal and multi-fractal analysis are required. These methods provide a set of numerical characteristics that make it possible to reflect the main peculiarities of the signals and processes under investigation (Lazorenko & Chernogor, 2023). Such characteristics have become especially important in applied physics, radio physics, geophysics, solar-terrestrial physics, signal processing, engineering and other fields where researchers deal with nonlinear, non-stationary and scale-dependent phenomena.

A fractal dimension is one of the most important numerical characteristics used in fractal analysis. In general, many different fractal dimensions can be estimated for mathematical and physical, or natural, fractal signals and processes. Each of them has its own calculation procedure and its appropriate field of application (Lazorenko & Chernogor, 2020; Lazorenko & Chernogor, 2023). In this paper, attention is focused on one such characteristic, namely the Hurst fractal dimension (D), and on one of the oldest and most widely used methods for its estimation, the rescaled range analysis method, which is often referred to as the R/S method.

The relevance of the study is determined by the fact that the R/S method remains one of the classical and reliable tools of mono-fractal analysis and is widely applied in different branches of modern science and technology. At the same time, the accuracy of estimating the Hurst fractal dimension by this method is of fundamental importance, since the obtained numerical value directly affects the interpretation of fractal properties, persistence, anti-persistence and memory effects in the analysed process. Therefore, any systematic distortion in the estimation of the Hurst fractal dimension may lead to incorrect conclusions about the physical nature of the signal.

The research problem addressed in this paper is connected with the existence of an undesirable nonlinear dependence between the estimated value of the Hurst fractal dimension and its true value when the R/S method is applied. In an ideal case, the estimated value should coincide with the true one and should not depend on the finite length of the signal. In practice, however, the estimation obtained by a mono-fractal analysis method may be distorted by a

nonlinear function depending on both the true fractal dimension and the number of signal points. This circumstance worsens the accuracy of Hurst fractal dimension estimation and becomes a negative factor for mono-fractal analysis as a whole.

The working hypothesis of the study is that the accuracy of Hurst fractal dimension estimation by the R/S method can be improved if the nonlinear dependence between the estimated and true values is determined on the basis of specially generated model stochastic mono-fractal signals and then compensated by means of a corrective function. In this case, the corrective function method may reduce systematic estimation errors and make the R/S method more reliable for the analysis of finite physical signals.

The scientific novelty of the paper lies in the construction and application of a corrective function for improving the estimation accuracy of the Hurst fractal dimension obtained by the R/S method. The corrective function is built on the basis of a specially created set of model stochastic mono-fractal signals with known and controlled values of the fractal dimension and signal length. This makes it possible to analyse the nonlinear dependence between the estimated and true fractal dimension values and to compensate for its influence. In addition, the proposed approach is tested not only on model signals, but also on a real natural physical process represented by the sunspot number time series.

The object of the investigation is the calculation of the Hurst fractal dimension using the R/S method.

The subject of the investigation is the improvement of the accuracy of Hurst fractal dimension estimation when the R/S method is applied to finite stochastic and natural physical signals.

The study aims to investigate the peculiarities of Hurst fractal dimension estimation by the R/S method, to improve the accuracy of this estimation through the corrective function method, and to analyse the corresponding practical results obtained for the sunspot number time series as a well-known fractal natural process.

To achieve this aim, the following research tasks are set:

- to consider the theoretical basis of the R/S method and its role in estimating the Hurst fractal dimension;
- to analyse the relationship between the Hurst exponent and the Hurst fractal dimension within the framework of the generalized Brownian motion model;
- to demonstrate the existence of nonlinear dependence between the estimated and true values of the Hurst fractal dimension when the R/S method is applied;
- to construct a corrective function using model stochastic mono-fractal signals with controlled parameters;
- to assess the effectiveness of the corrective function method for increasing estimation accuracy;
- to apply the R/S method and the corrective function method to the sunspot number time series;
- to compare mono-fractal results with multi-fractal characteristics obtained by the wavelet transform modulus maxima method and multifractal detrended fluctuation analysis;

- to evaluate the possibility of interpreting the sunspot number time series as a non-stationary, multi-fractal and second-order fractal process.

The methodological basis of the paper includes the R/S method, the corrective function method, the wavelet transform modulus maxima method, and multifractal detrended fluctuation analysis. The R/S method is used both for constructing the corrective function and for analysing the sunspot number time series. The corrective function method, proposed as a special method for improving mono-fractal analysis accuracy, is used to compensate for nonlinear distortions in Hurst fractal dimension estimation (*Lazorenko et al., 2022*). The wavelet transform modulus maxima method and multifractal detrended fluctuation analysis are used to investigate the multi-fractal properties and non-stationarity of the analysed natural process (*Mallat, 1998; Kantelhardt et al., 2002; Chernogor et al., 2025*).

The theoretical significance of the study consists in further developing the methodological foundations of mono-fractal analysis and clarifying the limitations of the R/S method when it is applied to finite stochastic signals. The paper contributes to the understanding of how nonlinear estimation distortions arise and how they may be corrected by means of a specially constructed corrective function. It also contributes to the broader theory of fractal and multi-fractal analysis by linking mono-fractal Hurst dimension estimation with the study of non-stationary multi-fractal characteristics.

The practical significance of the results lies in the possibility of applying the corrective function method to improve the reliability of Hurst fractal dimension estimation in real physical, geophysical, solar-terrestrial and engineering signals. The proposed approach is particularly useful in cases where the numerical value of the fractal dimension has practical interpretative significance. The analysis of the sunspot number time series demonstrates that the method can be used for natural processes with complex scale-dependent behaviour, including those characterised by non-stationarity, multi-fractality and long-range dependence.

Thus, the present study is aimed at improving the accuracy and reliability of one of the classical methods of mono-fractal analysis. By combining the R/S method with the corrective function method and comparing the obtained results with multi-fractal analysis, the paper offers a methodological contribution to the investigation of complex natural processes and provides a practical example based on solar activity data.

Methods

R/S Method and Hurst Fractal Dimension

Well known, that many signals and processes in nature having as natural, as artificial origin have fractal properties and, therefore, can be classified as the physical (or natural) fractals. It is important to note, that in the most cases, such properties of the physical fractals exist in statistical sense only. In these conditions, it is reasonable to assume that these fractals must be described by some numerical characteristics having a statistical origin too.

Being well-known statistical characteristics, the Hurst exponent H been introduced by H. E. Hurst in 1951 (24 years before the fractals!) in the paper (*Hurst, 1951*) is simultaneously appeared to be the oldest statistical numerical characteristic from ones, which are used usually for fractals describing. In bounds of the so-called GBM Model proposed by B. Mandelbrot

(Mandelbrot, 1982; Feder, 1988), the Hurst exponent H and fractal dimension D known as the Hurst fractal dimension are connected with the simple relation $D = 2 - H$.

It is important to point that in general case this relation is appeared to be incorrect (Lazorenko & Chernogor, 2020; Lazorenko & Chernogor, 2023). For example, for two-parametric fractal signal models, there is no dependence between the Hurst exponent H and the Hurst fractal dimension D at all. To explain this, seems, strange fact, it is necessary to consider the physical senses of these numerical characteristics (Lazorenko & Chernogor, 2020; Lazorenko & Chernogor, 2023). Having good localization in time domain, the Hurst fractal dimension D describes an existence of so-called SRD for a signal investigated. On contrary of this, for own correct estimation, the Hurst exponent H needs as long a signal as possible. As a result, its localization property is appeared to be poor, and the Hurst exponent H describes an existence of so-called LRD for a signal researched. Thus, there are the one-parametric fractal signal models, for which the SRD and the LRD are occurred to be the same (e.g., the GBM model, the FGN) model (Lazorenko & Chernogor, 2023). However, at the same time, for two-parametric fractal signal models, the SRD and the LRD are occurred to be different and independent (e.g., the Levi flight model, the Ornstein–Uhlenbek process model (FGN) model [16]). In this paper, we assume that all signals investigated exist in bounds of the GBM model and, therefore, the relation $D = 2 - H$ is assumed to be correct.

At present days, there are many different ways to estimate the Hurst exponent of a signal., The oldest and frequently the most reliable way to do this (Feder, 1988) is the Rescaled Range Analysis Method or simply the R/S method proposed by H. E. Hurst in 1965 (in the ‘pre-fractal’ era) (Hurst et al., 1965).

According to the new fractal analysis method classification introduced in 2023 (Chernogor et al., 2023), the R/S method having the statistical origin is appeared to be a member of the group of methods based on the statistical characteristics.

Let’s consider the main idea of the R/S method. For a discrete signal s_i containing N points (the counter i varies in the bounds $i = \overline{1, N}$), its partial sums

$$y(n) = \sum_{i=1}^n s_i, \quad n \in \overline{1, N},$$

the dispersion (the square of the standard deviations $S(n)$) given by the relation

$$S^2(n) = \frac{1}{n} \sum_{i=1}^n s_i^2 - \frac{1}{n} y(n)^2, \quad n \in \overline{1, N}$$

and so-called ‘range’ $R(n)$ should be estimated. The range $R(n)$ of a signal s_i is given by the relation:

$$R(n) = \max_{0 \leq t \leq n} \left(y(t) - \frac{t}{n} y(n) \right) - \min_{0 \leq t \leq n} \left(y(t) - \frac{t}{n} y(n) \right).$$

Grounding on the values obtained, the so-called R/S statistics is built:

$$\frac{R}{S}(n) \in \frac{R(n)}{S(n)} = \frac{1}{S(n)} \left(\max_{0 \leq t \leq n} \left(y(t) - \frac{t}{n} y(n) \right) - \min_{0 \leq t \leq n} \left(y(t) - \frac{t}{n} y(n) \right) \right), \quad n \in \overline{1, N}.$$

In 1951 (*Hurst, 1951*), basing on the results of his own empirical investigations, H. E. Hurst found that the mathematical expectation of the R/S statistics has a power-law relationship with the size of the observation window length n as:

$$E[R / S(n)] \approx C n^H, \quad (1)$$

where C is some limited, positive constant, which doesn't depend on n , H is the Hurst exponent, $E[]$ is the operation of a mathematical expectation calculation.

Thus, changing the window length n , the dependence of the logarithms of $E[R / S(n)]$ vs. the logarithms of n can be obtained. The corresponding plot of this dependence should be built namely on the log-log plain. It is important to point, that if a signal s_i investigated has really the self-affine (and, therefore, fractal) properties, the experimental points should be grouped around some straight line. The Hurst exponent H is occurred to be equal to the angle coefficient of this straight line and can be simply estimated with usage of the least square method. On contrary, if that points were appeared to be not somehow grouped around any straight line, it can be claimed, that a signal investigated as whole hasn't a self-affine property and, therefore, cannot be considered a fractal one. Thus, for whole signal in such case, the Hurst exponent H cannot be estimated.

On the same time, in most practical cases, a signal researched is appeared to be fractal in some limited scale range only, not in all existing one. In such case, only some part of the pointes placed on the double logarithmic coordinates (on the log-log plain) in some scale range only can be successfully approximated with a straight line discussed above. Namely this straight line allows estimating the Hurst exponent H value for such limited scale range, and, therefore, one can speak about the fractal properties of the signal or process researched in this limited scale range. By the way, sometimes, two or even more such limited scales ranges are occurred to be exist on the same plot (*Feder, 1988*). Such signals are classified as the multi-fractals (the bi-fractals etc.), not the mono-fractals (*Lazorenko & Chernogor, 2023*).

Now some words about the valid values of the Hurst exponent are needed. As it had been discovered by B. Mandelbrot (*Mandelbrot, 1982; Feder, 1988*), for fractals, the Hurst exponent value H should be limited in the range $0 < H < 1$. Otherwise, a signal researched is occurred to be not self-affine and, therefore, is not fractal (*Feder, 1988*) even in the case, when the experimental points on the log-log plain have been excellently approximated by a straight line. Only if the condition $0 < H < 1$ has successfully satisfied, then one can speak about existence of some mono-fractal properties in the given scale range for the signal investigated.

Moreover, the Hurst exponent values are directly connected with so-called 'memory' effect for the signals researched. It is well known (*Mandelbrot, 1982; Falconer, 1990; Feder, 1988*), that if $0.5 < H < 1$, then a fractal signal has the property of the persistence, if $0 < H < 0.5$, then it has the property of the anti-persistence, if $H = 0.5$, then the 'memory' effect is occurred to absent and, thus, any tendency in the signal behavior is not saved. Namely the existence of this 'memory' effect leads to the LRD appearance described above.

It is important to note, that one can to apply the R/S method for investigations as in the time domain, as in the space one. In the second case, it is necessary simply to replace formally a time variable with a space one.

The last peculiarity of the R/S method application in this paper deals with an absence of any time resolution for the Hurst exponent, since it is estimated for the entire signal. Nevertheless, in many cases, the real processes in the nature, especially being in open, non-linear, dynamical systems (*Chernogor, 2008*), are occurred to be significantly non-stationary. Therefore, their fractal properties can significantly vary with time too. A solution of this problem is simple: the Hurst exponent H should be estimated with usage of some well localized (or even finite), window $W(t)$ sliding in the time domain. In such case, the Hurst exponent value will be estimated for some defined part of the signal investigated, but not for entire signal at once. Therefore, the Hurst exponent becomes a function of the time $H = H(t)$. No doubt, the minimum of the possible window width is defined by the statistical requirements to the sample length. It is necessary to point, that, on our opinion, it is convenient to associate each Hurst exponent value calculated with usage of the sliding window $W(t)$ in time domain with corresponding given time location of the window center.

In this paper, the R/S method are used as for the Corrective Function building, as for the sunspot numbers time series analyzing.

Corrective Function Method

In 2022 in the paper (*Lazorenko et al., 2022*) by L. F. Chernogor, O. V. Lazorenko and A. A. Onishchenko, so-called ‘Corrective Function Method’ (CF method) as a special method of the mono-fractal analysis has been proposed. The main idea of this universal method is in following.

Let’s consider any mono-fractal analysis method, in which there is an estimation D^* of unknown fractal dimension D for a signal researched. This discrete signal s_i contains N points ($i = \overline{1, N}$). In general, the estimation D^* is an unknown non-linear function of D and N , $D^* = f(D, N)$. In an ideal case, which doesn’t exist on practice at all, this function should be linear and very simple, $D^* = D$, and should not be a function on N . Therefore, the estimation D^* obtained with using of the given mono-fractal analysis method, is occurred to be significantly distorted namely by this non-linear function $D^* = f(D, N)$. Understanding the reasons explained here, the idea of the CF method is appeared to be quite simple and clear.

The CF method purpose is neutralizing the influence of the function $D^* = f(D, N)$ non-linearity in some way and increasing an accuracy of the fractal dimension D estimation obtained with given mono-fractal analysis method. To do this, in the paper (*Lazorenko et al., 2022*), it was proposed an idea to inverse the non-linear function $D^* = f(D, N)$ on the base of the so-called ‘Corrective Function’ (CF). Using some test signal set, this CF should be constructed on the discrete grid over the (D, N) plain separately for each given mono-fractal analysis method. The test signal set should be based on the model fractal signals with known and controlled values of the variables D and N . The model fractal signals can be as deterministic and stochastic too. The steps of changing for D and N variables can be chosen in any reasonable way. Surely, the smaller, the better, but the time of the CF calculation matters significantly too.

Thus, when the CF on the discrete grid, $D_{ij}^* = f(D_i, N_j)$, $i = \overline{1, n}$, $j = \overline{1, m}$, has been ready, the inversion of the non-linear function $D^* = f(D, N)$ relatively first variable D should be started. Fixing N variable on the value $N = N_{sig}$, where N_{sig} is the length of the data vector containing the signal analyzed, we obtain the function $D^* = f(D, N_{sig})$ being a function of only one variable D on the interval $1 \leq D < 2$. Well known, that an inverse function $D = f^{-1}(D^*, N_{sig})$ can exist on some interval only in the case, when the direct function $D^* = f(D, N_{sig})$ is monotonic there. Moreover, in our case, the function $D^* = f(D, N_{sig})$ should be a rising function of D on the interval $1 \leq D < 2$.

Now let's return to the N_{sig} value. As a rule, for comparatively big values of N_{sig} , there are no problems with monotonicity of the function $D^* = f(D, N_{sig})$. But when N_{sig} value decreases, the N_{min} value, below of which ($N_{sig} < N_{min}$) the monotonicity of the function $D^* = f(D, N_{sig})$ is occurred to be disrupted, appears. As well as all detailed explanations of this process appearance causes and the bulky relations for the fractal dimension D and its estimation error ΔD are closely considered in the paper ([Lazorenko et al., 2022](#)), which, if needed, can be successfully downloaded for free, we avoid to repeat them here. Nevertheless, on our opinion, the algorithm of determination of the N_{sig} value is appeared to be very useful, since it allows to prepare a well-founded and reasonable answer on the question of what exactly is the minimum number of signal points N_{min} and why should be used in the given method of mono-fractal analysis. Before the appearance of the paper ([Lazorenko et al., 2022](#)), there was no such answer. For example, many years ago, in the book ([Feder, 1988](#)), the world famous fractalist J. Feder had claimed that for the R/S method, N_{min} value should be equal at least 2500. But in the paper ([Lazorenko et al., 2022](#)), the value N_{min} was shown to be principally much smaller ($N_{min} = 32$) due to the reasons described above. Nevertheless, it is necessary to point, that if N_{sig} value decreases, the error of the Hurst fractal dimension estimation ΔD , surely, rises.

In this paper, the CF method are used as for the Corrective Function building, as for the sunspot numbers time series analyzing.

Wavelet Transform Modulus Maxima Method

The WTMM method is based on the Continuous Wavelet Transform ([Mallat, 1998](#)). Being the basic informational characteristics of the multi-fractal analysis, the multi-fractal spectrum function $f(a)$ of the signal investigated is connected with the CWT SDF of the signal. The a value is known as the Holder exponent.

Suddenly, WTMM method has one significant disadvantage. It doesn't allow to consider the non-stationarity of the signal investigated as well as in this method the signal is investigated at once. At the same time, it is reasonable to predict that all multi-fractal characteristics of a non-

stationary signal can significantly vary with time. Thus, it is necessary to apply another method, which is free from this disadvantage.

Multi-Fractal Detrended Fluctuation Analysis Method

The MFDFA method is appeared to be convenient to the non-stationary signal investigations in sliding time window (*Kantelhardt et al., 2002*).

The basic idea of the MFDFA method is following. Basing on the signal multi-fractal spectrum $F(a)$ analysis (the multi-fractal spectrum of the whole signal was denoted above as $f(a)$) and the sliding time window $W(t)$ application, the time dependences of location (minimal $a_{\min}(t)$ and maximal $a_{\max}(t)$ values of a) and of width ($Da(t)$, $Da = a_{\max} - a_{\min}$) of the multi-fractal spectrum can be obtained. Special attention should be paid to the location a^* of the multi-fractal spectrum maximum, given by the requirement $F(a^*) = \max_a F(a)$. The a^* value is called as the generalized Hurst exponent as well as for mono-fractal signal we have $Da = 0$ and $a^* = H$. The generalized Hurst exponent a^* describes a multi-fractal support of the signal analyzed. Its fractal dimension is given by relation $D_a = 2 - a^*$.

In this paper, the WTMM method is used for investigation of the multi-fractal properties of the entire signal and the MFDFA method is applied to discover the non-stationarity of the multi-fractal properties of the signal and to compare these results with ones obtained with R/S method used with a sliding window in time domain. Namely such approach to the mono-fractal and multi-fractal analysis of a signal has been successfully used by the authors of this paper, for example, in (*Chernogor et al., 2025*).

Literature Review

The time series of sunspot numbers (well known as the ‘Wolf numbers’ too), which characterizes solar activity and is associated with the counting of sunspots, is unique in the sense that observations have been conducted since 1610, although complete and reliable data have only been available since 1849 (*Vitinskii, 1965*). It is well known that it has a pronounced 11-year cycle, superimposed perhaps on another slower component with a period of about a hundred years (*Frame & Urry, 2016*). However, this information was obtained in the “pre-fractal” era. Surprisingly, the first fractal analysis of the time series of Wolf numbers was performed by B. Mandelbrot and J. Wallis in 1969 in the work (*Mandelbrot & Wallis, 1969*), i.e. six years before the appearance of the concept of “fractal”. Been translated into current terminology, it turned out that in the ranges of periods from 3 to 30 months and from 30 to 100 years, the fractal dimension is $D \gg 1.1$. These results were obtained using the R/S method. In a number of later works quite similar results were obtained using other methods of fractal analysis, in particular, $D \gg 1.2$ in (*Ruzmaikin et al., 1994*), $D \gg 1.0 - 1.2$ in (*Ogurtsov, 2004*) and $D \gg 1.2 - 1.3$ in (*Rypdal & Rypdal, 2012*).

Thus, it has been established that the time series of sunspot numbers is a fractal process, well described by the model of generalized Brownian motion. The fractal dimension D of this

process is in the range $D \gg 1.1 - 1.3$. Consequently, the series of sunspot numbers has the property of persistence.

Since 2006 (*Movahed et al., 2006*), regular studies of the multifractal properties of the Wolf number series have been conducted. It has been established that the sinusoidal trend has a significant negative impact on the estimates obtained. After its removal, it turned out that the fractal dimension of the series as a whole is $D = 1.88 \pm 0.01$ (*Movahed et al., 2006*). And this value differs significantly from that given by mono-fractal analysis methods. The explanation for this is simple: it is necessary to compare either the results obtained without a trend or with a trend. And this, unfortunately, was not done in (*Movahed et al., 2006*). Moreover, in 2009, in the work (*Hu et al., 2009*), a different mechanism for removing the sinusoidal trend was proposed, and the value for the fractal dimension turned out to be different: $D \gg 1.26$, which is quite consistent with the results presented above. Let us add that one of the first attempts to study the multifractal properties of the sunspot number series was made in 2005 in the work (*Lazorenko et al., 2005*). The refinement of individual aspects of the multifractal properties of the sunspot number series continues to this day (*Wu et al., 2015*).

Results

Corrective Function Built with Stochastic Mono-Fractal Signals Usage

Let's consider the non-linear function $D^* = f(D, N)$, which can be created for the R/S method on a test signal set. In this paper, the test signal set is based on the model stochastic mono-fractal signals. Such model choice is explained by the next reason. As a rule, the signals and the processes analyzed with the R/S method application are occurred to be fractal in statistical sense only (not in geometrical or algebraical ones). Therefore, it is reasonable, if the test signals are stochastic too, not deterministic. By the way, in the paper (*Lazorenko et al., 2022*), the test signals sets based on the model deterministic fractal signals were successfully used.

All model stochastic mono-fractal signals used in this paper are based on the modified cosine Weierstrass – Mandelbrot function (*Bandt et al., 2024*):

$$MW_D(t) = \sum_{n=0}^{\Gamma} l^{(D-2)n} \cos(l^n t + j_n),$$

where l is a numerical parameter ($l > 1$), D is a fractal dimension ($1 \leq D \leq 2$), j_n are the stochastic phases having some chosen distribution law at the interval $[0, 2\pi]$, t is dimensionless time variable. At the (*Figure 1*), there are two examples of such model signal realizations with different fractal dimension D values. It is worth pointing that for the model signals we used the stochastic phases j_n with normal (Gaussian) distribution law and a discrete grid over the (D, N) plain, where D value was changed in bounds $1 \leq D \leq 2$, with the step 0.001, and N value was given by the relation $N = 2^k$, $k \in \Gamma$, Γ is the natural numbers set. Comparing with the paper (*Lazorenko et al., 2024*), in present case the step of D value changes was decreased ten times. Surely, this had requested much more time for calculations. Nevertheless, it was found that for most practical purposes, the step being equal to 0.01 is appeared to be quite sufficient and its decreasing seems to be no needed.

Due to the model fractal signals are stochastic, for the CF building, it is necessary to use many different realizations with the same combinations of D and N values with consequent averaging of the results obtained. In each case, the averaging has been provided over 300 different stochastic realizations of the model signals. For each combination of D and N values, as the estimation of the Hurst fractal dimension value D^* , as its error DD^* are calculated. In all calculations, the confidence level was assumed to be equal to 0.9.

At the (Figure 2), a comparison ‘ideal’ function $D^* = D$ (1) vs the non-linear function $D^* = f(D, N)$ having fixed N values: $N = 32$ (2), $N = 128$ (3), $N = 512$ (4) and $N = 2048$ (5) are shown. Discussed above non-linearity of this function is clearly shown. Three interesting tendencies in the $D^* = f(D, N)$ function behavior discovered in the paper (Lazorenko et al., 2024) have been successfully confirmed for the smaller step of the D value changes. First, for fixed D value, the difference between D^* and D decreases with N value raising. Second, the maximal error of the D^* value estimation doesn’t exceed approximately 3%. Third, the non-linearity of the $D^* = f(D, N)$ function leads to the following. Depending on the N value, there is some bound value D_0 , for which at the interval $1.0 \leq D \leq D_0$, the Hurst fractal dimension estimations D^* have the tendency to be overestimated, but at the interval $D_0 \leq D \leq 2.0$ – on the contrary, to be underestimated. So, for $N = 32 - 2048$, the D_0 value is found to be slightly increasing in bounds $1.3 < D_0 < 1.4$ with N value rising.

The small gray rectangle on the (Figure 2) is corresponding to some well-known ‘strange’ results obtained by H. E. Hurst with the R/S method application in the ‘pre-fractal’ era yet. He found (Feder, 1988; Hurst et al., 1965) that the Hurst exponent H is more or less symmetrically distributed about a mean of 0.73, with a standard deviation of about 0.09. In this case, the Hurst fractal dimension D has a mean of 1.27 and the same standard deviation, $D = 1.27 \pm 0.09$. In the paper (Lazorenko et al., 2024), a possible explanation of this fact has been proposed. As well as this paper is download free, we shall not retell its contents and should be limited only by main idea of this explanation listed below in ‘Discussion’. It is necessary to note that the results obtained in this paper has well agreed with this idea.

Thus, for any researches provided with the R/S method usage the CF method application is strictly recommended.

Mono-Fractal and Multi-Fractal Analysis of the Sunspot Numbers Time Series

To demonstrate the results of simultaneously application of the R/S method and the CF method for investigations of a real natural physical process, the sunspot numbers time series analysis is considered.

For present analysis, the daily total sunspot numbers from 1/1/1818 till 31/07/2024 were chosen (SILSO World Data Center, n.d.). Of course, as well as all useful information about fractal structure of a signal is consisted in high-frequency part of Fourier spectrum, any averaging is not preferable. But the low-frequency part impact on the Hurst dimension estimations can be

successfully reduced by differentiation operation usage. Namely this approach is used in our investigations.

As it had been found by B. Mandelbrot (*Mandelbrot & Wallis, 1969*), the sunspot time series in whole is not mono-fractal. However, there are some ranges of periods, where mono-fractal properties can be discovered. From the (*Figure 3*), where the dependence of $\log(R / S)$ vs $\log n$ given by the relation (1) is shown, such ranges and corresponding values of Hurst fractal dimension D are defined. It was found that in the ranges of periods from 7 to 70 days ($n = 1.95 - 4.25$) $D = 1.66 \pm 0.01$, from 3 to 30 months ($n = 4.50 - 6.80$) $D = 1.91 \pm 0.01$, from 30 to 90 months ($n = 6.80 - 7.90$) and from 30 to 200 years ($n = 9.29 - 11.20$) $D = 1.58 \pm 0.01$. In other ranges, where given dependence cannot be successfully approximated by a straight line, the sunspot time series is appeared to be not fractal. If for straight line approximation building, one uses all points shown at the (*Figure 3*), some averaged Hurst fractal dimension D value, which is able to characterize the whole signal investigated. This value is found to be $D = 1.78 \pm 0.01$.

At the same time, it well known (*Mandelbrot, 1999; Harte, 2001*), that a fractal, which has mono-fractal properties at least in two different ranges of periods, is appeared to be a multi-fractal. Therefore, it is worth investigating with application of special multi-fractal methods. The most popular from them are the WTMM method and the Multi-Fractal Detrended Fluctuation Analysis described above in this paper. First of them is suitable for investigations of multi-fractal properties of whole signal and second of them—for estimations of multi-fractal characteristics in sliding window in time domain.

In bounds of the WTMM method, it was found that the multi-fractal characteristics of the whole sunspot time series are following: $a_{\min} = -0.02$, $a_{\max} = 2.21$, $Da = a_{\max} - a_{\min} = 2.23$, $a^* = 0.28$ $\alpha^* = 0.28$. The corresponding multi-fractal spectrum is shown at the *Figure 4*. A good agreement between the obtained values of the Hurst fractal dimension $D \gg 1.78$ and the fractal dimension $D_a = 2 - a^* \gg 1.72$ is found. Moreover, it is suitable to suppose that both the properties mono-fractal and multi-fractal can be non-stationary in sense of their numerical characteristics should be been estimated in sliding window in time domain. This is fully realized as with R/S method for $H(t)$ (*Figure 5f*), as with MF DFA for $a_{\min}(t)$, $a_{\max}(t)$, $Da(t)$ and $a^*(t)$ (*Figure 5b–e*). Here the horizontal straight lines denote the corresponding values obtained for the whole signal with WTMM method. It is necessary to point that all these time functions were smoothed with the window, which had the width been equal to 1/20 of all function length in time domain. There is a good agreement between time variations of $H(t)$ (*Figure 5f*) and $a^*(t)$ (*Figure 5e*). All calculations were performed with usage of time domain window with width $T_w = 11$ years, which corresponds with well-known period existing in time-frequency structure of the sunspot number series (*Figure 5g*). On the (*Figure 5g*), the existence of the tree-like structure confirms well the presents of fractal properties for the sunspot numbers series.

In 2023 in the article (*Chernogor et al., 2023*), the concept of the so-called ‘second-order fractals’ has been introduced. By the definition, second-order fractal is a fractal, fractal dimension of

which is appeared to be a fractal function of time or space variable. A fractal signal with such property is called as second-order fractal signal. If the functions $H(t)$ and $a^*(t)$ are considered without smoothing (instead of that was done at the Figure 5), they were found to be namely a second-order fractal signals and, therefore, the sunspot time series was occurred to be a second-order fractal process too. The Hurst fractal dimensions of the functions $H(t)$ and $a^*(t)$ are $D = 1.68 \pm 0.01$ and $D = 1.53 \pm 0.01$ correspondently.

Discussion

With each new day, the methods of mono-fractal and multi-fractal analysis are occurred to be in demand more and more in different branches of the science, the engineering and the technologies. The fractal numerical characteristics, which produced by different analysis methods, have not a pure theoretical value only, but become a huge practical significance. At the same time, there are no ‘ideal’ estimators for these numerical characteristics. Each analysis method has a personal own set of as advantages, as disadvantages. Therefore, the problem of increasing the accuracy of the fractal numerical characteristics estimations is appeared to be valuable and important.

One of the possible ways this problem solving is the CF method application for any mono-fractal and multi-fractal analysis method. In this paper, this was successful performed on the example of the R/S method being one of the oldest mono-fractal analysis methods.

Surely, the CF method has some disadvantages too. First, at the time, there is no clear recommendation regarding test model sets. Each researcher can create his own fractal models as deterministic, as stochastic. And the CF created with this test signal set will be depend from this set. Second, the process of the CF building requires as many time, as big computing power. May be, in future, it would be advisable to combine the efforts of all researchers and, e.g., to create a corresponding library in the Internet.

It is surprisingly, but CF method appearance has caused, at least, one unexpected result. In the article ([Lazorenko et al., 2024](#)), a hypothesis trying to explain well-known ‘strange’ results obtained by H. E. Hurst with the R/S method application in the ‘pre-fractal’ era has occurred. On opinion of the authors of the article ([Lazorenko et al., 2024](#)), an existence of the significant shift for the Hurst fractal dimension D^* estimations observed for persistent natural physical processes can be explained rather by special features of the R/S method applied for processing of the experimental data, than by own really existing properties of these processes. Of course. This is a hypothesis only, but, at least, it tries to find an answer on the question being unanswered at all many times.

Conclusions

1. The R/S analysis method is the oldest and the most popular way to estimate a Hurst exponent for any signal or process. In bounds of the GBM model, the Hurst fractal dimension D and the Hurst exponent H are connected with a simple relation $D = 2 - H$
2. Grounding on the results of numerical modelling with simultaneous usage of the CF method and the set of model stochastic mono-fractal signals based on the modified cosine Weierstrass – Mandelbrot function, for R/S method, it was found that the dependence

between a fractal dimension value D^* estimation and a true own fractal dimension value D is appeared to be principally non-linear.

3. The main peculiarities of the R/S method as the most popular estimator of Hurst fractal dimension were investigated. The corresponding corrective function was built. At the example of the mono-fractal analysis of the sunspot time series, the possibilities of the simultaneous application of the R/S method and CF method are shown.
4. The results obtained with mono-fractal analysis were compared with the results of multi-fractal analysis as for whole signal (WTMM method), as in sliding time-domain window (MFDFA method). The set of mono-fractal and multi-fractal characteristics values for the sunspot time series were successfully specified and corrected.
5. The sunspot time series was found to be second-order fractal process.

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Conflict of Interest

The authors declare that there is no conflict of interest.

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Appendix

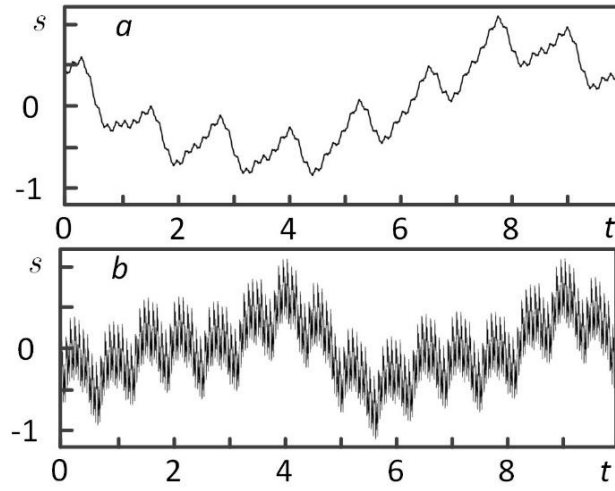


Figure 1. Model stochastic mono-fractal signals with different fractal dimension values: $D=1.2$ (a) and (b).

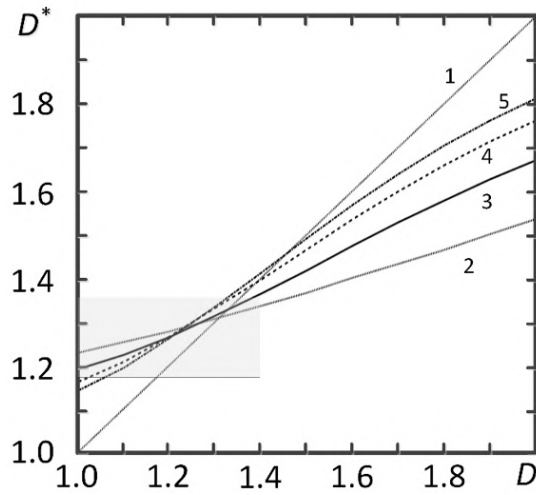


Figure 2. Comparison of the ‘ideal’ function $D^* = D$ (1) vs the non-linear function $D^* = f(D, N)$ having fixed N values: $N = 32$ (2), $N = 128$ (3), $N = 512$ (4) and $N = 2048$ (5). The gray rectangle denotes a graphical view of the ‘strange’ result obtained by H. E. Hurst.

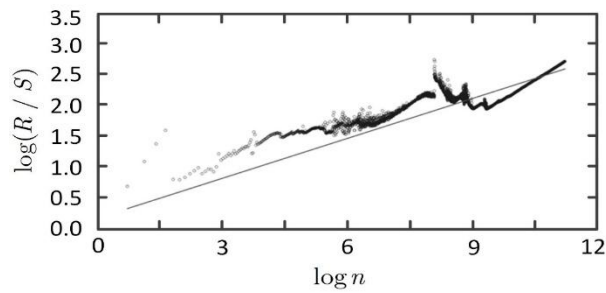


Figure 3. The dependence of $\log(R / S)$ vs $\log n$ defined by (1) and obtained with the rescaled range analysis method application for the sunspot numbers time series

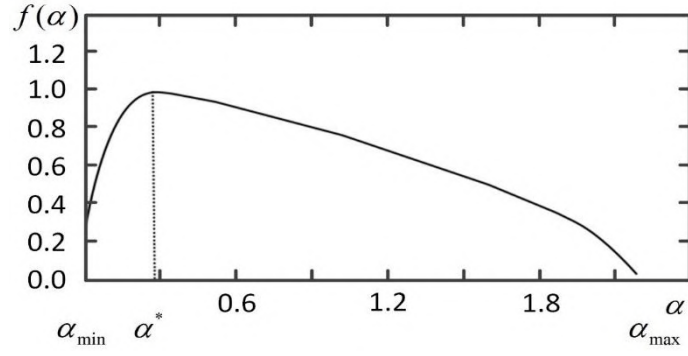


Figure 4. The multi-fractal spectrum function $f(a)$ obtained with the wavelet transform modulus maxima method application for the whole sunspot numbers time series

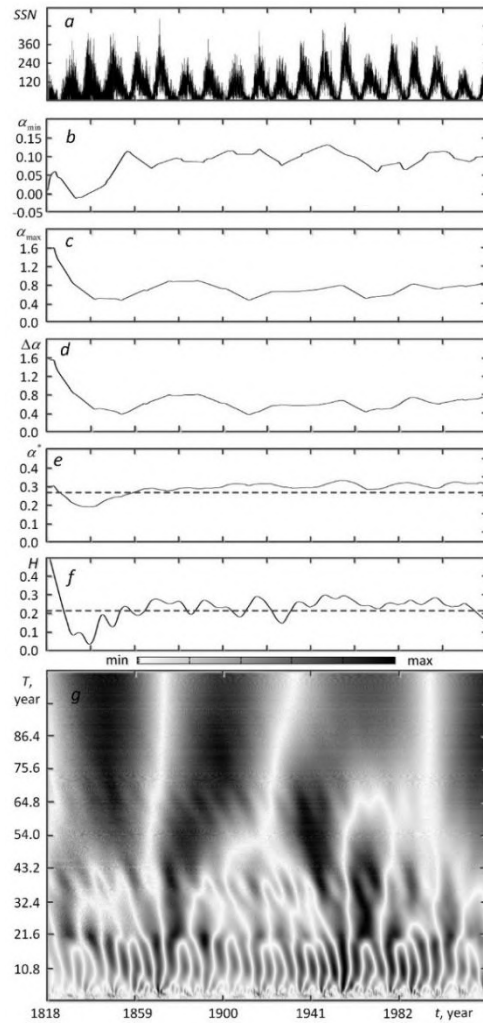


Figure 5. The results of the non-stationary fractal structure of the sunspot number time series from 1/1/1818 till 31/07/2024 with usage of the R/S method with sliding window and the MF DFA method: a – the sunspot time series in time domain, b – $\alpha_{\min}(t)$, c – $\alpha_{\max}(t)$, d – $\Delta\alpha(t)$, e – $\alpha^*(t)$, f – $H(t)$, g – the continuous wavelet transform spectral function module $|W(T, t)|$ obtained with usage of the fourth order Daubechie's wavelet

Use of Functional Ingredients in Health Food Products ^[18]

Abstract:

The growing deterioration of environmental conditions, the increasing prevalence of alimentary disorders, and the rising demand for preventive nutrition have intensified scientific and practical interest in functional food products. In contemporary food science, functional ingredients are regarded as physiologically active and safe substances capable of exerting a positive influence on metabolic processes, gastrointestinal physiology, cardiovascular function, immune response, and the overall adaptive potential of the human body. Against this background, particular attention has recently been paid not only to traditional functional components but also to plant-derived micronutrients and phytochemicals that expand the possibilities of health-oriented food design. The aim of this study was to analyse new classes of functional ingredients and their functional properties for further use in health food products. The study was based on an analytical review and systematization of contemporary scientific literature published in 2020–2025, with emphasis on current approaches to the development of functional foods, the integration of bioactive components into food matrices, and the growing relevance of ingredients that may support the organism under prolonged stress and adverse environmental conditions. The methodological framework of the study was guided by the principles of enrichment, replacement, and elimination as key approaches to the formulation of foods with improved health-promoting properties. The results demonstrate that the modern spectrum of functional ingredients has substantially expanded beyond traditionally recognized groups such as dietary fibre, probiotics, and omega-3 fatty acids. Special significance is now attributed to plant-origin functional compounds, including phytosterols, isothiocyanates, indoles, organic polysulfides, lignans, coumarins, tannins, flavonoids, and phenolic acids. These compounds are associated with antioxidant, anti-inflammatory, immunomodulatory, phytoestrogenic, and protective physiological effects and therefore represent a promising basis for the development of special-purpose and health-promoting foods. On this basis, the study identifies a group of practically relevant ingredients for possible inclusion in daily diets and food technologies, namely flaxseed, sesame seeds, sunflower seeds, garlic, horseradish, onions, lupine flour, walnuts, hemp oil, apples, and currants. Their value lies in the combination of biologically active composition, nutritional relevance, and accessibility as food raw materials. It is substantiated that the inclusion of plant-derived functional ingredients in food products can contribute to the diversification of daily diets and to the development of products with enhanced preventive potential. At the same time, the practical implementation of such ingredients requires further technological, nutritional, and product-specific validation. The study concludes that the systematization of plant micronutrients and their food sources broadens the scientific understanding of functional ingredients and provides a conceptual basis for the further development of health food products intended to support the body under conditions of stress, nutritional imbalance, and unfavourable environmental influences.

Keywords: functional ingredients, functional foods, health food products, plant-derived bioactive compounds, phytochemicals, preventive nutrition, food enrichment, health-promoting nutrition, dietary sources, food product development.

Introduction

At the present stage of food science and technology development, increasing attention is being paid to products that not only satisfy basic physiological needs for energy and nutrients but also contribute to the maintenance of health, adaptation, and disease prevention. This shift is associated with the growing deterioration of environmental conditions, the increasing prevalence of nutrition-related disorders, chronic stress, metabolic imbalance, and the need to improve the quality of daily diets through scientifically substantiated food solutions (*Gacche & Gacche, 2021; Jedrusek-Golińska et al., 2020; Stetsenko et al., 2023; Stetsenko, 2024*). In this context, functional foods have become one of the most dynamically developing areas of modern

nutrition science, as they are designed to provide benefits beyond basic nutritional value and to support specific physiological functions of the human body (*Alongi & Anese, 2021; Topolska et al., 2021*).

A functional ingredient is generally understood as a physiologically active and safe substance, or a complex of substances, of plant, animal, microbiological, or mineral origin that is intentionally incorporated into food products in order to produce a beneficial effect on the body (*Alongi & Anese, 2021; Topolska et al., 2021*). Such ingredients may influence metabolic regulation, gastrointestinal physiology, cardiovascular function, the condition of intestinal microflora, immune responsiveness, and the organism's resistance to adverse endogenous and exogenous factors (*Jedrusek-Golińska et al., 2020; Topolska et al., 2021*). Accordingly, the concept of health-promoting nutrition has evolved from simple nutrient replacement toward the creation of food products with targeted biological properties and a preventive orientation. In this paradigm, food is increasingly regarded not only as a source of nourishment but also as an important instrument for maintaining functional homeostasis and reducing the risk of nutrition-related disorders.

The development of functional foods has a substantial scientific, social, and technological basis. The concept itself, which gained international recognition after its institutionalization in Japan, has stimulated the formation of a broad research field focused on bioactive food components, enriched products, personalized nutrition, and the design of foods with improved physiological properties (*Alongi & Anese, 2021; Woollen, 1990*). Contemporary scientific literature demonstrates a rapid transition from traditional functional ingredients such as dietary fibre, vitamins, probiotics, minerals, and polyunsaturated fatty acids to more complex systems of biologically active compounds, including phytochemicals of plant origin (*Alongi & Anese, 2021; Capanoglu et al., 2024; Gacche & Gacche, 2021; Jedrusek-Golińska et al., 2020; Topolska et al., 2021*). Current research particularly emphasizes the need to combine high nutritional value, technological feasibility, bioavailability, and physiological relevance when introducing such compounds into food matrices (*Alongi & Anese, 2021; Capanoglu et al., 2024; Jedrusek-Golińska et al., 2020*).

In recent years, the scientific discourse on functional foods has increasingly focused on the role of plant-derived bioactive compounds as promising components of health-oriented food systems. These include phytosterols, flavonoids, phenolic acids, lignans, isothiocyanates, indoles, tannins, coumarins, and other classes of compounds naturally present in vegetables, fruits, berries, legumes, nuts, seeds, and plant oils. Their growing relevance is explained by a broad spectrum of reported physiological effects, including antioxidant, anti-inflammatory, immunomodulatory, cardioprotective, phytoestrogenic, and adaptive properties (*Alongi & Anese, 2021; Capanoglu et al., 2024; Gacche & Gacche, 2021; Jedrusek-Golińska et al., 2020; Topolska et al., 2021*). Such compounds significantly expand the conventional classification of functional ingredients and open new prospects for the design of foods intended for daily consumption, preventive nutrition, and special-purpose dietary support.

At the same time, despite the considerable volume of publications devoted to functional nutrition, a number of important issues remain insufficiently systematized. First, the scientific literature often addresses particular bioactive compounds or individual product categories, whereas the selection of plant-derived functional ingredients as a coherent group for health food

development is discussed less systematically. Second, although numerous studies describe the biological activity of phytochemicals, fewer works present them in a form directly relevant to food product design, that is, by linking the class of functional compounds, their natural dietary sources, and their practical applicability in health-promoting foods (*Alongi & Anese, 2021; Bomba et al., 2023; Capanoglu et al., 2024; Simakbina et al., 2024*). Third, in the context of current nutritional challenges, including prolonged stress and unfavourable environmental influences, there is a need for a clearer conceptual basis for selecting ingredients that are both biologically valuable and technologically relevant for incorporation into products of everyday diets (*Simakbina et al., 2024; Stetsenko et al., 2023; Stetsenko, 2024*).

The subject of the study is the functional properties, natural dietary sources, and practical relevance of selected plant-based bioactive compounds for their possible use in the development of health-promoting food products. The object of the study is health food products enriched with plant-derived functional ingredients. In this perspective, the study focuses not only on the biological significance of such ingredients, but also on their applicability in the diversification and nutritional improvement of foods intended for daily consumption.

This study proceeds from the assumption that the expansion of the functional ingredient spectrum through the systematization of plant-derived micronutrients and phytochemicals can strengthen the scientific basis for the development of health food products. In this regard, the object of the study is health food products enriched with plant-derived functional ingredients, while the subject of the study is the functional properties, dietary sources, and practical relevance of selected plant-based bioactive components for use in such products.

The aim of the study is to analyse new classes of functional ingredients and their functional properties for further use in health food products.

To achieve this aim, the following tasks were set: (1) to characterize the current range of functional ingredients in modern nutrition science; (2) to identify the principal classes of plant-derived functional compounds relevant to health-promoting foods; (3) to determine their major natural food sources; and (4) to substantiate the selection of ingredients that may be used in the development and diversification of foods intended for daily diets.

The scientific novelty of the study lies in the applied systematization of plant-derived functional ingredients not merely as isolated biologically active substances, but as a meaningful group of food-relevant components that can be used as a basis for expanding the range of health food products. In contrast to purely descriptive classifications of functional ingredients, this study focuses on those plant-origin compounds that combine physiological significance, natural occurrence in commonly available raw materials, and practical prospects for incorporation into food technologies. Particular attention is paid to ingredients that may be relevant in conditions where the body requires additional nutritional support, including prolonged stress, nutritional imbalance, and unfavourable environmental exposure (*Simakbina et al., 2024; Stetsenko et al., 2023; Stetsenko, 2024*).

The practical significance of the study is determined by the possibility of using the obtained systematization in the design of new food products with health-promoting properties, in the enrichment of daily diets, and in the substantiation of ingredient selection for restaurant, food-service, and food-manufacturing applications. The identification of promising plant-derived ingredients and the clarification of their functional roles can contribute to the development of

nutritionally improved foods that are more responsive to current public health needs. Thus, the study is positioned at the intersection of food technology, functional nutrition, and preventive dietetics and provides a conceptual basis for the further development of health-oriented food products.

The results of this study are intended for a broad interdisciplinary audience involved in the development, evaluation, and practical application of health-oriented food systems. They may be of particular relevance to researchers in food science, nutrition, and preventive dietetics; technologists engaged in the formulation of functional and special-purpose food products; specialists in restaurant and food-service innovation; and professionals concerned with improving dietary quality under conditions of stress, nutritional imbalance, and adverse environmental influences. In addition, the systematized findings may be useful for educators, postgraduate students, and graduate students working in the fields of food technology, public health nutrition, and the scientific substantiation of enriched and health-promoting diets.

Materials and Methods

This study was designed as an analytical review with elements of applied systematization aimed at identifying and substantiating plant-derived functional ingredients that may be relevant for the development of health food products. The research did not involve experimental laboratory modelling, sensory assessment, or clinical verification. Instead, it focused on the conceptual and analytical generalization of current scientific approaches to functional nutrition, the classification of bioactive compounds of plant origin, and the identification of food-relevant ingredients with potential health-promoting significance.

The choice of this design was determined by the purpose of the study, namely to analyse new classes of functional ingredients and their functional properties for further use in health food products. Accordingly, the study was oriented toward the structured interpretation of scientific data, the comparative consideration of plant-derived compounds in terms of their biological roles, and the selection of ingredients that may be incorporated into foods intended for daily diets and preventive nutrition.

The source base of the study consisted of contemporary scientific publications devoted to functional foods, functional ingredients, plant-derived bioactive compounds, and health-promoting nutrition. Particular attention was paid to publications issued in 2020–2025, since this period reflects the most recent stage in the development of scientific thought on enriched foods, bioactive food systems, and the role of plant micronutrients in the nutritional support of the human body under adverse environmental and physiological conditions.

The analytical materials included review studies, scientific articles, and selected Ukrainian and international publications addressing the concept of functional foods, the integration of bioactive components into food matrices, the technological development of health-oriented products, and the physiological relevance of plant-based micronutrients. In addition, the study considered sources focused on the practical use of plant raw materials and functional ingredients in special-purpose and health-promoting foods. The analysed publications were selected for their thematic relevance to the subject of the study and their ability to support the systematization of ingredients applicable to food product design.

The selection of plant-derived functional ingredients was carried out according to a set of conceptual and applied criteria. First, the ingredient had to be of plant origin and contain bioactive compounds that are recognized in the scientific literature as potentially relevant to the maintenance of health and the support of physiological functions. Second, the selected ingredient had to represent a meaningful source of one or more functional classes of compounds, such as phytosterols, flavonoids, phenolic acids, lignans, isothiocyanates, indoles, tannins, or related micronutrients.

Third, preference was given to ingredients that are naturally present in raw materials suitable for human consumption and compatible with the structure of daily diets. Fourth, the ingredient had to demonstrate practical potential for incorporation into food products, including dishes and formulations intended for health-promoting nutrition. Fifth, the selected set of ingredients was expected to reflect the diversity of plant-derived functional compounds rather than a single narrow phytochemical category. On this basis, the study concentrated on such ingredients as flaxseed, sesame seeds, sunflower seeds, garlic, horseradish, onions, lupine flour, walnuts, hemp oil, apples, and currants as representative raw materials combining biological relevance and practical food applicability.

The analytical procedure was implemented in several successive stages. At the first stage, the study summarized contemporary scientific approaches to the understanding of functional foods and functional ingredients, including the transition from traditional enrichment models toward foods with enhanced physiological and preventive properties. At the second stage, the main classes of plant-derived functional compounds described in the literature were identified and grouped according to their biological and nutritional significance.

At the third stage, natural food sources of these compounds were analysed in order to determine ingredients that may be realistically used in the development of health food products. This stage involved the systematization of vegetables, fruits, berries, seeds, nuts, plant oils, and other raw materials as carriers of bioactive compounds relevant to the subject of the study. At the fourth stage, the selected ingredients were generalized from the perspective of their possible contribution to the diversification and nutritional improvement of daily diets. Their significance was interpreted through the combination of three interrelated dimensions: the presence of bioactive compounds, the expected health-promoting potential, and the practical suitability of the ingredient for use in food technologies.

In methodological terms, the study also took into account the classical approaches commonly used in the development of functional foods, namely enrichment, replacement, and elimination. However, in this study these approaches were not treated as independent experimental procedures, but rather as a conceptual technological framework that explains how selected functional ingredients may subsequently be introduced into product formulations. Thus, the principal method of the present research was analytical systematization, whereas the technological approaches served as an interpretative basis for the further practical application of the identified ingredients.

The study has several limitations that should be taken into account when interpreting its results. First, it has an analytical and conceptual character and does not include experimental validation of the selected ingredients in specific food systems. Second, the study does not assess dosage parameters, bioavailability in particular matrices, organoleptic compatibility, or stability

during technological processing and storage. Third, the conclusions regarding the health-promoting significance of the selected ingredients are based on the generalization of scientific literature and should therefore be understood as a conceptual basis for further applied and experimental research rather than as final evidence of product efficacy.

Despite these limitations, the chosen methodological approach made it possible to identify and systematize a relevant group of plant-derived functional ingredients, clarify their principal food sources, and substantiate their potential relevance for the further development of health food products.

Literature Review

The scholarly understanding of functional foods has evolved from a market-oriented and category-defining concept into a multidisciplinary field that integrates food science, nutrition, preventive medicine, consumer research, and product development. One of the earlier signals of this transition was the recognition of functional foods as a distinct and emerging market segment, where value was created not only through conventional nutritional composition but also through added physiological relevance (*Woollen, 1990*). In contemporary research, however, the concept has moved considerably beyond the notion of a “new market” and is now treated as a scientific and technological platform for designing foods capable of supporting specific bodily functions and improving health outcomes. This shift has made functional ingredients central to the development of foods that combine nutritional adequacy with preventive and adaptive potential.

A major line of recent international research is connected with the expansion of the conceptual boundaries of functional food itself. Topolska et al. (*2021*) demonstrate that consumer interest in functional foods is shaped not only by health concerns in a general sense, but also by expectations of concrete physiological benefits, trust in product composition, and the perceived legitimacy of food as a vehicle of health support. This consumer-centred perspective is important because it shows that functional foods are not interpreted solely through laboratory or technological parameters; they also exist within a framework of public expectations regarding quality of life, disease prevention, and informed dietary choice. Complementing this view, Capanoglu et al. (*2024*) frame functional foods as a field in which added value is generated through the purposeful enrichment of foods with biologically meaningful compounds, thereby linking scientific innovation with nutritional relevance and product differentiation.

At the same time, the literature increasingly suggests that the development of functional foods cannot be reduced to the mechanical addition of isolated compounds to conventional products. Alongi and Anese (*2021*) argue for a holistic approach to functional food development, emphasizing that the success of such products depends on the interaction between ingredient functionality, food matrix compatibility, processing effects, bioavailability, and the intended physiological outcome. This position is especially important for current food technology, because it shifts the focus from a narrow enrichment logic to a systems-oriented model in which functional ingredients must be evaluated not only for their biological activity, but also for their technological feasibility and nutritional performance in real food systems. In

this sense, the contemporary literature increasingly supports the idea that the scientific validity of a functional ingredient must be matched by its practical applicability in product formulation.

Another major tendency in the literature is the differentiation of functional foods according to target groups and specific physiological or life-condition needs. Jedrusek-Golińska et al. (2020), e.g., demonstrate in their narrative review that functional foods for older adults should be considered within a highly specific nutritional framework that accounts for age-related physiological changes, health vulnerabilities, and the need for products with both nutritional density and functional efficacy. In a different but equally important direction, Gacche and Gacche (2021) examine the role of functional foods, nutraceuticals, and dietary supplements in cancer prevention, thereby extending the discussion toward food-mediated protective strategies in relation to one of the most serious contemporary health challenges. Together, these studies show that the field of functional nutrition is increasingly moving toward more differentiated, condition-sensitive, and population-oriented models, rather than relying on a universal or purely generalized understanding of beneficial food products.

Within the Ukrainian scientific context, the literature develops this logic further by linking functional ingredients with the nutritional needs of specific social groups and with the realities of adverse living conditions. Simakhina et al. (2024) address the conceptual foundations of combined food ration formation for extreme living conditions, thereby emphasizing that food design under such circumstances requires more than conventional nutrient balancing; it requires a strategic combination of ingredients capable of supporting adaptation, resilience, and physiological stability. A related applied direction is represented by Masliichuk and Kravets (2024), who consider functional ingredients as components of new food products for military personnel. Their contribution is important because it translates the broader functional-food discourse into the domain of specialized nutrition, where the requirements of bodily support, practicality, and nutritional efficiency are especially stringent. These studies indicate that, in the Ukrainian scholarly environment, functional nutrition is increasingly interpreted not only as a preventive public-health tool, but also as a strategic response to extreme, stress-related, and service-related conditions of life.

A similar problem orientation is found in recent Ukrainian works devoted to wartime nutrition and stress-related dietary support. Stetsenko et al. (2023) emphasize the importance of functional nutrition for maintaining the health of the population of Ukraine under wartime conditions, thereby underscoring the role of food products enriched with biologically active components in situations where ordinary dietary patterns are disrupted and the physiological burden on the body increases. Stetsenko (2024) further develops this line by focusing specifically on functional food products and ingredients aimed at overcoming the effects of stress among the population under martial law. Taken together, these studies strengthen the idea that functional ingredients should be evaluated not only from the standpoint of generic health improvement, but also in relation to their capacity to support the organism in circumstances of prolonged psycho-emotional strain, unstable living conditions, and increased exposure to harmful environmental factors. For the present study, this body of literature is especially significant because it helps justify the relevance of plant-derived ingredients as components of foods intended for supportive and adaptive nutrition.

Another important segment of the literature concerns the role of non-traditional and regionally specific plant raw materials in developing health-promoting foods and beverages. Bomba et al. (2022) examine the use of non-traditional raw materials in preparing health-promoting children's meals in restaurant establishments, thereby highlighting the technological and nutritional relevance of expanding the ingredient base beyond standard formulations. This contribution is methodologically important because it connects functional nutrition with the restaurant and food-service sector, where enriched and health-oriented dishes can be adapted for real consumer practice. In a related study, Bomba et al. (2023) analyse non-traditional plant raw materials of the Carpathians in the technology of preparing health-promoting beverages. This regional focus is valuable because it demonstrates that functional food development may rely not only on globally standardized ingredients, but also on local plant resources with significant health-promoting potential. Together, these studies support the view that non-traditional plant raw materials can serve as a meaningful basis for the diversification of functional foods and beverages, especially when local biodiversity and regional technological traditions are taken into account.

Across both international and Ukrainian sources, one of the most stable research tendencies is the growing importance of plant-derived bioactive compounds as functional ingredients. Although the cited sources vary in scale and focus—from broad conceptual discussions to population-specific and application-oriented studies—they collectively point to the increasing role of ingredients rich in phytochemicals, antioxidants, and other biologically active compounds in the design of modern health-oriented foods (Alongi & Anese, 2021; Capanoglu et al., 2024; Simakbina et al., 2023; Stetsenko, 2024). This convergence is particularly important for the present study because it supports the analytical shift from a narrow emphasis on conventional functional ingredients, such as fibre or probiotics alone, toward a broader classification that includes plant micronutrients and phytochemical complexes occurring naturally in seeds, nuts, fruits, berries, vegetables, and plant oils. In other words, the literature increasingly allows functional ingredients to be interpreted not only as isolated additives, but also as compounds embedded in natural food raw materials with potential technological and nutritional relevance.

Nevertheless, despite the breadth of existing studies, the reviewed literature also reveals a number of unresolved issues. First, many publications focus either on the general concept of functional foods or on specific target populations, without providing a sufficiently systematized selection of plant-derived ingredients that could serve as a practical basis for product development. Second, the connection between biological activity and food-technological applicability is not always made explicit: a compound may be recognized as promising in nutritional or biomedical terms, yet its relevance for actual food matrices, everyday diets, or specific product categories may remain insufficiently articulated. Third, while Ukrainian studies make an important contribution by addressing health-promoting foods in the contexts of restaurant practice, regional plant resources, military nutrition, wartime conditions, and stress adaptation (Bomba et al., 2022; Bomba et al., 2023; Masliichuk & Kravets, 2024; Stetsenko et al., 2023; Stetsenko, 2024), this body of work still requires stronger analytical systematization around classes of plant-derived functional compounds and their major dietary sources.

Therefore, the current state of research makes it possible to identify a clear scholarly rationale for the present study. On the one hand, the literature convincingly demonstrates that functional foods are now understood as an important means of supporting health, preventing nutrition-related disorders, and responding to the needs of specific population groups and adverse living conditions (*Gacche & Gacche, 2021; Jedrusek-Golińska et al., 2020; Stetsenko et al., 2023*). On the other hand, there remains a need for a more integrated and application-oriented systematization of plant-derived functional ingredients that would connect their biological significance, natural dietary sources, and potential use in health food products (*Alongi & Anese, 2021; Bomba et al., 2023; Capanoglu et al., 2024; Simakhina et al., 2024*). It is precisely this gap that defines the relevance of the present research, which aims to analyse new classes of functional ingredients and substantiate their value for the further development of health-promoting foods.

Results

Expansion of the Functional Ingredient Spectrum in Modern Nutrition

Japanese researchers initially identified lactic acid bacteria and bifidobacteria, oligosaccharides, dietary fiber, and omega-3 fatty acids as the principal categories of physiologically functional ingredients used in the production of functional foods (*Woollen, 1990*). At present, however, this list has expanded significantly. Functional products and dietary supplements now include previously less studied functional ingredients of plant origin, namely phytochemicals, which have no energy or plastic value and are not essential nutrients in the classical sense, yet play an important role in maintaining human health.

This expansion of the functional ingredient spectrum reflects a broader understanding of health-promoting nutrition. Modern scientific research confirms that plant-based micronutrients and phytochemicals significantly broaden the classification of functional ingredients in foods intended for daily consumption and in special-purpose products. Various plant raw materials act as natural carriers of these compounds, including vegetables, fruits, berries, cereals, legumes, nuts, seeds, and plant oils. In this context, the inclusion of plant-origin bioactive components in the diet represents an important direction in the diversification and nutritional improvement of food products.

Major Classes of Plant-Derived Functional Compounds

The plant-derived functional ingredients identified in the study include several important groups of biologically active compounds. These comprise phytosterols from beans, vegetables, fruits, sunflower seeds, and nuts; isothiocyanates and indoles from cruciferous vegetables; organic polysulfides from garlic and onions; lignans (aglycone phytoestrogens) from flax seeds, sesame seeds, bran, and soybeans; coumarins from celery, parsley, and parsnips; plant quinones (tannins) from walnuts, leafy vegetables, spinach, and soybeans; flavonoids from fruits and vegetables, tea, and wine; and phenolic acids from fruits and vegetables, berries, tea, wine, cocoa, and chocolate.

A substantial part of these compounds is associated with antioxidant and protective activity. Flavonoids, phytosterols, tannins, phenolic acids, lignans, saponins, terpenoids, and carotenoids are regarded as antioxidants that may reduce the risk and slow the development of degenerative

processes in the body. Their significance is linked to their ability to participate in maintaining metabolic balance, protecting tissues from oxidative damage, and supporting adaptive physiological mechanisms.

Special attention should be paid to cruciferous vegetables as sources of glucosinolates and related compounds. Brussels sprouts, broccoli, other types of cabbage, rutabaga, turnips, horseradish, and watercress may serve as valuable dietary sources of indoles and isothiocyanates. These compounds help normalize endocrine system function, maintain hormonal balance, and strengthen immune defense. In the context of specialized and supportive nutrition, such properties make cruciferous raw materials promising components of health-oriented food products.

Selected Ingredients for Health Food Products

In order to expand the range of functional foods in daily diets, a group of practically significant ingredients was selected in this study ([Table 1](#)). These ingredients are flaxseed, sesame seeds, sunflower seeds, garlic, horseradish, onions, lupine flour, walnuts, hemp oil, apples, and currants. Their selection was based on their functional properties, their natural occurrence as food raw materials, and their potential suitability for incorporation into health-promoting products.

The selected ingredients represent different groups of plant-derived functional compounds and therefore provide a broad basis for the enrichment and diversification of foods. Flaxseed and sesame seeds are important sources of lignans; sunflower seeds contribute phytosterols and isoflavone-related compounds; garlic and onions are valuable due to their sulfur-containing phytochemicals; walnuts provide tannins and other antioxidant compounds; apples and currants are important sources of flavonoids and phenolic acids; and hemp oil serves as a plant-derived lipid component of high nutritional relevance. Lupine flour is of particular interest as a technologically convenient ingredient that may expand the protein and functional composition of food systems.

Given their functional properties, the incorporation of these ingredients into foods may contribute to the production of higher-quality products with health-promoting characteristics. Their use appears especially promising for the development of foods intended for daily diets, product diversification, and the support of the organism under conditions requiring improved nutritional quality.

Functional Characteristics of Selected Compound Groups

Among the selected groups of compounds, phytoestrogens and lignans deserve particular attention. Isoflavones are described as compounds that inhibit the formation of blood clots in blood vessels, thereby helping to prevent the blockage of coronary arteries and reducing the risk of myocardial infarction. The consumption of phytoestrogens is also associated with a lower risk of colon, breast, prostate, stomach, and lung cancer. In this regard, ingredients containing such compounds may be considered especially relevant for foods with preventive nutritional orientation.

Lignans are characterized by a wide spectrum of functional properties, including antiviral, antibacterial, antifungal, antioxidant, phytoestrogenic, and oncoprotective effects. Their

presence in flax seeds, sesame seeds, and several other plant raw materials further supports the selection of these ingredients for use in health food products. From the standpoint of functional nutrition, lignan-containing ingredients are valuable because they combine biological activity with accessibility in ordinary diets.

Flavonoids also occupy a central place among plant-derived functional compounds. Under the influence of enzymes, flavonoids are broken down into sugars and aglycones. Representatives of flavanols include catechins and proanthocyanidins. Catechins are antioxidants that inhibit the development of cancerous tumors and the activation of carcinogens. Pycnogenol exhibits anticoagulant properties comparable to those of aspirin and therefore may reduce the risk of myocardial infarction and stroke. Proanthocyanidins strengthen and restore connective tissue, including in the cardiovascular system, and reduce allergic inflammatory manifestations by decreasing histamine production.

In addition, flavonoids demonstrate anti-allergic and anti-inflammatory effects through the inhibition of the formation and release of inflammatory factors, as well as considerable antiviral activity, slowing the reproduction and activity of viruses. Quercetin is described as having particularly high antiviral activity against herpes, parainfluenza, and other viruses. Many flavonoids, especially catechins and anthocyanins, also possess P-vitamin activity. They normalize and strengthen capillary condition, enhance the effect of ascorbic acid by protecting it from oxidation, and help normalize blood pressure due to their antispasmodic effect on the smooth muscles of blood vessels.

Main Dietary Sources of the Identified Compounds

The identified classes of plant-derived functional compounds are linked to specific dietary sources, which makes their inclusion in food systems technologically and nutritionally feasible. As shown in Table 1 ([Appendix](#)), phytosterols are associated with unrefined vegetable oils, soybeans, oats, amaranth, vegetables, and fruits; sulfur-containing phytochemicals are present in cruciferous vegetables, garlic, and onions; isoflavones occur in soybeans and other legumes, sunflower seeds, dates, cabbage, and hops; lignans are found in flax seeds, sesame seeds, bran, rye, nuts, cherries, apples, parsley, carrots, and garlic; saponins are associated with green vegetables, potatoes, and edible green shoots; flavonoids are abundant in berries, fruits, vegetables, citrus fruits, tea, wine, and soy; and phenolic acids are present in apples, blueberries, cherries, plums, potatoes, nuts, soy, and coffee beans.

Thus, the results obtained in the study confirm the importance of plant-based micronutrients in the daily diet and substantiate the relevance of their use in the development of health food products. Since many of these compounds are naturally distributed across commonly available plant foods, their inclusion in daily diets may be considered a realistic and promising strategy for improving nutritional quality. In this regard, the recommended minimum daily intake of vegetables and fruits at the level of 500–600 g acquires additional significance, since such products serve not only as nutrient sources in the conventional sense but also as carriers of important functional compounds.

Discussion

Scientific Interpretation of the Identified Plant-Derived Functional Ingredients

The results of the present study confirm that the contemporary understanding of functional ingredients has moved far beyond the classical categories that were initially associated with functional foods, such as dietary fibre, probiotics, and omega-3 fatty acids. In current food science, increasing importance is attached to plant-derived bioactive compounds that, although not essential nutrients in the strict classical sense, may significantly contribute to the physiological support of the body and to the preventive orientation of daily nutrition. In this respect, the identified groups of substances—phytosterols, isothiocyanates, indoles, sulfur-containing phytochemicals, lignans, flavonoids, phenolic acids, and related compounds—should be interpreted not merely as isolated biochemical components, but as a meaningful functional basis for the development of health-promoting food systems (*Alongi & Anese, 2021; Capanoglu et al., 2024*).

This interpretation is consistent with the broader shift in the scientific literature toward a more integrated understanding of food functionality. Functional foods are increasingly perceived not only as enriched products but also as carriers of adaptive, protective, and physiologically relevant compounds that may contribute to the maintenance of homeostasis under adverse dietary and environmental conditions (*Jedrusek-Golińska et al., 2020; Topolska et al., 2021*). Against this background, the present results are important because they substantiate the relevance of naturally occurring plant ingredients as practical sources of such compounds, thereby connecting the biochemical dimension of food functionality with the raw-material and product-development dimension of food science.

A particularly important finding of the study is that plant-derived ingredients can be grouped not only according to their botanical origin, but also according to their expected functional roles in the diet. Seeds, nuts, fruits, berries, oils, cruciferous vegetables, and leguminous raw materials provide different but complementary classes of bioactive compounds. This means that the functional potential of a product is determined not by a single universal ingredient, but by the possibility of combining various plant sources that differ in phytochemical profile, nutritional density, and technological use. Such an interpretation strengthens the argument that the practical development of health food products should rely on a diversified ingredient strategy rather than on a narrowly additive approach (*Alongi & Anese, 2021; Simakbina et al., 2024*).

Relevance of the Selected Ingredients for Health Food Product Development

The selected ingredients identified in the study—flaxseed, sesame seeds, sunflower seeds, garlic, horseradish, onions, lupine flour, walnuts, hemp oil, apples, and currants—should be viewed as a functionally heterogeneous yet technologically meaningful group. Their relevance lies in the fact that they combine three important characteristics: first, they are natural dietary sources of biologically active compounds; second, they are potentially compatible with a wide range of food matrices; and third, they are sufficiently accessible to be considered realistic components of foods intended for everyday consumption. This combination of biological significance and practical applicability is especially important for developing health-promoting foods, because a theoretically valuable ingredient has limited importance if it cannot be reasonably incorporated into food products or daily diets.

From this standpoint, the identified ingredients may be interpreted as particularly promising for the design of foods with preventive and supportive nutritional properties. Flaxseed and sesame seeds are of special value because they are associated with lignans and related phytoestrogenic compounds, which broadens their relevance for foods intended to support metabolic and hormonal balance. Garlic, onions, and horseradish are important due to sulfur-containing phytochemicals and compounds characteristic of cruciferous or related plant systems, which are associated in the literature with protective and adaptive physiological effects. Apples and currants are significant as familiar and accessible carriers of flavonoids and phenolic acids, while walnuts and hemp oil contribute to the enrichment of food systems through antioxidant and lipid-related nutritional value. Lupine flour deserves separate attention because, unlike some ingredients that function mainly as bioactive carriers, it also has clear technological relevance as a structurally useful and nutritionally meaningful component in product formulations.

In this context, the results of the study support the idea that the development of functional foods should not be limited to the use of highly specialized or costly ingredients. On the contrary, one of the strengths of the selected set is that it includes raw materials that are relatively familiar, available, and acceptable within ordinary food culture. This characteristic increases the practical significance of the study, because it makes the proposed ingredients relevant not only for theoretical classification but also for actual application in food-service practice, restaurant technologies, and the development of health-oriented foods for wider population groups (*Bomba et al., 2022; Bomba et al., 2023*).

Functional Ingredients as a Bridge between Preventive Nutrition and Specialized Dietary Support

The discussion of the present findings also needs to be placed within the broader framework of target-oriented and condition-sensitive nutrition. Contemporary literature increasingly demonstrates that functional food systems are especially relevant when nutrition must serve not only a general health-maintenance role, but also a supportive role under specific physiological or social conditions. This is evident in studies addressing older adults, chronic-disease prevention, military nutrition, and wartime or stress-related dietary challenges (*Gacche & Gacche, 2021; Jedrusek-Golińska et al., 2020; Masliuchuk & Kravets, 2024; Stetsenko et al., 2023*).

Within this perspective, the selected ingredients in the present study may be regarded as especially relevant for nutritional contexts in which the body is exposed to prolonged stress, unstable living conditions, or increased adaptive burden. Ukrainian researchers have already emphasized the importance of functional nutrition for the support of the population under wartime conditions and for the development of special-purpose products aimed at maintaining resilience and health under adverse circumstances (*Stetsenko et al., 2023; Stetsenko, 2024*). Similarly, Simakhina et al. (2024) underline the need for conceptually substantiated food rations for extreme living conditions, where the combination of nutritional adequacy and biologically active support becomes critically important. The results of the present study do not claim to provide direct experimental evidence for stress mitigation; however, they do support the idea that plant-derived functional ingredients may form a meaningful nutritional basis for foods intended to strengthen the preventive and adaptive properties of daily diets.

This interpretation is further reinforced by the applied relevance of selected ingredients to foods designed for specific groups. Masliichuk and Kravets (2024) argue that the inclusion of functional ingredients in products for military personnel should be regarded as a strategically important direction in the development of new food products. In a broader sense, this implies that the scientific value of plant-derived bioactive components lies not only in their abstract physiological potential, but also in their ability to serve as components of food systems intended for populations facing increased physiological and psycho-emotional stress. Thus, the present study contributes to the ongoing scholarly discussion by systematizing ingredients that may be relevant both for preventive nutrition and for more specialized health-supportive dietary contexts.

Technological and Food-System Implications

An important contribution of the present results lies in their technological interpretability. Modern food science increasingly emphasizes that functional food development must consider not only the presence of bioactive compounds, but also the way these compounds can be incorporated into actual food systems (Alongi & Anese, 2021). In this regard, the ingredients identified in the study possess different technological profiles that may be used in the formulation of a broad range of products. Seeds and seed-derived components may be incorporated into bakery items, porridges, bars, salads, fermented products, and dry mixes. Hemp oil and walnut-derived components may enrich sauces, dressings, spreads, and cold dishes. Apples and currants may be used in beverages, desserts, fillings, snacks, fruit-based sauces, and functional semi-finished products. Garlic, onions, and horseradish may be integrated into savory dishes, sauces, marinades, meat analogues, vegetable systems, and complex multi-component formulations. Lupine flour has additional importance for its structuring, protein-enriching, and textural role in flour-based and hybrid food systems.

This technological diversity is especially important because it allows plant-derived functional ingredients to be considered within the logic of product architecture rather than as abstract nutritional additives. The present study therefore supports the idea that functional ingredients can be introduced through several pathways: enrichment of conventional food products, replacement of nutritionally weaker components with more valuable analogues, and the design of new dishes or products in which selected ingredients are integral rather than auxiliary elements. This interpretation also resonates with Ukrainian applied studies on the use of non-traditional plant raw materials in restaurant practice and health-promoting beverages, where raw-material innovation is directly linked to the diversification of food offerings and to the practical realization of health-oriented nutritional concepts (Bomba et al., 2022; Bomba et al., 2023).

At the same time, the study suggests that technological promise should not be equated automatically with proven efficacy. A functionally promising ingredient may remain underutilized if its sensory characteristics, dosage thresholds, compatibility with other ingredients, or stability during processing are not sufficiently studied. Therefore, the practical value of the present results lies less in the claim that all selected ingredients are equally ready for immediate industrial deployment, and more in the creation of a scientifically grounded shortlist of ingredients whose further technological elaboration appears justified.

Comparison with Current Literature and Conceptual Contribution of the Study

When considered in relation to the reviewed literature, the present findings occupy an intermediate position between conceptual discussions of functional food development and applied classifications of food-relevant raw materials. International sources emphasize the importance of holistic product design, the growing scientific and market relevance of functional foods, and the need to align biological functionality with consumer expectations and product feasibility (*Alongi & Anese, 2021; Capanoglu et al., 2024; Topolska et al., 2021*). Ukrainian sources, in turn, place stronger emphasis on the use of plant raw materials, the practical development of health-promoting foods and beverages, and the significance of functional ingredients under wartime, stress-related, and special-purpose nutritional conditions (*Bomba et al., 2022; Bomba et al., 2023; Stetsenko et al., 2023; Stetsenko, 2024*).

The conceptual contribution of the present study lies in connecting these two lines of scholarship. On the one hand, it adopts the broader international understanding of functional foods as products with scientifically meaningful added value. On the other hand, it translates this understanding into a concrete set of plant-derived ingredients that are relevant to food technologies, daily diets, and the nutritional realities addressed in Ukrainian applied research. In this sense, the study does not merely reproduce the already established idea that plant-derived compounds are important; rather, it systematizes selected ingredients as carriers of functional classes of compounds and situates them within an applied food-development perspective. This gives the study a bridging role between theoretical food-functionality discourse and ingredient-oriented product design.

Limitations of the Research

Despite its conceptual and applied relevance, the study has several limitations that should be acknowledged. First, the work is analytical rather than experimental in nature. It does not include laboratory validation of ingredient performance in specific food matrices, nor does it assess the stability of bioactive compounds during thermal processing, storage, or combined formulation. Second, the study does not provide dosage modelling or quantitative comparison of the selected ingredients in terms of concentration, bioavailability, or physiological effectiveness. Third, the functional interpretations of the ingredients are based on literature generalization and should therefore be understood as a conceptual substantiation of their relevance rather than as direct proof of the efficacy of particular products.

A further limitation concerns the level of technological specificity. Although the study demonstrates that the selected ingredients have potential practical applicability, it does not yet differentiate sufficiently between product categories, processing conditions, sensory constraints, or target population needs. Moreover, some of the physiological effects associated with particular classes of compounds in the literature may depend strongly on intake level, food matrix, long-term dietary context, and individual variability. For this reason, the present findings should be treated as a scientifically grounded basis for subsequent product-oriented and experimental research, not as a final formulation model.

Directions for Further Research

The results of the study define several promising directions for future work. First, there is a clear need for formulation studies in which the identified ingredients are tested in specific product categories, including beverages, bakery products, snacks, sauces, desserts, and special-purpose foods. Second, future research should evaluate the organoleptic acceptability of such formulations, because the successful implementation of functional ingredients depends not only on physiological value but also on taste, aroma, texture, and consumer perception. Third, technological studies should assess the stability and retention of bioactive compounds during processing and storage, especially in systems involving heat treatment, fermentation, drying, or fat-containing matrices.

Further research should also include quantitative nutritional characterization, dosage justification, and comparative assessment of the contribution of individual ingredients to the overall functional profile of a product. In addition, studies focused on target groups—such as persons under prolonged stress, older adults, military personnel, or consumers requiring health-supportive daily diets—would make it possible to refine the practical relevance of ingredient selection. Finally, a particularly productive direction would be the development of integrated functional food models that combine several of the identified plant-derived ingredients in order to achieve complementary nutritional and physiological effects. Such work would allow the field to move from conceptual systematization toward validated product solutions with real preventive and supportive potential.

Conclusion

The present study has confirmed the growing scientific and practical relevance of plant-derived functional ingredients in the development of health food products. The conducted analytical review and systematization of contemporary scientific literature made it possible to demonstrate that the modern spectrum of functional ingredients extends far beyond the traditionally recognized categories and increasingly includes a broad range of plant-origin bioactive compounds with potential preventive and health-promoting significance. In this respect, the study supports the view that functional nutrition should be interpreted not only as a strategy of nutrient enrichment, but also as an approach to designing foods with enhanced physiological value, improved adaptive potential, and greater relevance to current nutritional challenges.

The purpose of the study, namely to analyse new classes of functional ingredients and their functional properties for further use in health food products, has been achieved. In accordance with this aim, the principal tasks of the research were completed. First, the current range of functional ingredients in modern nutrition science was characterized, and it was shown that contemporary functional food development increasingly incorporates plant-derived micronutrients and phytochemicals alongside classical ingredients. Second, the main classes of plant-based functional compounds relevant to health-promoting nutrition were identified, including phytosterols, isothiocyanates, indoles, sulfur-containing phytochemicals, lignans, flavonoids, phenolic acids, and related compounds. Third, their major natural food sources were determined and systematized, which made it possible to establish the nutritional and raw-material basis for their inclusion in food products. Fourth, the selection of ingredients with practical relevance for health food development was substantiated, and such ingredients as

flaxseed, sesame seeds, sunflower seeds, garlic, horseradish, onions, lupine flour, walnuts, hemp oil, apples, and currants were identified as promising components for the diversification and nutritional improvement of daily diets.

The results obtained in the study indicate that plant-derived functional ingredients possess a dual significance. On the one hand, they are carriers of biologically active compounds associated in the literature with antioxidant, anti-inflammatory, protective, adaptive, and other health-supporting effects. On the other hand, they are represented by food raw materials that are sufficiently accessible and technologically meaningful to be considered for practical incorporation into food systems. This combination of physiological relevance and food-technological applicability gives such ingredients particular importance for the development of health-promoting foods intended for daily consumption, preventive nutrition, and nutritionally supportive dietary strategies.

At the same time, the study has shown that the scientific substantiation of plant-derived functional ingredients should not be limited to the description of their biological activity alone. Their value becomes most significant when considered in relation to food matrices, technological feasibility, ingredient compatibility, and the broader task of creating products that are both nutritionally useful and practically acceptable. In this sense, the study contributes to the further development of the functional food concept by linking the classification of plant bioactive compounds with their natural dietary sources and their applied potential in food design.

The conducted research also confirms the practical significance of the proposed systematization for specialists in food science, nutrition, food technology, and health-oriented product development. The identified ingredients may serve as a conceptual basis for the enrichment of conventional foods, the formulation of new products with preventive potential, and the expansion of ingredient strategies in restaurant, food-service, and food-manufacturing practice. This is particularly important under conditions in which the quality of nutrition must be improved not only for general well-being, but also for strengthening the body's resistance to stress, dietary imbalance, and unfavourable environmental influences.

At the same time, the conclusions of the study should be interpreted with due regard to its analytical character. The research did not include experimental validation, dosage modelling, sensory evaluation, or technological testing in specific food systems. Therefore, the findings should be understood as a scientifically grounded conceptual basis for further applied research rather than as final evidence of the efficacy of particular food formulations. Future studies should focus on the development of product prototypes, the assessment of organoleptic and technological characteristics, the evaluation of bioactive compound stability during processing and storage, and the substantiation of effective ingredient combinations for different target groups.

Thus, the study confirms that the systematization of plant-derived functional ingredients and their natural food sources broadens the scientific understanding of health food products and creates a meaningful foundation for the further development of nutritionally improved and functionally oriented foods.

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Conflict of Interest

The author declares that there is no conflict of interest.

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Appendix

Table 1. The main food sources that will be included in the diet

Groups of substances	Main food sources
Phytosterols	All unrefined vegetable oils, soybeans, oats, amaranth, vegetables, fruits
Thiols (sulfur-containing phytochemicals)	Cruciferous vegetables: all types of cabbage, radishes, mustard, horseradish, garlic, onions
Isoflavones	Soybeans and other legumes, sunflower seeds, dates, cabbage, hops
Lignans	Flax seeds, sesame seeds, bran, rye, nuts, cherries, apples, parsley, carrots, garlic
Saponins	Green vegetables, potatoes, edible green shoots from vegetables (onions, garlic, parsley, lettuce, sorrel, etc.)
Flavonoids	Berries, fruits, vegetables, citrus fruits, tea, wine, soy
Phenolic acids	Fruits (apples, blueberries, cherries, plums), potatoes, nuts, soy, coffee beans

Visualizing Polymer Dispersion in PmB: Practical Aspects and Methodological Considerations ^[19]

Abstract:

The relevance of this study is determined by the increasing use of polymer-modified bitumen (PmB) in road pavement construction, where binder performance depends not only on macroscopic rheological characteristics but also on the stability and morphology of the polymer–bitumen two-phase system. The research problem lies in the methodological uncertainty of fluorescence microscopy for PmB analysis, since sample preparation, reheating, stirring, cooling rate and surface selection may substantially distort the observed microstructure and reduce the reliability of interpretation. The scientific novelty of the study consists in clarifying practical methodological conditions for visualising polymer dispersion in PmB and in demonstrating the analytical potential of digital image processing for estimating polymer phase volume and polymer concentration within that phase. The object of the study is polymer-modified bitumen containing styrene-butadiene-styrene block copolymer and, additionally, a thermoreactive polymer capable of interacting with bitumen components. The aim of the research is to analyse the practical aspects of polymer dispersion visualisation in PmB, assess the influence of sample preparation on the observed micromorphology, and determine how microstructural parameters may be used to evaluate binder stability and polymer–bitumen compatibility. The methods include storage stability testing according to EN 13399, penetration, softening point and elastic recovery tests according to EN 1426, EN 1427 and EN 13398, fluorescence microscopy according to EN 13632, UV-based micromorphological observation, and digital image processing of PmB specimens. The source base of the study includes European standards for bituminous binders and polymer dispersion visualisation, as well as research on polymer-modified bitumen morphology, storage stability, rheological performance, image texture analysis and SBS-modified asphalt binders. The study examines how reheating and hand stirring may change the original PmB microstructure, how internal and external specimen surfaces differ in their representativeness, and how phase dispersion is related to storage stability. It also analyses the correlation between the penetration of the initial bitumen and the scale of polymer dispersion, showing that a decrease in oil content leads to coarser morphology and higher destabilisation risk. In addition, the paper considers a specific case of apparent polymer phase autodispersion in PmB modified with a thermoreactive polymer and demonstrates that digital processing of fluorescence microscopy images can provide quantitative parameters of polymer–bitumen interaction. The results show that pouring PmB into moulds immediately after production provides a more reliable preservation of the original microstructure than reheating and hand stirring. The analysis of drop surfaces may be used only as a rapid field-oriented comparative check, because surface tension and cooling conditions may distort the volumetric representation of the polymer phase. Microstructural analysis cannot fully replace standard storage stability testing, but it can quickly indicate PmB systems at risk of phase separation during storage. The study concludes that fluorescence microscopy combined with digital image analysis is a promising additional method for operational control and research evaluation of PmB, since it enables the estimation of polymer phase volume, polymer concentration in the phase, compatibility of bitumen and polymer, and the stability of PmB as a multicomponent road binder system.

Keywords: polymer modified bitumen; luminescence; micromorphology; storage stability; epifluorescence microscope.

Abbreviations:

DIs is Destabilization Indices,

PmB is polymer modified bitumen,

SBS is styrene-butadiene-styrene block copolymer,

UV is ultraviolet radiation.

Introduction

Over the last century, global requirements for road pavement performance have increased substantially. In many cases, conventional road bitumen used as a component of asphalt mixtures can no longer provide the required performance characteristics under growing traffic loads, more intensive exploitation conditions and higher expectations regarding pavement durability. To meet these requirements, neat bitumen is increasingly replaced with PmB, which is more expensive but provides improved performance parameters, higher resistance to permanent deformation, better fatigue behaviour and enhanced durability of asphalt pavements (*Pyshyev et al., 2016; Kashkool & Hamdan, 2024; Zofka et al., 2021*).

The relevance of the present study is determined by the fact that the quality of PmB depends not only on traditional macroscopic rheological and empirical indicators, but also on the internal state of the polymer–bitumen system formed at the microscopic level. Polymer modification usually produces a two-phase system in which the polymer-rich phase and the bitumen-rich phase interact with each other. The morphology of this system, including the fineness of polymer dispersion, the size and distribution of polymer-rich domains, and the degree of interaction between polymer and bitumen components, has a direct influence on binder performance and asphalt mixture behaviour (*Wang et al., 2017; Emtiaç et al., 2023*). Therefore, the study of PmB micromorphology is an important direction in both road material science and practical quality control.

Despite the widespread use of polymer-modified bitumen in road construction, its quality indicators remain the subject of academic and industrial discussion. Traditionally, researchers and practitioners have paid considerable attention to macroscopic rheological parameters of PmB, such as complex modulus, temperature susceptibility, penetration, softening point and elastic recovery. These characteristics are undoubtedly important and are standardised in technical practice (*European Committee for Standardization, 2024, 2015, 2017a*). However, they do not always provide sufficient information about the internal structure of the binder, the degree of polymer dispersion and the stability of the polymer-rich phase. In this respect, microstructural analysis provides critical insights into the internal condition of the material and allows for a more comprehensive understanding of polymer–bitumen interaction.

The analysis of the PmB phase structure is facilitated by the fact that the polymer-rich phase typically exhibits luminescence under ultraviolet radiation. This makes it possible to observe polymer dispersion directly by means of fluorescence microscopy. The European standard EN 13632 provides a methodological basis for the visualisation of polymer dispersion in polymer-modified bitumen (*European Committee for Standardization, 2010*). At the same time, the method is sensitive to sample preparation, reheating, hand stirring, cooling conditions and the selection of the surface to be analysed. Therefore, the same PmB may produce different microscopic images depending on how the specimen was prepared. This creates a methodological problem because the observed morphology may reflect not only the actual structure of the binder, but also structural changes induced during sample treatment.

The research problem of this article lies in the insufficiently clarified practical conditions under which fluorescence microscopy can provide reliable information about PmB

micromorphology. Although the method has high analytical potential, its reproducibility and interpretative value depend on the control of sample preparation procedures. Reheating, stirring and surface selection may alter the original microstructure of the binder and thus lead to inaccurate conclusions regarding polymer dispersion, storage stability and polymer–bitumen compatibility. This problem is especially important for operational control at asphalt plants and for laboratory research where rapid and reliable information about the internal structure of PmB is required.

The scientific novelty of the study consists in the methodological clarification of practical aspects of polymer dispersion visualisation in PmB and in the demonstration of the potential of digital image processing for quantitative evaluation of polymer–bitumen interaction. The study does not treat fluorescence microscopy merely as an illustrative technique, but considers it as an analytical method capable of providing additional structural parameters, including polymer phase volume and polymer concentration within the polymer-rich phase. This makes it possible to connect visual micromorphological observations with the assessment of storage stability, compatibility of bitumen and polymer, and the expected performance of the modified binder.

The object of the study is polymer-modified bitumen as a multicomponent two-phase binder system used in road pavement construction.

The subject of the study is the micromorphological structure of PmB, the visualisation of polymer dispersion under ultraviolet radiation, and the influence of sample preparation procedures on the reliability of fluorescence microscopy results.

The study aims to analyse the practical and methodological aspects of polymer dispersion visualisation in PmB, to determine how sample preparation affects the observed micromorphology, and to assess the possibility of using fluorescence microscopy and digital image processing for evaluating PmB stability and polymer–bitumen interaction.

To achieve this aim, the following research tasks are set:

- to describe the methodological basis of polymer dispersion visualisation in PmB by fluorescence microscopy;
- to analyse the influence of reheating and hand stirring on the observed PmB microstructure;
- to compare the representativeness of internal and external specimen surfaces for microscopic analysis;
- to examine the relationship between PmB microstructure and storage stability indicators;
- to evaluate the influence of the initial bitumen properties on the scale and character of polymer dispersion;
- to analyse the specific behaviour of PmB modified with a thermoreactive polymer during storage;
- to demonstrate the possibility of using digital image processing for estimating polymer phase volume and polymer concentration within the polymer-rich phase;
- to determine the practical applicability of micromorphological analysis for laboratory research and rapid operational control of PmB.

The methodological basis of the study includes storage stability testing of modified bitumen according to EN 13399, determination of needle penetration according to EN 1426,

determination of softening point by the Ring and Ball method according to EN 1427, determination of elastic recovery according to EN 13398, and visualisation of polymer dispersion according to EN 13632 (*European Committee for Standardization, 2017b, 2024, 2015, 2017a, 2010*). The core analytical method is fluorescence microscopy under ultraviolet radiation, supported by digital image processing of PmB microstructure images. The study focuses primarily on SBS block copolymer as one of the most widely used polymer modifiers for road bitumen, while also considering a thermoreactive polymer capable of chemical interaction with bitumen components.

The theoretical significance of the study lies in deepening the understanding of PmB as a two-phase polymer–bitumen system whose performance is governed not only by composition and macroscopic properties, but also by microstructural organisation. The study contributes to the interpretation of the relationship between polymer dispersion morphology, bitumen composition, polymer swelling, phase separation and storage stability. It also develops the methodological discussion on the reliability of fluorescence microscopy in PmB analysis and highlights the need to account for specimen preparation as a factor that may transform the observed structure.

The practical significance of the results lies in the possibility of improving laboratory and field control of polymer-modified bitumen. The findings may be useful for researchers, road material laboratories, asphalt plant technologists and quality control specialists who use fluorescence microscopy to assess polymer dispersion. The proposed approach can help identify PmB systems at risk of phase separation, support rapid preliminary assessment of storage stability, and provide additional quantitative indicators of polymer–bitumen compatibility. At the same time, the study emphasises that micromorphological analysis should not replace standard testing procedures, but may serve as an effective complementary method for faster and more informative evaluation of PmB quality.

Thus, the present article addresses a practically significant methodological issue in the analysis of polymer-modified bitumen. By examining how sample preparation affects fluorescence microscopy results and by demonstrating the potential of digital image analysis, the study contributes to the development of more reliable procedures for evaluating PmB microstructure, storage stability and polymer–bitumen interaction.

Materials

The PmB research objects were prepared under laboratory conditions by modifying base pavement bitumen with varying concentrations of SBS copolymer and a thermoreactive polymer. SBS was selected as a commonly used modifier for road bitumen, the thermoreactive polymer was included due to its capacity for chemical interaction with bitumen components. All PmB samples were produced in low shear mixture with a consistent mixing duration of one hour at a temperature of 180°C.

Methods

In this study, to assess the storage stability of PmB, fresh samples were heated in sealed tubes in a vertical position, with no air allowed in the sample, for a total of 24 hours, divided into three 8-hour cycles, at 180 °C in accordance with the EN 13399 procedure (*European*

Committee for Standardization, 2017b). After the heating period, only the top and bottom sections of the sample, corresponding to one-third of the specimen, were collected for further analysis.

To quantitatively evaluate the storage stability of PmB, penetration, softening point and elasticity tests were performed for the top and bottom parts of the sample (*European Committee for Standardization, 2024, 2015, 2017a*). The discrepancy in properties between the top and bottom sections of the sample indicates PmB destabilisation.

The core method employed in this study is the visualisation of polymer dispersion in the PmB matrix by fluorescence microscopy, in accordance with the EN 13632 standard (*European Committee for Standardization, 2010*). UV radiation within the 360 to 440 nm range induces fluorescence in specific bitumen components. The fluorescence of low-molecular-weight bitumen fractions, namely bitumen oils, is particularly intense within the visible spectrum ranging from orange to green, enabling their visual detection (*Jelčić et al., 2016*).

In this study, the polymer phase of PmB is observed under UV radiation owing to the capacity of the SBS polymer to absorb bitumen oils. For this purpose, a specialised fluorescence, or epifluorescence, microscope configured to irradiate the sample with UV rays through the optical system was used. A set of filters isolates the required UV wavelengths from the broad-spectrum light source, which are then directed onto the sample by a beam splitter. This dichroic mirror reflects wavelengths shorter than 440 nm towards the specimen, while transmitting the resulting fluorescence, with wavelengths greater than 440 nm, into the binocular system for characterisation of sample morphology.

While the homogeneous distribution of components in neat bitumen makes this method ineffective, the internal structure changes significantly in PmB. The polymer typically forms a two-phase system with bitumen components. One phase consists of the polymer, which swells by absorbing bitumen oils, while the other phase is a residual bitumen composition of resins and asphaltenes, depleted of bitumen oils. The morphology of a PmB sample can be observed because of the distinct fluorescence intensity of both phases under UV radiation.

The resulting digital image, captured by a camera with the required resolution, allows for quantitative assessment of the PmB structure (*Gümüştekin et al., 2011*). The ratio of the polymer phase to the bitumen phase of the PmB was calculated as follows. The resulting images of the PmB specimens were corrected to eliminate uneven illumination of the sample surface within the microscope field, after which they were converted into a black-and-white image without greyscale. The three stages of the process are shown in the Appendix (*Figure 2*). For further image processing, a software package developed in our laboratory was used to determine the ratio of the area painted black in the frame to the area of the entire frame. If the sample was highly homogeneous, two frames were selected for analysis. For a non-homogeneous sample, the number of frames was increased, up to four.

Literature Review

The modification of bitumen with polymers has become a common technology in contemporary road construction. According to published data, the share of modified bitumen among other binders used in European road construction exceeds 10% and shows a consistent upward trend (*Pyshtyev et al., 2016*). Numerous studies have analysed the influence of polymer modifiers on the performance of both bitumen and asphalt. Despite the specific features of

each research work, most authors conclude that polymer incorporation significantly reduces the temperature susceptibility of the binder by increasing its viscosity at elevated environmental temperatures (*Kashkool & Hamdan, 2024; Zaumanis et al., 2026*).

Although the Fraass breaking temperature often remains unchanged, the softening point of polymer-modified bitumen is substantially higher, which results in greater resistance of road pavement to permanent deformation, or rutting. At intermediate temperatures, PmB exhibits higher stiffness, which is indicated by lower penetration values. This provides an important advantage in material design. For bitumen and PmB with the same penetration value, that is, with equal stiffness, the Fraass breaking temperature will be lower for PmB because the Fraass breaking temperature of the initial bitumen was lower and the polymer keeps it unchanged. Consequently, cracking of asphalt pavement with PmB occurs at lower temperatures compared with unmodified bitumen. An additional effect of PmB is the increase in asphalt fatigue resistance, which has also been reported in the literature (*Pyshyev et al., 2016; Zofka et al., 2021*).

Many researchers have emphasised the decisive influence of PmB morphology on the quality indicators of the binder and asphalt produced with it. At the microscale, the polymer forms a dispersion within the bitumen matrix. The geometry of this dispersion, including its fineness, particle size and distribution, as well as the degree of crosslinking between the polymer-rich phase, is considered an influential factor affecting the behaviour of PmB (*Emtiazi et al., 2023; Wang et al., 2017*). In turn, the morphology of PmB depends on the chemical composition of the bitumen, the amount and type of polymer, and the mixing parameters, such as shear rate, mixing temperature and mixing duration.

Despite these advantages, PmB is generally not recommended for storage because of its tendency towards phase separation. If storage without mixing cannot be avoided in the technological process, PmB should be tested for its ability to maintain sufficient homogeneity under static storage conditions. This test includes a comparison between the properties of the top and bottom parts of the PmB sample after long-term heating (*Zani et al., 2017; Zhu & Kringos, 2015*). Usually, this procedure takes several days if 24 hours of storage can be maintained in one cycle. Otherwise, four or five days may be required to obtain the results. For this reason, it is impossible to perform operational control during storage and make a quick decision concerning PmB stability.

The potential of fluorescence microscopy as a tool for evaluating the quality of PmB and predicting its performance characteristics has been demonstrated in numerous publications (*Larsen et al., 2009; Hanyu et al., 2005*). The micromorphology of PmB significantly affects the entire complex of properties enhanced by polymer modification. Hanyu et al. (2005) found that PmB samples differing only in the scale of their internal microstructure show superior asphalt performance when the phases are more finely dispersed. This effect becomes stronger as the polymer concentration increases.

This fact has drawn the attention of researchers to the analysis of PmB microstructure. However, Kou et al. (2015) showed that sample preparation methods significantly influence the resulting structure of PmB specimens. Various uncertain and uncontrolled factors during specimen sampling for analysis may affect the observed morphology, reduce reproducibility and distort the resulting image. Therefore, it is reasonable to examine several key aspects of the

analysis in a single set of test samples prepared under controlled conditions using the same equipment.

Results

Analysis of Reheated PmB Samples

A primary challenge in the PmB sampling for microstructure analysis is the necessity in reheating the samples. The EN 13632 standard for visualisation of polymer dispersion in polymer modified bitumen prescribes a homogenization of the sample by the “gentle hand stirring” of the sample for a duration of 1 to 5 minutes. To prevent localized overheating during the process the basin with the sample placing on a sand bath. However, in the text of this standard noted that any operations with samples (sample preparation and treatment) influenced a lot on the test results. This suggests that the process of homogenization of the melted sample creates the conditions for the microstructural changes. The question is: to what extent does the minimal sample treatment alter the original PmB morphology?

Figure 3 illustrates one of the most heterogeneous samples produced via hand steering. The left image captures the edge of the sample (dark field on the top of the image is the void space), while the right image displays the central part of the sample. The variations in structure are observable throughout the entire volume of the sample and cannot be attributed to different rates of cooling on a surface and in core. Regardless of process that cause the change of the structure during the sample treatment, the observed scale of microstructure change in the field of view varies by a factor five or more.

As a result, the analysis of such samples becomes complicated. The significant change in structure scale is accompanied by a transition in the type of structure. Large-scale formations relate to the intermediate type of PmB, where it is hard to say which phase is continuous, bitumen or polymer one. Small-scale formation clearly exhibits polymer phase as continuous. While the stirring of reheated sample may help reveal the difference in PmB structure if it changes in specimen volume (for instance if the top of PmB tube after storage stability test is under analysis), the reheating and stirring process themselves may induce these very changes. This applies certain limitations on the “hand stirring” method, included in standard EN 13632 as one of necessary steps in test sample preparation.

Internal Versus External Surfaces

The standard methodology requires freezing the sample of PmB to a brittle state and breaking it into pieces. For microscopic analysis, fragments are selected from the central part of the specimen, provided they have at least one sufficiently smooth surface. This methodology has two primary complications. First, this process is taking time to pour a PmB sample into the prepared mold and freeze the sample to the brittle state to break it, which requires a refrigerator. Second, samples with high polymer content (this can be the top of the tube PmB sample that lost its stability) can exhibit a glass transition temperature that lower than minus 40°C. In most cases it's hard to break this kind of sample, because even at low temperatures it is still maintains its elastic properties. It should mention that even after breaking you can get surfaces unsuitable for the microscope analysis.

The increasing in the speed of the test procedure can be achieved through alternative option, however it induces structural discrepancies. Figure 4 compares the same PmB sample, but the method of preparation differs. Left the traditional preparation method is presented. The piece of the sample core provides PmB morphology as it is. The right image is the surface of the drop of PmB. It's morphology differs in two aspects. The surface of bitumen phase occupies larger area and the polymer dispersion appears finer. The last one can be explained with the high rate of cooling the small-scale drop surface.

Figure 5 illustrates the structural difference between the core and the edge of the same sample. The core cools at a relatively low rate, it has more time for phase separation. The coalescence of polymer dispersion results in rougher sample structure in this case. Near the side surface, where the sample is in contact with the mold, its edge cooling rapidly, which preserve the initial dispersion. This explains the difference in size of PmB structure on the drop surface and in the core of the larger sample. The difference in the area of PmB phases much more dangerous, because its observation on the drop surface can lead to wrong conclusions.

This phenomenon is driven by surface tension within the liquid sample. On surface of PmB drop at the interface with air polymer and bitumen phases form a classical three phase system, that has its contact angles. The surface tension of the PmB phase seems to be higher than the bitumen one, so the polymer phase dipping into the sample to minimize its surface area at the air interface. This migration stops (or slowing down to a very low rate) when PmB cooling to the environmental temperature and its viscosity increases, but the result of it is noticeable. It can prevent the objective volumetric estimation of PmB structure, but it still remains valid for comparison analysis.

Correlating the PmB Storage Stability with Microstructural Parameters

For the set of the PmB specimens the stability assessment was performed according to the EN 13399 method, using penetration, softening point, and elasticity values given in the Appendix ([Table 1](#)). DIs were calculated as the difference between the values of the top and bottom sections of the sample, expressed as a percentage of their arithmetic mean. The four analyzed PmB samples differed in the penetration of initial bitumen. All initial bitumen spacemen were obtained from one source to minimize the side chemical variables that might influence the PmB stability. Before stability testing for the PmB there were obtained images of their microstructure, presented in the Appendix ([Figure 6](#)).

The images reveal a clear correlation between PmB microstructure and the base bitumen penetration. A decrease in penetration reflects a reduction in the concentration of bitumen oils, that makes polymer swell. For PmB a deficiency in bitumen oils leads to the formation of coarser “rougher” polymer dispersion in the PmB sample, which is inherently less stable.

Consequently, this allows for the preliminary estimation of a storage stability based on microstructure analysis of PmB. The scale of PmB microstructure can point on its tendency to keep stability at storage, or to lose it. Though for each case, depending on the type of mixer that produces the PmB, type and amount of polymer, the critical size of dispersion that indicates the risk of destabilization can change, in a consistent technological process it can be a reliable indicator. This method offers a rapid “field check” to identity PmB batches at risk of phase separation during storage.

The Phenomenon of PmB Autodispersion during Storage

Under several specific conditions during the storage of PmB without mixing, a phenomenon of polymer phase autodispersion may occur. In this research, this process was observed in the specimen modified with thermoreactive polymer, as shown in the Appendix (*Figure 7*). The left one image displays the initial PmB microstructure. The central and right images represent the top and bottom parts of the tube sample of the PmB after storage. The distinct phase dispersion after the storage is no longer observable. The evidence of the polymer's presence in the sample after heating is provided by the retention of penetration, softening point, and elasticity of the modified binder, presented in Table 2. The difference between top and bottom of the sample is minimal, so the polymer keeps stable in the bitumen matrix.

A possible explanation for the observed changes in the PmB microstructure lies in the capacity of the thermoreactive polymer to form chemical bonds between its chain complexes and the chemically active components of the bitumen. This interaction makes the polymer dissolve in the bitumen matrix to an undetectable degree of dispersion or release oils from the polymer phase, preventing identification of the polymer phase dispersion using their luminescence.

Quantitative Analysis of PmB Microstructure Via Digital Image Processing

The result of the computation of digital images of selected PmB samples is shown in the Appendix (*Table 3*). A comparative analysis of PmB samples with 3% and 9% SBS, prepared using the same initial BM bitumen, demonstrates that the volume of the polymer phase in the PmB is directly proportional to the amount of polymer added. Thus, as the polymer concentration in the BM bitumen increases from 3% to 9%, the volume of the polymer phase increases from 13.3% to 36.8%.

At the same polymer concentration, the volume of the polymer phase depends on the chemical composition of the initial bitumen. In high-penetration bitumens, characterized by a higher oil content, the volume of the polymer phase in the PmB ranges from 43% to 45%. With decreasing penetration, accompanied by a reduction in oils and maltenes overall, the volume of the polymer phase consistently decreases from 37% to 32%.

With the known polymer content in the PmB samples and the determined volume of the polymer phase, the polymer concentration in the polymer phase of the PmB can be calculated. For PmBs on the same bitumen with 3% and 9% SBS, the polymer concentrations in the phase are similar—21.8% and 22.4%, respectively. However, polymer concentrations in the polymer phase of PmBs on bitumens with different penetrations vary significantly—from 18.5% to 26.1%.

The similarity of polymer concentrations in the phase for PmBs on the same initial bitumen indicates that, when bitumen is modified with polymer, a process of limited polymer swelling occurs in the oil environment of the bitumen. The magnitude of polymer swelling at a concentration of up to 9% is constant and depends on the composition of the maltene environment, deteriorating with decreasing penetration of the initial bitumen.

Discussion

The sampling of PmB influence its microstructure, so this process must be minimized in time and number of operations with binder. The described in EN 13632 method must be used when the sample delivered to laboratory in the cooled state. If it is possible (during the research work or field control) to pour the sample in the molds right after its producing, the analysis will be more reliable. The analysis of polymer drops surface may be used in a limited cases such as quick check of PmB stability during the operation storage. The visual comparison of two drops of PmB from top and bottom of the storage container under UV radiation can provide the quick information for operation control. The size of phase dispersion in PmB directly depends on compatibility of polymer and bitumen. The higher compatibility results in forming the finer dispersion during PmB mixing, that more stable in time. The potential of this analysis is high and it can become the alter method of storage stability estimation. Here, using this method, is possible to quickly indicate PmB systems that is under a risk of losing storage stability and shouldn't storage without mixing. With this the digital image analysis of PmB microstructure allows to create the complex of indicators that can improve the operation control of PmB. The assessment of PmB morphology can fulfill the need in parameters that can be checked quickly during the operations on asphalt plant not cancelling of the other indicators. For the research work the calculation of parameters such as polymer concentration in polymer phase in PmB can provide the valuable information on expected parameters of PmB and ways to improve them.

Conclusion

One of the best decisions to obtain the unchanged PmB structure is to pour samples into molds right after the PmB producing. With the rapid cooling of the samples in the molds the structure changes less than in other methods and its visualization gives more reliable information on the PmB structure. The reheating and the hand stirring of the sample according the EN 13632 standard is not objective method because the microstructure of PmB changes in the process.

The changes in microstructure on the surface of the PmB drop not allow using this method for sample preparation. But for the quick field estimation of the PmB stability this method can be used. Two drops from the top and the bottom of the tank with PmB will differ will differ in fluorescent intensity under UV radiation that can be checked even visually.

In the case where operative information about stability risks of PmB is required, the test of PmB storage stability takes several days, but the microstructural analysis can provide the quick preliminary estimation of the PmB storage stability. Though it can't replace the whole analysis, it can quickly indicate the polymer-bitumen combinations that has large-scaled microstructure. Such a structure inherent to fewer compatible combinations and indicates a high risk to lose stability at storage.

The traditional phase separation can be replaced with the opposite process that close to autodispersion if the polymer able to react with bitumen components. It can create situation when polymer dispersion that can be observed after PmB preparation disappear after storage process.

The digital processing of the PmB microstructure images can be made on modern equipment with rather simple devices and programs. The results of microstructural analysis can

be used for calculation of specific parameters of PmB which provides valuable additional information on polymer-bitumen interaction. It can be useful analytical method to understand how the performance of PmB can be improved. The estimation of the volume of polymer phase and concentration of polymer in it gives two key parameters that can show the compatibility and stability of PmB as a multicomponent system.

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Conflict of Interest

The author declares that there is no conflict of interest.

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Appendix

Table 1. Destabilization of PmB with 3% SBS depending on the initial bitumen

Binder index	Penetration at 25 °C, 0.1 mm			Softening point, °C			Elasticity at 25 °C, %		
	Top	Bottom	DI, %	Top	Bottom	DI, %	Top	Bottom	DI, %
GM P3	243	256	-5.2	48.2	47.2	2.1	95	94	1.1
BMK P3	123	109	12.1	48.6	46.1	5.3	80	59	30.2
BM P3	72	53	30.4	57.6	53.1	8.1	93	47	65.7
BMO P3	52	32	47.6	78.0	64.9	18.3	95	60	45.2

Table 2. Stability of PmB with termoreactive polymer

Binder index	Penetration at 25 °C, 0.1 mm				Softening point, °C				Elasticity at 25 °C, %			
	Before	Top	Bottom	DI, %	Before	Top	Bottom	DI, %	Before	Top	Bottom	DI, %
Tr P2	95	90	83	8	50	56	57	2	67	68	72	6

Table 3. Structural properties of PmB by digital image analysis

Binder index	BM P3	GM P9	BMK P9	BM P9	BMO P9
Polymer concentration	3	9	9	9	9
Penetration at 25 °C, 0.1 mm	67	99	53	35	24
Softening point, °C	54.3	110.1	108.3	103.2	100.6
Volume of bitumen phase, %	86.7	57.0	55.3	63.2	68.4
Volume of polymer phase, %	13.3	43.0	44.7	36.8	31.6
Concentration of polymer in polymer phase, %	21.8	19.2	18.5	22.4	26.1
Amount of bitumen components, absorbed by polymer, %	10.4	34.7	36.4	28.6	23.4

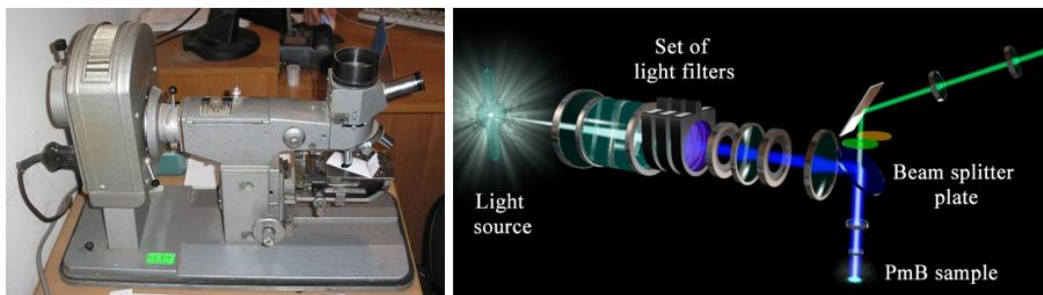


Figure 1. The fluorescence microscope and its optical scheme

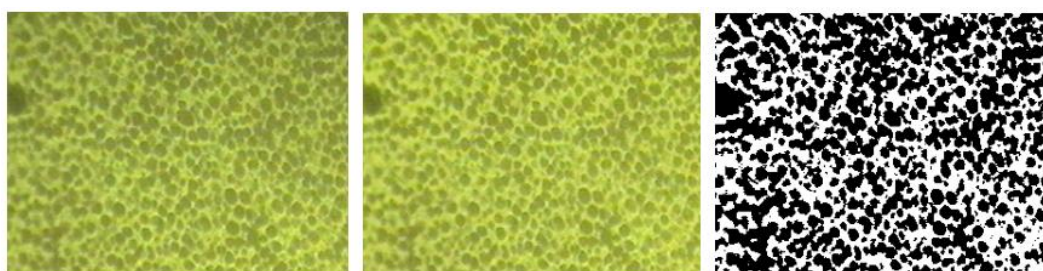


Figure 2. Stages of image processing for a polymer phase volume estimation

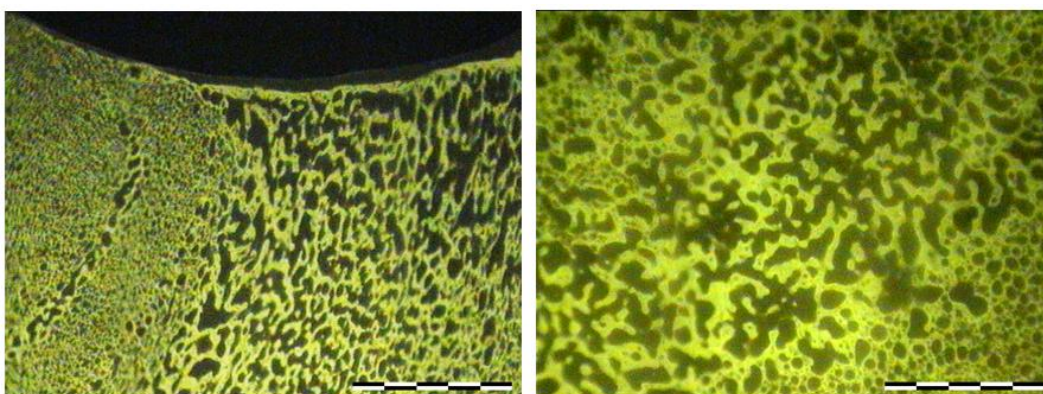


Figure 3. The heterogeneity in PmB sample structure after hand stirring

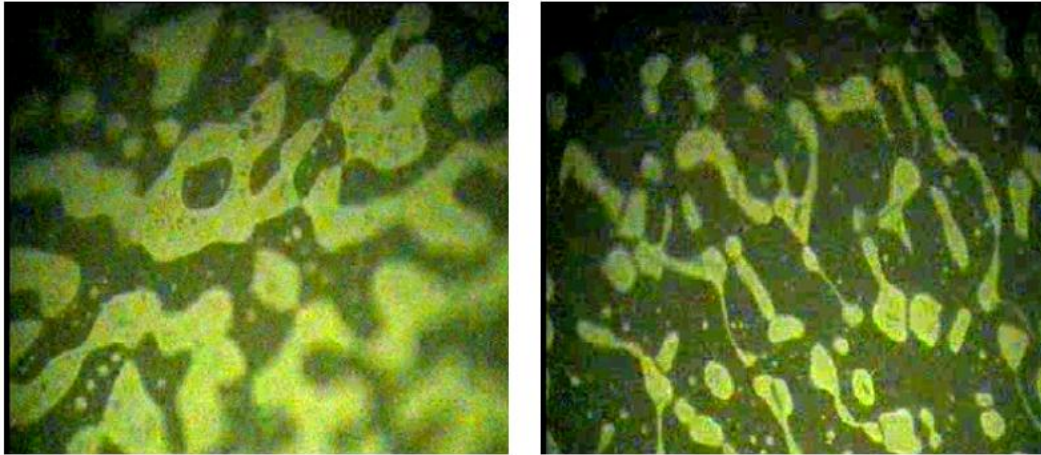


Figure 4. The inner surface (left) versus external (right) surface of the same PmB sample

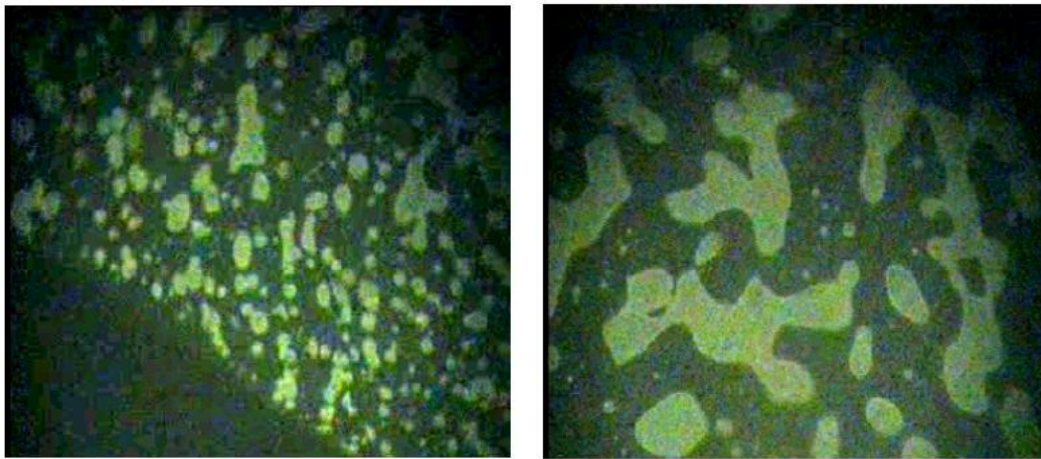


Figure 5. The difference between the edge (left) and the core (right) of the same PmB sample

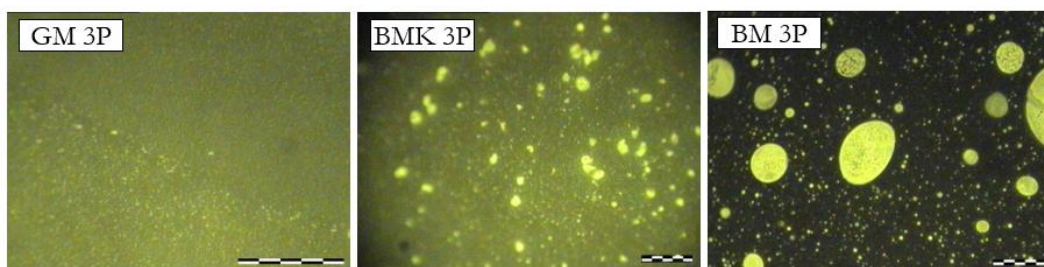


Figure 6. Difference in microstructure of PmB samples with 3% of SBS polymer depending on the initial bitumen



Figure 7. The results of the storage stability test for the sample with thermoreactive polymer

Elasticity Modulus as a Criteria of Asphalt Concrete Frost Resistance^[20]

Abstract:

The relevance of this study is determined by the need to improve the assessment of asphalt concrete frost resistance under cyclic freezing and thawing, especially in road pavements exposed to continental climatic conditions, water saturation and de-icing agents. The research problem lies in the fact that traditional frost resistance assessment is usually based on strength indicators before and after freeze–thaw exposure, whereas changes in elastic modulus and load-bearing capacity are insufficiently considered. The scientific novelty of the study consists in substantiating the elasticity modulus as an informative criterion for evaluating asphalt concrete frost resistance and in considering linear viscoelastic deformation analysis as a non-destructive testing approach. The object of the study is asphalt concrete subjected to cyclic freezing and thawing. The aim of the research is to determine how repeated freeze–thaw cycles and subsequent rest periods affect the elastic modulus of asphalt concrete and the frost resistance coefficient. The methodology includes cyclic freezing and thawing, water saturation, controlled temperature exposure, dynamic testing of asphalt concrete beams at different temperatures and frequencies, and analysis of elastic moduli within the region of linear viscoelastic deformation. The source base includes studies on freeze–thaw damage, frost resistance of asphalt concrete, bituminous binder brittleness, self-healing behaviour, internal void structure, de-icing resistance, and relevant CIS and European testing standards. The study analyses the influence of temperature, loading frequency, curing duration, freeze–thaw cycles and rest periods on the deformation characteristics of asphalt concrete. Particular attention is paid to the dependence of the frost resistance coefficient on time–temperature testing conditions and to the recovery effect, through which the elastic modulus may partially or almost completely return after ageing or rest at positive temperatures. The results show that asphalt concrete requires at least 30 days of curing before frost resistance testing, since structural formation continues after specimen preparation. The frost resistance coefficient increases with decreasing temperature and increasing test frequency, which indicates a strong relationship between frost resistance assessment and the rheological state of the material. The study also demonstrates that defects formed during cyclic freezing and thawing may undergo partial self-healing during rest at positive temperatures. It is concluded that linear viscoelastic deformation methods may serve as a reliable non-destructive approach for evaluating structural changes, damage and recovery processes in asphalt concrete after cyclic freeze–thaw exposure.

Keywords: asphalt concrete, frost resistance, linear viscoelasticity, elasticity modulus, heat recovery, cyclic freezing and thawing.

Abbreviations:

CFT is Cyclic Freezing and Thawing,

CIS is Commonwealth of Independent States,

K_{CFT} is frost resistance coefficient

Introduction

Due to its technological and operational advantages, asphalt concrete remains the most widely used material for road surfacing. Its advantages include relatively simple construction, high repairability, the possibility of tailoring mixture properties to specific operating conditions, rapid opening of pavement to traffic after construction, and a comparatively low noise level during use. However, despite extensive research on asphalt concrete performance, a number of

technological and climatic factors affecting its long-term durability remain insufficiently investigated. Among these factors, special attention should be paid to temperature transitions around 0°C, cyclic freezing and thawing, moisture saturation, and the combined influence of de-icing materials.

The relevance of this study is determined by the need to improve the assessment of asphalt concrete frost resistance under real pavement operating conditions. In regions with continental climates, cyclic freezing and thawing are seasonal processes that repeatedly affect asphalt concrete during the service life of road pavements. These processes are complicated by water penetration, ice formation, traffic loading and the possible use of de-icing agents. As a result, asphalt concrete may undergo changes in its internal structure, mechanical response and deformation characteristics, which ultimately influence the load-bearing capacity and durability of the entire pavement structure (*Cao et al., 2022; Mohi Ud Din et al., 2020; Lövqvist et al., 2021*).

Cyclic freezing and thawing are known to adversely affect asphalt concrete in road conditions. Although the consequences of this damage are visible from season to season in the form of flaking, potholes, surface degradation and local pavement failure, the mechanisms of asphalt concrete resistance to such damage have been studied less thoroughly than the mechanisms of low-temperature cracking. The complexity of these processes is associated with the simultaneous action of several factors: reduced temperature, vitrification of the bituminous binder, freezing of water in the pore space, temperature-induced microstresses, hydraulic pressure, and changes in the behaviour of the binder at phase boundaries (*Golovko, 1983; Gokhman & Gershkoben, 1997; Mauduit et al., 2007*).

The research problem lies in the fact that frost resistance has traditionally been evaluated mainly by comparing strength indicators of asphalt concrete specimens before and after freeze–thaw cycles. In many testing approaches, compressive strength, flexural strength or tensile strength are used as the main criteria for judging frost resistance (*STB 1115-2004, 2004; GOST 12801-98, 1999; SOU 42.1-37641918-110:2014, 2014*). However, this approach does not sufficiently reflect changes in the load-bearing capacity of pavement structures, especially when these changes are associated with the elastic modulus and deformation behaviour of asphalt concrete. A reduction in frost resistance may be directly expressed through changes in deformation parameters, and this can compromise both the asphalt concrete layer and the road structure over the design period.

The problem is further complicated by the uncertainty surrounding structural changes in asphalt concrete after freeze–thaw cycles and during subsequent rest periods in the warm season. Asphalt concrete is a material whose properties depend strongly on temperature, loading frequency and time-dependent deformation processes. Under decreasing temperature, it gradually passes from a visco-plastic state to a viscoelastic state and then towards an elastic and brittle state. Therefore, the frost resistance coefficient may depend not only on the number of freeze–thaw cycles, but also on the specific time–temperature testing conditions, the loading frequency, the duration of temperature exposure, and the possibility of partial structural recovery after rest at positive temperatures.

The working hypothesis of the study is that the elasticity modulus of asphalt concrete can serve as a more informative criterion of frost resistance than strength indicators alone, because it reflects changes in the material's deformation behaviour and load-bearing capacity after cyclic

freezing and thawing. It is also assumed that some structural defects formed during freeze–thaw exposure may be partially reversible, and that this recovery effect can be detected through changes in the elastic modulus after rest periods at positive temperatures. Consequently, linear viscoelastic deformation analysis may be used as a non-destructive method for evaluating damage and recovery in asphalt concrete.

The scientific novelty of the study consists in substantiating the elasticity modulus as a criterion for assessing asphalt concrete frost resistance under cyclic freeze–thaw exposure. Unlike traditional approaches based mainly on destructive strength testing, the proposed approach focuses on the rheological and deformation characteristics of asphalt concrete within the region of linear viscoelastic behaviour. The study also considers the recovery of elastic modulus after rest periods, thereby highlighting the reversible component of structural changes in asphalt concrete. This makes it possible to evaluate not only damage accumulation, but also the capacity of the material for partial self-healing or restoration of mechanical properties (*Qiu et al., 2020; Wang et al., 2021*).

The object of the study is asphalt concrete subjected to cyclic freezing and thawing.

The subject of the study is the change in the elastic modulus and frost resistance coefficient of asphalt concrete under different temperature, frequency, curing and rest conditions.

The study aims to determine how cyclic freezing and thawing, together with subsequent rest periods, affect the elastic modulus of asphalt concrete and to substantiate the applicability of linear viscoelastic deformation analysis as a non-destructive method for evaluating frost resistance.

To achieve this purpose, the following research tasks are set:

- to analyse the influence of cyclic freezing and thawing on the deformation characteristics of asphalt concrete;
- to examine how temperature and loading frequency affect the frost resistance coefficient calculated from elastic modulus values;
- to determine the influence of curing duration on the elastic modulus of asphalt concrete specimens;
- to evaluate the recovery effect after rest periods at positive temperatures following freeze–thaw exposure;
- to compare the behaviour of asphalt concrete before freeze–thaw cycles, after freeze–thaw cycles, and after subsequent rest periods;
- to substantiate the use of elastic modulus as a criterion for assessing changes in frost resistance;
- to assess the potential of linear viscoelastic deformation methods as a non-destructive testing approach for asphalt concrete frost resistance evaluation.

The methodological basis of the study includes cyclic freezing and thawing of asphalt concrete specimens, water saturation, controlled temperature exposure, dynamic loading of beam specimens at different temperatures and frequencies, and measurement of elastic moduli in the region of linear viscoelastic deformation. The study also takes into account existing approaches to determining frost resistance and resistance to de-icing fluids in standards and

testing procedures (*European Committee for Standardization, 2023; EN 12697-26, n.d.; GOST 12801-98, 1999; SOU 42.1-37641918-110:2014, 2014*).

The theoretical significance of the study lies in developing the understanding of frost resistance as a property connected not only with strength loss, but also with time-dependent deformation behaviour, elastic modulus variation, temperature–frequency sensitivity and structural recovery. The study contributes to the interpretation of asphalt concrete as a viscoelastic material whose resistance to freeze–thaw damage should be analysed through rheological parameters as well as through traditional strength indicators.

The practical significance of the results lies in the possibility of improving laboratory assessment of asphalt concrete frost resistance and making it more closely related to pavement performance. The use of elastic modulus as a criterion may reduce dependence on destructive testing, allow repeated testing of the same specimen, increase the reliability of comparisons, and provide more informative data on the structural condition of asphalt concrete after cyclic freezing and thawing. The proposed approach may be useful for road material laboratories, pavement designers and engineers working in regions where freeze–thaw cycles and de-icing agents significantly affect pavement durability.

Thus, the present study addresses the need to refine the evaluation of asphalt concrete frost resistance by shifting attention from strength indicators alone to deformation characteristics and elastic modulus changes. This approach makes it possible to analyse both damage accumulation and recovery processes and to develop a more reliable basis for assessing the durability of asphalt concrete under cyclic environmental loading.

Methods

The main factors affecting asphalt concrete under freeze–thaw conditions are reduced temperature, vitrification of the bituminous binder, and freezing of water within the material structure. At the same time, asphalt concrete changes from a two-phase system to a three-phase system when water is introduced and then, after ice formation, to a more complex multi-phase system (*Lövqvist et al., 2021*). This process is associated with the transition of asphalt concrete from a viscoelastic state to an elastic and brittle state when the temperature falls below a critical value. This critical value depends on the consistency of the bituminous binder, including its grade, penetration and type, as well as on the ratio between dispersed mineral powder content and binder content. Temperature-induced microstresses are intensified by water-related processes. As temperature changes, the density, degree of structuring and wetting ability of the binder also change, as does its behaviour at phase boundaries with the surface of mineral aggregates and the walls of bituminous films and capillaries. The ice formed in the material may be amorphous, crystalline or anisotropic.

According to observations reported in previous studies, the filtration and water saturation coefficients of asphalt concrete vary throughout the year: they decrease at the beginning of autumn, reach their maximum in April of the following year, and then decrease again as a result of water evaporation, although they remain higher than in the previous year. This development may result in extensive pavement destruction after 8–10 years of service. Based on widespread spring and winter damage to asphalt pavements in France in 2004–2005, it has been estimated that the total number of freeze–thaw cycles over 12–15 years may reach 500–1,200 or more,

which can lead to catastrophic pavement failure (*Manduit et al., 2007*). It has also been shown that even after 200 cycles of “dry” bending of bituminous membranes, microcracks may develop, indicating increased brittleness of the asphalt concrete and creating favourable conditions for pavement destruction during the transition period (*Gokhman & Gershkoben, 1997*).

Several studies consider thermal freeze–thaw damage to be primarily caused by large internal forces arising in the asphalt concrete structure when water freezes, as well as by hydraulic shock pressures occurring in spring under vehicle traffic (*Zhang et al., 2020; Manduit et al., 2007*). Other studies attribute this damage to temperature-induced microstresses (*Golovko, 1983*). This interpretation is supported by data on dry and wet freeze–thaw cycles, including up to 70 cycles at temperatures from -20°C to -40°C , from which it may be inferred that, in some cases, “dry” and wet freeze–thaw cycles have comparable destructive effects.

Frost resistance coefficients are generally used to compare the strength values of asphalt concrete specimens before and after freeze–thaw cycles, similarly to the assessment of stone materials and cement concrete. Requirements for the frost resistance coefficient of asphalt concrete, (K_{CFT}), are included in the standards of various CIS countries (*STB 1115-2004, 2004; GOST 12801-98, 1999; SOU 42.1-37641918-110:2014, 2014*). As a rule, these requirements are similar to those established for long-term water resistance. At the same time, a decrease in asphalt concrete frost resistance is reflected in its deformation parameters and may reduce the load-bearing capacity of both the asphalt concrete pavement layer and the entire road structure during the design service period. Therefore, the relationship between cyclic freezing and thawing and deformation characteristics should be evaluated in order to estimate this reduction more objectively. The present study is primarily aimed at examining the influence of cyclic freezing and thawing on the rheological properties of asphalt concrete.

The research methods selected by different scholars at different times have generally not been aligned in terms of either the duration of exposure or the temperature regimes applied to test specimens. Golovko (*1983*) studied freezing under different conditions, including temperatures of -20°C and below -40°C , with the number of freeze–thaw cycles varying up to 70. According to one standard method, specimens are saturated with a 5% sodium chloride solution, frozen at -18°C , thawed for two hours in the same solution, and then subjected to compressive strength testing (*STB 1115-2004, 2004*). In GOST 12801-98, a four-hour freeze–thaw cycle at -18°C and $+18^{\circ}\text{C}$, respectively, is recommended, with the number of freeze–thaw cycles set at 5, 10, 15, 25 or 50 (*GOST 12801-98, 1999*). The Ukrainian reference standard indicates freezing at -25°C for four hours and thawing at 20°C for four hours, with the minimum number of freeze–thaw cycles set at 25; in this case, the frost resistance coefficient is determined by the ratio of compressive strength to tensile strength along the cross-section (*SOU 42.1-37641918-110:2014, 2014*).

European standards define a method for determining the resistance of asphalt concrete to de-icing fluids, but they do not provide a full analysis of frost resistance mechanisms as such (*European Committee for Standardization, 2023*). None of the above methods makes it possible to reveal the nature of changes in asphalt concrete properties under freeze–thaw cycles. Their function is mainly to record the effect of exposure rather than to explain the mechanisms of structural change.

The research approaches described in other studies differ from the methods mentioned above. In particular, values of (K_{CFT}) calculated from the ratio of stiffness moduli under bending and from indirect tensile loading associated with cyclic loading have been reported (*Zhang et al., 2020; Yu et al., 2022*). The approach proposed by Yu et al. (2022) is non-traditional because it involves freezing for 24 hours at -18°C and thermostating at 60°C for 24 hours. After ten cycles under these conditions, the frost–heat resistance coefficient may decrease to approximately 0.3. However, the regime proposed by Liang (2008) may be considered insufficiently representative of actual asphalt concrete operating conditions in pavement because it combines two processes: freezing and water exposure. Moreover, water exposure may dominate the frost effect, since high temperatures cause rapid degradation of adhesion and water resistance in asphalt concrete (*Kodirov, 2022*).

Nevertheless, the results reported by Yu et al. (2022) are original and methodologically significant. In addition, the European standard for determining the modulus of elasticity under indirect tensile loading may be considered a non-destructive testing method, because the same specimen can be tested before and after exposure to water. The present study follows a similar logic by using a classical European test rig for determining elastic moduli under cantilever bending and for investigating resistance to frost-induced stress (*EN 12697-26, n.d.*).

To determine the elastic moduli at different temperatures and loading frequencies, a HADI vibration test rig was used (*Wang et al., 2021*). It was necessary to determine the elastic moduli within the region of linear deformation, which is limited by critical stresses and strains; beyond these limits, asphalt concrete enters the region of non-linear deformation (*Figure 1*).

The frost resistance tests were carried out as follows. On the second day, asphalt concrete specimens were placed under vacuum at 10–15 mm Hg, sealed, immersed in water at a temperature of $19\text{--}22^{\circ}\text{C}$, and then kept in air for two hours at room temperature, also within the range of $19\text{--}22^{\circ}\text{C}$. On the third day, the specimens were placed in a freezer pre-cooled to $-20 \pm 1^{\circ}\text{C}$. After freezing, the specimens were removed from the freezer and kept in water for four hours, after which they were frozen again for four hours. During overnight periods, from 8 p.m. to 8 a.m., the specimens were kept in water at a temperature of $19\text{--}21^{\circ}\text{C}$. In the studies dealing with property recovery, the required rest periods were provided in air at temperatures of 21°C and 30°C .

It should be noted that, because the effect of water content on the elastic modulus has been insufficiently studied, and in order to improve measurement accuracy, homogeneous sand-based asphalt concrete of type “G” was selected. The mixture was composed of separate fractions so that the particle size distribution curve occupied an average position between the boundary curves of dense mixtures. The content of mineral powder particles smaller than 0.071 mm was 11%. The content of bitumen of refinery grade BND 70/100 was 6%. The physical properties of the bitumen were as follows: penetration at 25°C — 82×0.1 mm; softening point— 50.5°C ; brittleness point— -17°C ; elongation at 25°C —94 cm.

A complete cycle of testing involved a number of technical difficulties. Therefore, during unavoidable interruptions, the test specimens were stored in a water bath at 21°C .

The standard stress–relative strain relationships shown in Figure 1 demonstrate that, at a given strain level, approximately corresponding to that experienced in road pavement, namely 0.2×10^{-3} , the critical stress before 50 freeze–thaw cycles is considerably higher than after 50

cycles. The difference is approximately 1.76 times. This indicates a change in the structural condition of asphalt concrete and a reduction in its load-bearing capacity, under which traffic loads may generate stresses exceeding the limits of linear deformation.

Literature Review

The main factors are: a drop in temperature, the bituminous binder undergoing vitrification, and water freezing. In this process, the asphalt concrete transitions from a two-phase system to a three-phase system, as water is added, and subsequently, following ice formation, to a four-phase system (*Löqvist et al., 2021*). This is accompanied by its transition from a viscoelastic state to an elastic state, and subsequently to a brittle state as the temperature drops below a critical value, which, in turn, depends on the consistency, grade, penetration and type of the bituminous binder and the ratio between the content of dispersed mineral powder and the binder. Temperature-induced microstresses are compounded by processes associated with the influence of water. As the temperature decreases, the density, degree of structuring, wetting ability and behaviour at the phase boundaries with the surface of stone materials and the walls of bituminous surfaces and capillaries change. The ice formed can be amorphous, crystalline and anisotropic.

A.S. Barankovsky (*1980*), based on observations of 11 sites on the streets of Moscow, stated that the filtration and water saturation coefficients of asphalt concrete fluctuate throughout the year: they decrease at the start of autumn, reach a maximum by April of the following year due to the central heating system, and thereafter, due to water evaporation, they decrease but remain higher than in the previous year (*Zhang et al., 2020*). According to Cao et al. (*2022*), after 8–10 years of such development, widespread destruction occurs. Based on widespread spring and winter damage in France in 2004–2005, French researchers concluded that the total number of cycles over 12–15 years can reach 500–1,200, after which the pavement undergoes catastrophic failure (*Mauduit et al., 2007*).

Gokhman and Gershkohen (*1997*) show that even after 200 cycles of ‘dry’ bending of bituminous membranes, microcracks form on them, indicating greater brittleness of the asphalt concrete and creating favourable conditions for the destruction of the asphalt concrete pavement during the transition period. Zhang et al. (*2020*) and Mauduit et al. (*2007*) consider the main causes of thermal-freeze-thaw damage to be the enormous forces affecting the structure of asphalt concrete when water freezes, and hydraulic shock pressures in spring during vehicle traffic. In Golovko (*1983*), the damage is explained by temperature-induced microstresses. In support of this, data on dry and wet freeze-thaw cycles, at temperatures of minus 20°C and minus 40°C based on up to 70 cycles, are presented, from which it follows that in some cases ‘dry’ and wet freeze-thaw cycles are comparable in terms of their destructive effect.

To assess frost resistance, coefficients are typically used which define the ratio of the strength values of asphalt concrete specimens before and after freeze-thaw cycles, in a similar manner to that used for stone materials and cement concrete. Requirements for the frost resistance coefficient, (K_{CFT}), of asphalt concrete are included in the standards of various CIS countries (*STB 1115-2004, 2004; GOST 12801-98, 1999; SOU 42.1-37641918-110:2014, 2014*).

As a rule, they are similar to the requirements for long-term water resistance specified in the same standards.

At the same time, a reduction in the frost resistance of asphalt concrete is directly reflected in its deformation characteristics, impairing the load-bearing capacity of the asphalt concrete pavement and the entire road structure over the design period. The extent of this reduction can only be assessed by evaluating the effect of cyclic freezing and thawing on the deformation characteristics themselves. This study is devoted to investigating the effect of cyclic freezing and thawing on the rheological characteristics of asphalt concrete.

Results

The frequency-dependent characteristics of the elastic moduli determined under these conditions across a frequency spectrum from 0.01 Hz to 10 Hz (three orders of magnitude) and at various temperatures (-10°C , 0°C , 20°C , 35°C) closely align with power-law relationships. At lower temperatures and higher frequencies, the elasticity modulus reaches up to 24,000 MPa, akin to grade 300 cement concrete levels. Conversely, under elevated temperatures (35°C) and reduced frequencies (0.01 Hz), this modulus declines dramatically to 400 MPa—a six-fold decrease. The temperature dependence of the elastic moduli across different frequencies illustrates an ongoing transition of asphalt concrete during its service life on road surfaces—from visco-plastic to visco-elastic states and ultimately toward brittleness (*Wang et al., 2021*). Even at sub-zero temperatures, asphalt concrete typically approaches a brittle state. It is this brittle material that encounters cyclic stresses and strains while also being affected by water action, which cools it down and can lead it into a frozen state; this sequence reduces both the strength and elastic moduli of the asphalt concrete.

Table 1 represents data from investigations involving beams prepared through different methods. One beam underwent dynamic loading just one day post-manufacturing, whereas another was pre-cured for a duration of 90 days at a temperature of 21°C . It is well-established that structural formation within asphalt concrete continues after production, concluding typically between 25–35 days. The findings displayed in the Appendix (*Table 1*) support this notion: across all tested frequencies and temperatures, pre-curing enhanced resistance against dynamic loading in the specimens. This discrepancy raises initial concerns regarding the methodological rigor applied in preparing specimens for evaluating other mechanical properties.

The data presented in Table 1 illustrates specific attributes of the K_{CFT} response under tested conditions, for which prior evidence is lacking. The K_{CFT} values across all temperatures exhibit an upward trend with increasing measurement frequency. This trend parallels the rise in elastic moduli and tensile strength values as test speeds increase, as noted by N.N. Ivanov and A.V. Rudensky. It can be inferred that at elevated deformation frequencies, the damping effect of significant structural defects does not have sufficient time to influence elastic moduli, similar to how long-term relaxation processes do not occur during rapid deformation.

Considering the principle of temperature-time superposition within viscoelastic systems, one can comprehend the rise in K_{CFT} values as temperature decreases across all frequencies. Consequently, the lowest K_{CFT} values are observed at higher temperatures and lower frequencies, while the highest are recorded at lower temperatures and higher frequencies. In the former scenario, asphalt concrete behaves like a viscoelastic material; in the latter, it exhibits

brittle characteristics. This raises a pertinent question: which combination of time (frequencies) and temperature presents a more accurate basis for investigation? It is suggested that this combination should align with the climatic conditions experienced by the asphalt concrete.

If we accept that frost resistance defines asphalt concrete's capacity to remain intact within pavement structures, whereas crack resistance pertains to its ability to preserve continuity along its length, it is essential to recognize that these mechanisms are fundamentally different. In terms of frost resistance, various microstructural failures arise due to water and frost exposure predominately affecting performance. Conversely, transverse cracks emerge from stresses within the pavement that exceed asphalt concrete's strength or from insufficient deformability relative to thermal linear contraction occurring along the pavement strip.

These disparate failure mechanisms can yield varying consequences throughout their respective life cycles. Cracks induced by temperature-related shrinkage typically do not self-heal and may only receive temporary repairs through sealing methods. In contrast, defects originating from thermal shrinkage may indeed recover under ambient temperature influences coupled with tire compaction effects. Generally, wheel tracks exhibit minimal flaking or spalling incidents, with potholes being infrequent occurrences.

To substantiate these hypotheses, heating tests were conducted on 50 samples of asphalt concrete that underwent pre-heating for 12 days at 21°C followed by an additional 10 days at 30°C. The results obtained (*Table 2*) demonstrate a notable increase in moduli during the initial stage: at 20°C—between 27% and 28%; at 30°C—up to 40%. Furthermore, prolonged ageing at 30°C results in a diminished rate of increase; this reduction becomes more pronounced as both test temperature and frequency decrease.

These findings corroborate a recent discovery that has been supported by numerous scientists, while others, including one of the authors of this study, have raised objections (Qiu et al., 2020). Consequently, it can be inferred that the defects produced during the CFT process possess the ability to self-repair, and efforts should be made to activate this healing mechanism. The increase in critical stress values at a relative strain of 2×10^{-4} , as illustrated in Figure 1, reinforces the proposed mechanisms of damage and recovery. It would also be beneficial to validate these observed phenomena through physico-chemical methods. Ultrasonic testing may lack sufficient sensitivity for these processes; however, scanning gamma-densitometry and electro-densitometry—techniques suggested by French researchers—might effectively identify internal defects (*Fauchard et al., 2016*).

The patterns discerned throughout this research and systematic control measurements regarding the reproducibility of initial test data suggest that the linear deformation method can indeed be recognized as a non-destructive approach for evaluating the frost resistance of asphalt concrete. In broader terms, this entails conditioning moulded specimens at temperatures between 18°C and 22°C for a duration of 30 days before assessing their modulus of elasticity at temperatures of 0°C, 10°C, and 20°C. The research findings indicate that employing higher temperatures is inadvisable due to potential self-healing of defects during tests lasting between 4 to 8 hours. Subsequently, samples undergo an appropriate number of CFT stages tailored to the specific climatic conditions of the region. After each stage, the modulus of elasticity is measured; utilizing known values from samples not subjected to CFT allows for determining corresponding K_{CFT} values. A significant advantage of this proposed methodology lies in its

enhanced reliability since it eliminates reliance on results from heterogeneous samples while also reducing the total number tested.

The intricate nature of changes in elastic moduli during the initial testing phase is depicted in Table 3. The beam was evaluated on day six post-manufacturing. Following a period of exposure to air at 20°C for 32 days, elastic moduli values exhibited an increase by a factor of 1.5. At a testing temperature of 10°C, there was approximately a 1.3-fold increase in elastic moduli; however, this increment diminished to between 1.1 and 1.2 times at temperatures ranging from 0°C to -10°C. An additional aging period of eighteen days at these lower temperatures had minimal impact on elastic moduli values. Furthermore, subjecting samples to ten freeze-thaw cycles resulted in decreased elastic moduli values alongside reductions in K_{CFT} : at temperatures of 20°C they fell to between 0.78–0.97; at 10°C they ranged from 0.82–1.03; at 0°C they were recorded between 0.74–0.92; and, finally, at -10°C they varied from 0.83–1.00.

As observed in prior instances, the CFT values exhibited an increase with frequency and a decrease in temperature. This particular case illustrates that, for an individual sample, there is an observable rise in modulus during the air-curing phase, which is subsequently followed by a decline after undergoing cyclic freeze-thaw testing.

Discussion

The results of the study demonstrate that the frost resistance of asphalt concrete cannot be adequately assessed only through conventional strength indicators measured before and after cyclic freezing and thawing. Although compressive, tensile or flexural strength values remain useful for standardised comparison, they do not fully reflect the changes that occur in the deformation behaviour and load-bearing capacity of asphalt concrete during environmental cycling. The elastic modulus appears to be a more sensitive and informative parameter because it reflects the internal structural state of the material, its rheological response, and its transition between viscoelastic, elastic and brittle behaviour under different temperature–frequency conditions.

The obtained results confirm that asphalt concrete is strongly dependent on both temperature and loading frequency. At lower temperatures and higher frequencies, the elastic modulus increases significantly, indicating that the material approaches a more rigid and brittle state. Conversely, at higher temperatures and lower frequencies, the elastic modulus decreases sharply, reflecting the dominance of viscoelastic and viscoplastic deformation mechanisms. This behaviour is consistent with the general theory of bituminous materials as temperature- and time-dependent systems. It also confirms the importance of the temperature–time superposition principle for interpreting frost resistance, because the same material may demonstrate substantially different mechanical responses depending on the selected testing temperature and loading frequency.

This dependence has direct implications for the interpretation of the frost resistance coefficient, (K_{CFT}). The study shows that (K_{CFT}) tends to increase as the testing temperature decreases and the loading frequency increases. This means that the coefficient is not a fixed material constant, but a parameter determined by the testing regime. Therefore, the selection of temperature and frequency conditions becomes a methodological issue of central importance. If the testing regime does not correspond to actual pavement operating conditions, the obtained

frost resistance coefficient may either overestimate or underestimate the real durability of asphalt concrete under cyclic environmental loading.

The observed reduction in elastic modulus after freeze–thaw cycles indicates that cyclic freezing and thawing causes structural degradation in asphalt concrete. This degradation may be associated with several mechanisms: water penetration into pores and microcracks, ice formation, hydraulic pressure, temperature-induced microstresses, weakening of bitumen–aggregate adhesion, and increased brittleness of the bituminous binder. These mechanisms are consistent with previous studies that describe freeze–thaw damage as a complex process involving water, low temperature, internal pressure and microstructural change (*Cao et al., 2022; Lövqvist et al., 2021; Mauduit et al., 2007*). The reduction in critical stress after 50 cycles also indicates that the material becomes less capable of maintaining linear deformation under traffic loads.

A significant finding of the study is the recovery effect observed after rest periods at positive temperatures. The increase in elastic modulus after ageing or rest at 21°C and 30°C suggests that some defects formed during cyclic freezing and thawing are at least partially reversible. This effect may be connected with relaxation processes in the bituminous binder, redistribution of internal stresses, partial restoration of adhesive bonds, closure of microdefects, and self-healing of bituminous films. Such behaviour corresponds to the broader concept of self-healing in asphalt materials, according to which bituminous binders may restore part of their mechanical integrity under favourable thermal and temporal conditions (*Qiu et al., 2020*).

At the same time, the recovery effect should not be interpreted as complete restoration of asphalt concrete durability in all cases. The degree of recovery depends on temperature, duration of rest, initial structural condition, number of freeze–thaw cycles, binder properties, air void structure, water saturation and previous ageing of the material. The results indicate that recovery is more pronounced at positive temperatures and may be more limited at lower testing temperatures. This suggests that frost damage in asphalt concrete includes both reversible and irreversible components. Reversible changes may be associated with relaxation and self-healing processes, whereas irreversible changes may include permanent microcracking, loss of adhesion and structural weakening of the mineral–bitumen matrix.

The findings also highlight the importance of specimen curing before testing. The increase in elastic modulus during the initial curing period confirms that structural formation in asphalt concrete continues after specimen preparation. This means that insufficiently cured specimens may produce distorted results in frost resistance testing. The conclusion that asphalt concrete should be cured for at least 30 days before testing is therefore methodologically significant. It reduces the risk of confusing the effects of structural formation with the effects of freeze–thaw damage and allows a more objective evaluation of material behaviour.

The comparison between specimens tested shortly after preparation and those subjected to longer curing demonstrates that the initial structural state of asphalt concrete plays a decisive role in its response to cyclic freezing and thawing. A specimen that has not completed its structural formation may show lower resistance to dynamic loading and may respond differently to moisture and temperature cycling. This observation is important for laboratory practice because reproducibility and comparability of frost resistance results depend not only on the freezing–thawing regime, but also on specimen preparation, curing history and storage

conditions before testing.

The results also question the adequacy of traditional frost resistance standards based mainly on destructive strength testing. Existing standards in CIS countries generally calculate frost resistance through ratios of strength values before and after freeze–thaw exposure (*STB 1115-2004, 2004*; *GOST 12801-98, 1999*; *SOU 42.1-37641918-110:2014, 2014*). Such methods can indicate that damage has occurred, but they do not reveal the nature of the structural changes or their influence on the deformation behaviour of pavement. By contrast, elastic modulus measurement in the linear viscoelastic range allows the same specimen to be tested repeatedly, making it possible to trace the evolution of damage and recovery over time.

The use of linear viscoelastic deformation analysis as a non-destructive testing approach is one of the most important methodological implications of the study. Since the same specimen can be measured before freeze–thaw exposure, after selected numbers of cycles, and after rest periods, this method reduces the influence of specimen heterogeneity. It also improves the reliability of comparisons because changes are assessed within the same material sample rather than between different specimens. This is particularly important for asphalt concrete, whose composition, air void content, aggregate structure and binder distribution may vary even within a single laboratory batch.

The proposed approach also provides a more pavement-oriented understanding of frost resistance. In actual road structures, asphalt concrete is subjected not only to low temperature and moisture, but also to repeated traffic loading. Therefore, changes in deformation characteristics are directly relevant to pavement performance. A reduction in elastic modulus and critical stress may indicate a decrease in the load-bearing capacity of the pavement layer, increased susceptibility to deformation, and a higher risk of crack development or surface distress. Thus, the elasticity modulus is not only a laboratory parameter, but also a performance-related indicator.

The study also supports the need to distinguish between frost resistance and low-temperature crack resistance. These two phenomena are connected with low temperatures, but their mechanisms are different. Frost resistance concerns the ability of asphalt concrete to withstand damage caused by water, freezing, thawing and repeated environmental cycling. Low-temperature crack resistance, by contrast, is associated primarily with thermal stresses and insufficient deformability under contraction. The results show that freeze–thaw damage may include microstructural failures that can partially recover, whereas transverse thermal cracks usually do not heal spontaneously and often require repair. This distinction is important for both material testing and pavement design.

From a theoretical perspective, the study contributes to the understanding of asphalt concrete as a complex viscoelastic material whose frost resistance should be considered in relation to rheological state, loading frequency, temperature and structural evolution. The elastic modulus reflects the internal balance between stiffness, relaxation capacity and damage accumulation. Therefore, frost resistance should not be reduced to a single strength ratio. It should be interpreted as a dynamic property that changes under cyclic environmental loading and may partially recover under favourable thermal conditions.

From a practical perspective, the findings may be used to improve laboratory procedures for evaluating asphalt concrete in regions exposed to repeated freeze–thaw cycles. The proposed

method can support more informative frost resistance testing by including elastic modulus measurements at selected temperatures and frequencies. It may also help pavement engineers select asphalt concrete compositions that maintain sufficient stiffness and linear deformation capacity after environmental cycling. In addition, the method may be useful for comparing binders, aggregate structures, air void contents and mixture designs in terms of their resistance to frost-induced degradation.

The study also has implications for pavement construction timing. The recommendation that pavement installation should be limited by ambient temperature and seasonal conditions is justified by the continuing structural formation of asphalt concrete after placement. If asphalt concrete does not have sufficient time and favourable thermal conditions to develop its structural integrity, it may enter the cold season with lower resistance to freeze–thaw damage. This is especially important in spring and autumn, when temperature fluctuations around 0°C are frequent and moisture conditions are unfavourable.

However, several limitations should be acknowledged. First, the study focuses on one asphalt concrete type and one bitumen grade, which limits the generalisability of the results to other mixture compositions, binders, aggregate structures and air void contents. Secondly, the testing programme involves specific freezing, thawing, rest and loading regimes; other climatic regions may require different combinations of temperature, duration and number of cycles. Thirdly, although the recovery effect is clearly observed through elastic modulus changes, its physicochemical mechanisms require further confirmation using additional methods. Fourthly, the study does not fully separate the influence of water saturation, freeze–thaw action, binder ageing and thermal relaxation, although all of these factors may contribute to the observed response.

Future research should therefore include a broader range of asphalt concrete mixtures, binder grades, polymer-modified binders, air void contents and aggregate gradations. It would also be useful to compare dry and wet freeze–thaw regimes, as well as the influence of de-icing agents, under controlled laboratory conditions. Additional physicochemical and microstructural methods may help confirm the mechanisms of damage and recovery. Scanning gamma-densitometry, electro-densitometry, X-ray computed tomography, acoustic emission, digital image correlation and microscopic analysis may be particularly useful for detecting internal defects and monitoring their evolution.

Further research should also aim to develop a unified testing framework that connects elastic modulus changes with pavement design parameters. Such a framework could include recommendations for specimen curing, temperature–frequency testing conditions, number of freeze–thaw cycles, rest periods and interpretation of recovery effects. This would make it possible to move from empirical frost resistance coefficients towards a more mechanistic and performance-related assessment of asphalt concrete durability.

Overall, the discussion confirms that the elasticity modulus is a valuable criterion for assessing the frost resistance of asphalt concrete. It reflects damage accumulation, structural weakening, rheological state and recovery potential more comprehensively than traditional strength-based indicators alone. The use of linear viscoelastic deformation analysis enables non-destructive monitoring of the same specimen over successive stages of testing and provides a more reliable basis for evaluating the durability of asphalt concrete under cyclic freezing and

thawing. Therefore, the proposed approach may contribute to improving both laboratory assessment and practical pavement design in cold and variable climates.

Conclusion

The study confirms that the assessment of asphalt concrete frost resistance should take into account not only conventional strength indicators, but also changes in the elastic modulus, since this parameter reflects the deformation behaviour and load-bearing capacity of the material after cyclic freezing and thawing. The results show that asphalt concrete continues to undergo structural formation after specimen preparation; therefore, a curing period of at least 30 days should be provided before testing the modulus of elasticity and frost resistance indicators. This requirement is important for obtaining reliable and comparable results, because insufficiently cured specimens may demonstrate unstable mechanical behaviour that does not objectively represent the material's resistance to freeze–thaw damage.

The findings also indicate that the frost resistance coefficient is strongly dependent on testing conditions. It increases as the temperature decreases and as the loading frequency rises, which corresponds to the relaxation behaviour of asphalt concrete and the temperature–frequency dependence of its elastic modulus. This confirms that the frost resistance coefficient cannot be treated as an absolute material constant without reference to the selected testing regime. Consequently, the choice of test temperature and loading frequency must be scientifically justified and correlated with the actual climatic and operational conditions of the pavement.

A further important result is the observed ability of asphalt concrete to partially restore frost resistance after rest or ageing at positive temperatures. This recovery effect becomes more pronounced at elevated positive temperatures, indicating that some structural changes caused by cyclic freezing and thawing may be reversible. The restoration of elastic modulus after rest periods suggests the presence of relaxation and self-healing processes within the asphalt concrete structure. At the same time, this recovery should be understood as partial, since freeze–thaw exposure may also produce irreversible defects that accumulate during pavement service life.

The results have practical implications for both laboratory testing and road construction practice. Since structural formation and recovery processes are temperature-dependent, pavement construction should be limited by ambient air temperature and seasonal conditions. In particular, asphalt concrete pavement installation should not be carried out at temperatures below 5°C in spring and below 10°C in autumn, similarly to the restrictions applied to pavement layers made with cold asphalt concrete mixtures. These limits are necessary to ensure proper structural formation before the pavement is exposed to intensive freeze–thaw action.

The study substantiates the use of linear viscoelastic deformation methods as a non-destructive approach for analysing the structure, damage and recovery of asphalt concrete after cyclic freezing and thawing. This method makes it possible to test the same specimen at different stages of exposure, thereby reducing the influence of specimen heterogeneity and improving the reliability of frost resistance assessment. Overall, the elasticity modulus can be considered an informative criterion for evaluating asphalt concrete frost resistance, while linear viscoelastic deformation analysis provides a promising methodological basis for more accurate and

performance-oriented testing of asphalt concrete in cold and variable climatic conditions.

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Conflict of Interest

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Appendix

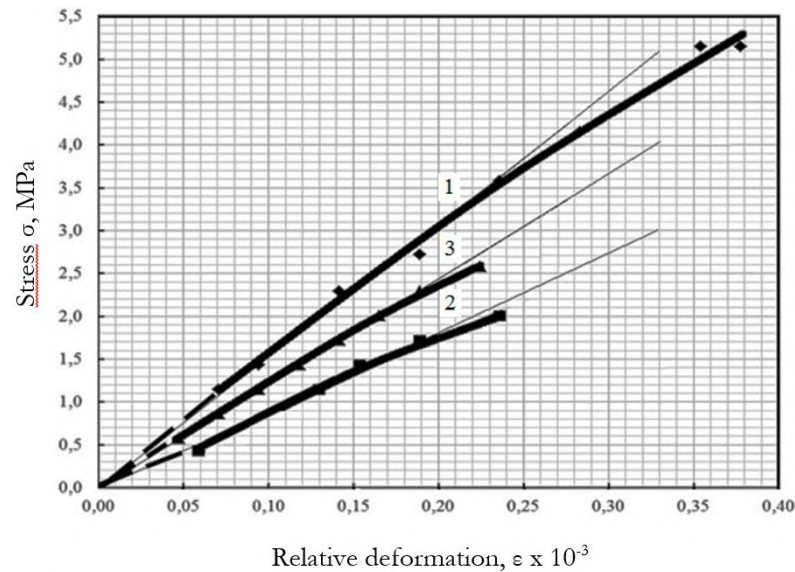


Figure 1. Differences between deformation and stress in asphalt concrete at 0.5 Hz: 1—Before 50 cycles; 2—After 50 cycles; 3—After 50 cycles and 12 days of curing at 21°C

Table 1. Dependence of the frost resistance coefficients of asphalt concrete after 21 cycles of freezing and thawing, 17 days of immersion in water and 29 cycles of freezing and thawing on temperature and frequency

Frequency, Hz	Frost resistance coefficients at temperatures, °C				
	35	20	15	0	–10
0,01	0,63 / –	0,53 / 0,27	0,53 / 0,35	0,63 / 0,63	0,85 / 0,91
0,1	–	0,54 / 0,33	0,56 / 0,30	0,78 / –	–
0,5	–	0,58 / 0,33	0,63 / 0,40	0,85 / –	–
1,0	–	0,61 / 0,38	0,63 / 0,45	0,63 / 0,71	–
5,0	0,85 / –	0,64 / 0,38	0,77 / 0,44	–	1,0 / 0,95

Note: In the numerator—a beam that was left to stand for 90 days at a temperature of +21°C prior to the load test; in the denominator—a beam that was formed prior to the load test.

Table 2. The effect of dormancy on frost resistance

Temperature, °C	Frequency, Hz	Increase in frost resistance coefficients after curing			
		Modulus relative to the reference value, MPa	K _{CFT} after 50 CFT's	K _{CFT} after 12 days of ageing (21°C)	K _{CFT} after 12 days of rest (21°C) and 10 days of rest (30°C)
20	0,01	2344	0,27	0,56	0,78
	0,1	3467	0,33	0,61	0,79
	0,5	4786	0,33	0,62	0,78
	1,0	5248	0,38	0,67	0,76
	5,0	6918	0,38	0,65	0,72
15	0,01	3019	0,35	0,66	0,74
	0,1	6025	0,30	0,52	0,62
	0,5	6310	0,40	0,60	0,72
	1,0	6920	0,45	0,72	0,76
0	0,01	6606	0,63	1,0	0,98
	0,1	9332	0,68	1,0	0,98
	0,5	11430	0,69	1,0	0,98
	1,0	13180	0,68	1,09	0,92
	5,0	14790	0,71	1,12	0,83

Table 3. The effect of the CFT regime and rest periods on frost resistance indicators

Temperature, °C	Frequency, Hz	Complex elasticity moduli E*×10 ⁻³ , MPa					Ratio of modules and K _{CFT} 's		
		Test mode							
		After CFT (for 6 days)	Rest (for 32 hours)	Rest (for 50 hours)	10 CFT's	50 CFT's			
		E ₁	E ₂	E ₃	E ₄	E ₅	E ₃ /E ₁	K _{CFT} E ₄ /E ₃	K _{CFT} E ₅ /E ₃
20	0,01	1,03	1,56	1,55	1,21	1,13	1,51	0,78	0,73
	0,5	2,13	3,34	3,87	3,38	3,38	1,80	0,87	0,87
	10	3,5	5,43	5,57	5,43	5,43	1,59	0,97	0,97
10	0,01	3,1	4,06	3,53	2,89	2,70	1,31	0,82	0,76
	0,5	6,0	7,67	6,8	6,79	6,79	1,28	1,00	0,99
	10	7,99	9,60	9,63	10,05	8,51	1,20	1,03	0,88
0	0,01	6,54	8,72	8,82	6,55	7,25	1,33	0,75	0,82
	0,5	11,05	14,75	13,6	10,88	10,9	1,33	0,82	0,80
	10	11,68	15,88	14,80	13,7	13,6	1,36	0,92	0,91
-10	0,01	12,16	13,27	12,50	10,41	10,15	1,09	0,83	0,81
	0,5	16,34	17,70	16,34	16,34	15,64	1,08	1,00	0,96
	10	17,47	21,80	20,33	18,31	17,45	1,16	0,90	0,86

Formation of the Structure and Physical and Mechanical Properties of Non-autoclaved Foam Concrete with an Activated Soluble Component ^[27]

Abstract:

This article presents the results of an experimental study on the influence of mechanochemical activation of the mortar component on the physical and mechanical properties of non-autoclaved foam concrete. The relevance of the topic is обусловлена the need to increase the strength and operational reliability of cellular concretes while simultaneously reducing cement consumption and the energy intensity of production. The object of the study is non-autoclaved foam concrete, and the subject is the processes of structure formation and strength development under conditions of mechanochemical activation. The aim of the study is to establish the patterns of influence of combined mechanical and chemical activation on material properties and to determine the possibilities for their regulation. The Box-Behnken plan is applied. The study employed methods of physical experimentation, experimental design (in particular, a multifactor approach), and analysis of the obtained dependencies. The theoretical basis includes the works of domestic and foreign researchers in mechanochemical activation and concrete technology. It has been established that the use of high-speed mixing in combination with chemical accelerating additives ensures a redistribution of structural changes in the solid phase, intensifies cement hydration processes, and promotes the formation of a denser material structure. The obtained results confirm the possibility of a significant increase in the strength of foam concrete up to 325% and controlled regulation of its properties in a wide range, which opens up prospects for effective use of the material in modern construction.

Keywords: foam concrete, mechanochemical activation, cement hydration, strength, filler, additives.

Abbreviations:

Ad is admixture,

AT is activation time,

C is cement,

HMT is heat-moisture treatment,

PC is Portland cement.

Introduction

The industrial production experience of non-autoclaved foam concrete accumulated in recent years has made it possible to identify a number of persistent disadvantages of this material. As before, the issues of strength development and crack resistance remain insufficiently resolved. In the manufacture of products in individual moulds, the deviation of geometrical dimensions from the required indicators becomes a significant technological problem. Due to the non-uniform dimensions of blocks, their installation using adhesive mortars becomes difficult or even impossible. Another disadvantage of block foam concrete is the smoothness of its lateral surfaces, which reduces the adhesion of plaster mortar to the block surface and requires additional costs for the installation of reinforcing meshes. In addition, in the production of non-autoclaved foam concrete on stationary equipment, the slow strength gain reduces mould turnover and consequently increases the cost of products.

At the same time, foam concrete retains a number of unquestionable advantages that justify

its further technological development. These include the possibility of production without autoclaving, dimensional stability during pore formation, availability of raw materials, relative simplicity of technology and equipment, low density, and favourable thermal insulation properties. The use of foam concrete is particularly promising in modern monolithic-frame housing construction, where it may serve as an enclosing wall material. However, such application requires the development of technological solutions aimed at improving the physical and mechanical properties of non-autoclaved foam concrete, especially its compressive strength, structural stability and reliability under service conditions.

The relevance of this study is determined by the need to improve the strength and operational performance of non-autoclaved foam concrete while reducing cement consumption, production cost and energy intensity. For non-autoclaved cellular concretes, the problem is especially important because, unlike autoclaved materials, their structure formation occurs under normal or moderately intensified curing conditions. Therefore, the mechanical properties of the final material depend strongly on cement hydration, the stability of the porous structure, the ratio between binder and filler, the use of chemical additives, and the technological method of mixture preparation. Previous studies emphasise that the properties of cellular and foam concretes are governed by multiple factors, including mixture composition, pore structure, rheological behaviour, curing regime and activation of cementitious systems (*Martynov et al., 2021a; Martynov et al., 2021b; Liew et al., 2021; Xiong et al., 2025*).

The research problem lies in the contradiction between the technological and economic advantages of non-autoclaved foam concrete and its insufficient strength characteristics when produced by conventional methods. Increasing cement content may improve strength, but it also increases the cost of the material, raises the water demand of the mixture, intensifies shrinkage processes and may contribute to crack formation. Conversely, replacing part of the cement with filler can reduce cost and shrinkage-related risks, but excessive filler content may reduce strength. Therefore, it is necessary to identify technological methods that can increase the efficiency of Portland cement, accelerate hydration, improve structure formation and compensate for the strength loss associated with partial cement replacement.

One of the promising approaches to solving this problem is mechanochemical activation of the mortar component of foam concrete. This approach combines mechanical activation in a high-speed mixer with the use of chemical hardening accelerators. Mechanical activation can intensify cement hydration, increase the degree of dispersion of the solid phase, promote the formation of cementitious hydrates and improve the distribution of components in the mixture. Chemical activation, in turn, may accelerate strength gain and improve the early structural stability of foam concrete. The combined use of both mechanisms may produce a synergistic effect, making it possible to regulate the structure and properties of non-autoclaved foam concrete more effectively than by either mechanical or chemical activation alone (*Barabash & Harashchenko, 2018; Rakhimov et al., 2020; Shcherban et al., 2021*).

The scientific novelty of this study consists in the experimental substantiation of the combined influence of filler content, chemical hardening accelerator dosage and activation time of the mortar mixture in a high-speed mixer on the structure formation and strength characteristics of non-autoclaved foam concrete. Unlike approaches that consider these factors separately, the present study analyses their joint effect within a three-factor experimental design.

This makes it possible to evaluate not only the individual influence of each technological factor, but also their interaction and synergistic contribution to strength development.

The object of the study is non-autoclaved foam concrete intended for use as a lightweight wall and enclosing material in building construction.

The subject of the study is the formation of the structure and physical and mechanical properties of non-autoclaved foam concrete under conditions of mechanochemical activation of the mortar component.

The study aims to improve the strength properties of non-autoclaved foam concrete by changing the character and mechanical properties of the solid phase through activation of the mortar component and by determining the influence of recipe-technological factors on the final material properties.

To achieve this purpose, the following research tasks are set:

- to analyse the main technological disadvantages of non-autoclaved foam concrete that limit its wider use as a wall material;
- to determine the influence of filler content in the cement–filler mixture on the strength characteristics of foam concrete;
- to evaluate the effect of the “Plastidor” chemical hardening accelerator on cement hydration and strength development;
- to determine the influence of activation time of the mortar mixture in a high-speed mixer on the physical and mechanical properties of foam concrete;
- to identify the combined effect of mechanical and chemical activation on the structure formation of non-autoclaved foam concrete;
- to assess the influence of curing conditions, including normal-humidity curing, natural curing and heat-moisture treatment, on strength gain;
- to establish the possibility of reducing Portland cement consumption by introducing filler without reducing the required strength indicators;
- to determine whether activated non-autoclaved foam concrete can reach performance characteristics comparable with those of autoclaved cellular concretes.

The methodological basis of the study is a three-factor experiment carried out using mathematical methods of experimental design. The experiment was implemented according to a standard Box–Behnken design of type B-3. The selected variable factors are the content of filler in the mixture with cement, the content of a chemical hardening accelerator as a percentage of cement mass by dry substance, and the activation time of the mortar mixture in the reactor of a high-speed mixer. This design makes it possible to compare different technological routes for producing foam concrete and to analyse the combined influence of recipe and technological parameters.

The theoretical significance of the study lies in developing scientific understanding of structure formation in non-autoclaved foam concrete under conditions of mechanochemical activation. The research clarifies the role of Portland cement hydration intensity, filler content, chemical acceleration and mechanical activation in the formation of the solid phase and in the development of strength. It also contributes to the broader theory of cellular concrete technology by showing how the properties of non-autoclaved foam concrete may be controlled

through coordinated regulation of mixture composition and technological activation.

The practical significance of the study is connected with the possibility of producing non-autoclaved foam concrete with improved strength and reduced cost. The proposed technological approach allows part of expensive Portland cement to be replaced with filler while maintaining or increasing the required strength indicators through activation of the mortar component. This may improve the economic efficiency of production, increase mould turnover, reduce the energy intensity of manufacturing and expand the field of application of foam concrete from thermal insulation material to structural and thermal-insulating wall material. In practical construction, such material may be used in monolithic-frame housing construction and in low-rise buildings as an enclosing or wall material.

Thus, the present study addresses an important technological problem in the production of non-autoclaved foam concrete: how to improve strength and structural reliability without increasing cement consumption and production complexity. The proposed combination of chemical acceleration and mechanical activation offers a promising route for controlled regulation of the structure and physical and mechanical properties of foam concrete, making the material more competitive for modern construction applications.

Methods

To achieve the aim, a three-factor experiment was carried out using mathematical methods of experimental design. The experiment was conducted according to the standard Box–Behnken design of type B-3.

The selection of variable factors, as well as the levels of their variation, was based on a priori information. From the wide range of mix-design and technological factors affecting the quality of foam concrete, factors were selected which, on the one hand, influence the kinetics of plastic strength development and the final strength of foam concrete and, on the other hand, increase the efficiency of the binder by accelerating and increasing the degree of cement hydration.

The selection of variable factors, as well as the levels of their variation, was based on a priori information. From the wide range of mix-design and technological factors affecting the quality of foam concrete, factors were selected which, on the one hand, influence the kinetics of plastic strength development and the final strength of foam concrete and, on the other hand, increase the efficiency of the binder by accelerating and increasing the degree of cement hydration.

The following factors were selected:

X1—the content of filler in the mixture with cement, expressed as fractions of a unit, (C);

X2—the content of the admixture accelerating cement hardening, expressed as a percentage of cement mass by dry substance, (A);

X3—the activation time of the mortar mixture in the reactor of a high-speed mixer, (T), s.

The following assumptions were used when selecting the factors and assigning the variation levels.

Factor X1 is the content of filler in the mixture with cement. It is known that an increase in the amount of binder increases the strength of porous composite building materials. However, in cellular concretes, the content of solid components, including the binder, is limited

by the need to ensure the required average density of the material. On the other hand, the binder, as a component of the raw mixture, is the most expensive constituent, and its contribution to the cost of the material is the most significant. Another argument in favour of limiting cement consumption is explained by the specific nature of non-autoclaved foam concrete.

The process of setting and hardening of non-autoclaved foam concrete is accompanied by significant volume changes, which ultimately lead to crack formation and a decrease in its physical and mechanical properties. The main sources of volume changes are the chemical reactions of cement hydration, namely contraction shrinkage, and moisture shrinkage. Both types of volume change are directly related to cement consumption. As cement consumption increases and cement hydration proceeds, the amount of hydration products increases; their volume is smaller than the volume of the initial reactants, which is the cause of contraction. On the other hand, as the amount of cement increases, the quantity of cement gel also increases. Subsequently, after the loss of moisture, shrinkage cracks occur. Increased initial mixing-water content contributes to the growth of shrinkage deformations due to moisture loss in the material. The amount of mixing water is also directly related to cement consumption, since cement is the component of the raw mixture with the highest water demand. To reduce cement consumption, a certain amount of filler was introduced into the raw mixture according to the experimental design. At the upper level of factor X1, the filler content was limited to 30% of the mass of solid components. This is due to the fact that, as previous experiments have shown, increasing the filler content above 30% in the dry components of foam concrete with an average density of 600 kg/m³ leads to a significant decrease in strength.

Factor X2 is the content of the chemical hardening-accelerating admixture. Modern composite building materials cannot be imagined without the use of chemical admixtures. Chemical admixtures are introduced to impart the required properties to construction mortars and, in finished materials, to enhance functional performance and reduce the energy intensity of the production process.

The selection of chemical admixtures is usually made according to the following criteria: achievement of the required effect, availability, cost, and compliance with sanitary and hygienic requirements.

A wide range of plasticising admixtures affecting the characteristics of concretes is known (*Pashkevych et al., 2021*).

In the experiment, the cement-hardening accelerator admixture “Plastidor”, produced by “Doronyk Ukraine”, Kyiv, Ukraine, was used.

Acceleration of strength gain is a highly relevant problem for foam concrete. The need to use a mortar mixture with increased water–cement ratio values, caused by the technological features of production, as well as the influence of foaming agents on the cement hydration process, substantially slows down the hardening time of foam concrete, which negatively affects the productivity of technological lines.

Factor X3 is the activation time of the mortar mixture in a high-speed mixer.

The selection of factors and their variation intervals was made in such a way as to enable comparison of different methods of foam concrete production. The first point of the experimental design, in which all factors are at the lower level of variation, was adopted as the control point. Movement along the axis of factor X1 makes it possible to determine the

influence of filler quantity on the properties of foam concrete. Movement along the axis of factor X2 or X3 makes it possible to determine the degree of influence of activation methods, conventionally referred to as chemical or mechanical activation, on changes in the properties of foam concrete. At other points of the mix-design and technological field, the combined influence of the experimentally adopted variable factors, that is, mechanochemical activation, is manifested.

The constant factors were as follows: density of the foam concrete mixture— 760 ± 10 g/l; spread diameter of the mortar according to the Suttard viscometer— 270 ± 10 mm.

Thus, the specific feature of the experimental design is that its results make it possible to analyse and compare different technologies for obtaining foam concrete.

The physical and mechanical properties, as well as the deformative characteristics of cellular concretes, are largely determined by the temperature and humidity conditions of the environment in which the initial structure forms and subsequent strength development takes place (*Liew et al., 2021*).

It is known that the theoretical strength of autoclaved concretes will always be higher than the strength of normally cured cellular concretes at the same degree of hydration and with the same volume and composition of hydration products.

Consequently, one of the tasks of the experiment was to study the influence of curing conditions on foam concrete strength. For this purpose, some of the specimens were stored in a normal curing chamber and tested on the 28th day of storage, corresponding to grade strength; some specimens were stored under natural conditions, that is, ambient environmental conditions. In addition, some specimens were subjected to heat treatment in a sealed chamber equipped with electric heaters, with an isothermal heating temperature of 50°C and a duration of 8 hours. After this, some specimens were tested immediately after heat treatment, while others were placed in a normal curing chamber and tested on the 28th day of curing.

Literature Review

Many factors influence the characteristics of cellular concretes (*Martynov et al., 2021a*). An important aspect of foam concrete production technology is the formation of stable foam (*Xiong et al., 2025*).

In addition to chemical admixtures, other activation methods are used in building materials technology. Such methods include the activation of both initial raw materials and semi-finished products. All of them are associated with the additional input of energy at particular stages of material production. The type, point of energy input and duration of exposure are determined by the intended purpose, the technological features of production and economic parameters. In building materials technology, thermal, electrical, magnetic, electromagnetic and mechanical effects are the most widely used. Heat treatment of concretes with steam or electricity is used to accelerate strength development (*Zhang et al., 2022*). Electrical heating and steam heating are applied at the stage of activating concrete and mortar mixtures. Methods for controlling material properties through activation of the mixing liquid, namely magnetisation of water, are also known.

However, mechanochemical activation has gained the widest application in the production of building materials. The issue of mechanochemical activation of raw materials is particularly

relevant in the technology of porous concretes (*Rakhimov et al., 2020*). This is due to the need to ensure the stability of the porous structure, accelerated development of structural strength and the formation of a sufficient quantity of cementitious hydration products (*Korjakins & Shakhmenko, 2019*). For this purpose, grinding is carried out both for individual raw materials, such as sand grinding, and for the joint grinding of sand with binders in various grinding units, including ball mills, vibration mills, rod mills and jet mills.

A method has also been proposed for using a high-speed mixer for the separate preparation of cement–water compositions, which are subsequently combined with fillers in a conventional concrete mixer (*Barabash & Harashchenko, 2018; Xia et al., 2020; Shcherban et al., 2021*). Methods for activating the binder or mortar component in high-speed mixers are also known. With this method, the degree of hydration of binders increases, which leads to accelerated growth of structural strength and an increase in grade strength. This method was used in the experiment. The mortar mixture was activated in a laboratory high-speed mixer developed by I. V. Barabash.

Results

Table 1 presents the results for the strength of foam concrete cured under normal-humidity conditions for 28 days, corresponding to grade strength, in MPa, as well as the relative strength of foam concrete under different curing conditions, expressed as a percentage of the grade strength.

The analysis of changes in the strength characteristics of non-autoclaved foam concrete was carried out with reference to the base composition, which was cured under normal-humidity conditions for 28 days, corresponding to grade strength (*Martynov et al., 2021a*). In accordance with the requirements of DSTU B V.2.7-45:96 “Building Materials. Cellular Concretes. Technical Specifications”, the minimum permissible strength of non-autoclaved foam concrete with an average dry density of 600 kg/m³ is 1.5 MPa, while the maximum is 2.5 MPa.

Figure 1 shows the strength isosurfaces of foam concrete. At the control point of the experiment, where all variable factors are at the lower level of variation, a strength of 1.4 MPa was recorded, which is lower than the standard values. It should be noted that in this case the material was produced solely on the basis of cement, without the use of filler. This, on the one hand, leads to an increase in cost and, on the other hand, causes a number of negative effects described earlier.

Thus, achieving the required physical and mechanical indicators of foam concrete is possible only under conditions of intensification of Portland cement hydration processes.

The graphs show that the greatest increase in strength, up to 325%, occurs at the maximum admixture content of 3%, a cement content of 100%, and a mortar activation time in the high-speed mixer within the range of 20–30 s. These graphs clearly demonstrate the synergistic effects of the mutual influence of the factors. Thus, in foam concrete produced without the introduction of the “Plastidor” admixture, strength increases in direct proportion to mortar activation time according to a linear relationship. The introduction and subsequent increase in filler content in the mortar mixture have an insignificant effect on changes in strength. The activation of the mortar in a high-speed mixer leads to an increase in strength of more than 150% compared with the control composition.

The introduction of the “Plastidor” admixture leads to a transformation in the character of

the dependencies and changes them from linear to parabolic, which also indicates a significant interaction between factors X2 and X3. At the same time, the strength of the foam concrete also increases considerably. Even in the region of the factor space with the maximum filler content, the strength of foam concrete increases by 125–200% compared with the control composition.

Discussion

The results of this study address a persistent technological problem in the production of non-autoclaved foam concrete: the need to improve the quality characteristics of the material while simultaneously reducing production cost and simplifying the manufacturing process. Non-autoclaved foam concrete is traditionally known primarily as a thermal insulation material; however, an increase in its strength may allow it to be transferred into the category of structural and thermal-insulating materials. This, in turn, can expand the field of its application as a wall material in low-rise construction and monolithic-frame housing systems.

The main conclusion drawn from the analysis of foam concrete strength development is that it is not possible to obtain non-autoclaved Portland cement-based foam concrete with standardised strength indicators without using intensifiers that increase the rate and degree of cement hydration. The “Plastidor” admixture and the activation of the mortar component of foam concrete in a high-speed mixer proved to be highly effective intensifiers of Portland cement hardening. Their effectiveness increases further when they are used jointly, that is, under conditions of mechanochemical activation. In addition, the use of mechanochemical activation of the mortar component makes it possible to introduce up to 30% or more filler instead of expensive Portland cement, thereby reducing the cost of production.

The experimental results confirm that the strength of non-autoclaved foam concrete is governed not by a single technological factor, but by the combined effect of mix composition, chemical acceleration, mechanical activation and curing conditions. The strength range obtained in the recipe-technological field of the experiment demonstrates that the material can be deliberately regulated within a broad interval. The fact that strength increased by up to 325% in comparison with the control point indicates that mechanochemical activation does not merely improve one isolated property, but changes the overall process of structure formation in the foam concrete matrix.

The observed effect can be explained by the intensification of cement hydration and by changes in the solid phase of the material. Mechanical activation in a high-speed mixer increases the dispersion and reactivity of the cementitious system, improves contact between cement particles and water, and promotes more uniform distribution of the components. Chemical acceleration additionally stimulates hydration reactions and accelerates the formation of cementitious hydration products. As a result, the foam concrete structure becomes denser and more mechanically stable, while the porous system remains sufficiently preserved for the material to retain the functional advantages of cellular concrete. This interpretation is consistent with studies that emphasise the importance of mechanochemical activation for the hydration and structure formation of cement-based materials (*Rakhimov et al., 2020; Barabash & Harashchenko, 2018; Shcherban et al., 2021*).

A particularly important finding is the synergistic interaction between the chemical

admixture and mechanical activation. When the “Plastidor” admixture was not used, the increase in strength was mainly proportional to the activation time of the mortar mixture. However, the introduction of the admixture changed the character of the dependence from linear to parabolic, which indicates a more complex interaction between the factors. This means that the maximum effect cannot be obtained simply by increasing the duration of mechanical activation or the amount of chemical additive separately. Instead, the technological optimum should be sought in the combined field of factor interaction, where the content of filler, admixture dosage and activation time are balanced.

The results also show that the use of filler may be technologically and economically justified if it is combined with activation of the mortar component. Under conventional conditions, an increase in filler content can lead to a reduction in strength because part of the Portland cement is replaced by a less reactive component. However, mechanochemical activation compensates for this effect by increasing the efficiency of the binder and improving the formation of hydration products. Even at the maximum filler content, the strength of foam concrete increased by 125–200% in comparison with the control composition. This confirms that filler should not be viewed only as a cost-reducing component, but also as an element of the structure-forming system, provided that the binder phase is properly activated.

From a technological point of view, these findings are significant because Portland cement is the most expensive and most shrinkage-sensitive component of the mixture. Excessive cement consumption increases material cost, water demand, contraction shrinkage and the risk of crack formation. Therefore, the possibility of replacing part of the cement with filler while maintaining or increasing strength is important for both economic and durability considerations. The results suggest that mechanochemical activation may provide a practical route for reducing cement consumption without compromising the required physical and mechanical properties of non-autoclaved foam concrete.

The study also confirms the importance of curing conditions for the strength development of non-autoclaved foam concrete. The most favourable conditions for strength gain were normal-humidity conditions with an ambient temperature of $20 \pm 2^\circ\text{C}$ and humidity of 98%. This result is theoretically consistent with the hydration mechanism of Portland cement and with the specific nature of cellular concrete structure formation. Since the pore structure and cement matrix develop simultaneously, insufficient humidity or unfavourable thermal conditions may disturb hydration, increase shrinkage and reduce final strength. At the same time, heat treatment may accelerate early hardening, but it does not necessarily provide the same structural quality as normal-humidity curing over the full 28-day period.

The comparison with autoclaved cellular concretes is also important. Autoclaved materials usually achieve higher and more stable strength because their structure forms under elevated temperature and pressure, leading to the development of specific hydration products. Non-autoclaved foam concrete is technologically simpler and less energy-intensive, but its structure formation is more sensitive to curing conditions and mixture composition. The results of this study show that foam concrete with an activated mortar component may approach autoclaved cellular concretes in terms of physical and mechanical properties. This creates a basis for improving the competitiveness of non-autoclaved foam concrete in modern construction practice.

The findings correspond to the broader research context in which the properties of cellular concretes are understood as the result of the interaction between pore structure, binder hydration, rheological behaviour and curing environment (*Martynov et al., 2021a; Liew et al., 2021; Xiong et al., 2025*). Stable foam formation is necessary but insufficient for obtaining high-quality foam concrete. The porous structure must be supported by a sufficiently strong cementitious matrix, especially during the early stages of hardening. Therefore, the activation of the mortar component should be considered not only as a method for increasing compressive strength, but also as a means of stabilising the entire structure-forming process.

The practical implications of the study are substantial. The proposed approach can increase mould turnover in stationary production because accelerated strength gain reduces the time required before demoulding and further handling. It can also reduce the cost of products through partial replacement of Portland cement with filler. In addition, the ability to produce stronger non-autoclaved foam concrete may expand its use from purely insulating applications to enclosing and wall elements in low-rise and monolithic-frame construction. This is especially relevant for construction systems where low density, thermal insulation, ease of production and sufficient strength must be combined in one material.

At the same time, the results should be interpreted with several limitations in mind. The study focuses on a specific density range, a specific hardening accelerator and a particular laboratory high-speed mixing method. Therefore, the obtained dependencies should not be mechanically transferred to all types of foam concrete without additional verification. The experiment also primarily evaluates strength characteristics, while long-term durability, shrinkage, crack resistance, thermal conductivity, moisture resistance and pore-size distribution require further investigation. Since foam concrete performance depends strongly on the stability and geometry of the porous structure, future studies should include microstructural analysis in addition to mechanical testing.

Another limitation concerns the industrial scalability of laboratory activation. The laboratory high-speed mixer used in the experiment makes it possible to achieve effective activation of the mortar component, but the transfer of this method to industrial production requires optimisation of equipment parameters, energy consumption, mixing time and process stability. It is also necessary to determine whether the same activation effect can be maintained in larger batches, where mixing intensity, heat generation and component distribution may differ from laboratory conditions.

Further research should therefore focus on several directions. First, it is necessary to establish optimal combinations of filler content, admixture dosage and activation time for different target densities of foam concrete. Secondly, the influence of mechanochemical activation on shrinkage, crack resistance and long-term durability should be studied. Thirdly, the pore structure of activated foam concrete should be analysed using microstructural methods in order to connect strength development with pore distribution and matrix density. Fourthly, the economic and energy efficiency of the proposed technology should be assessed under industrial conditions.

Overall, the study demonstrates that mechanochemical activation is an effective technological approach for regulating the structure and physical and mechanical properties of non-autoclaved foam concrete. The combined use of a chemical hardening accelerator and

activation of the mortar component in a high-speed mixer intensifies cement hydration, increases strength, allows partial replacement of Portland cement with filler and improves the technological potential of the material. These results support the conclusion that activated non-autoclaved foam concrete can be considered a promising structural and thermal-insulating material for modern construction.

Conclusion

The three-factor experiment carried out using mechanochemical activation made it possible to determine effective ways of substantially increasing the strength of non-autoclaved foam concrete while simultaneously reducing the cost of production. The study confirms that the physical and mechanical properties of foam concrete can be purposefully regulated through the combined influence of filler content, the dosage of a chemical hardening accelerator and the activation time of the mortar component in a high-speed mixer. This indicates that the quality of non-autoclaved foam concrete is determined not only by its composition, but also by the technological conditions under which the cementitious matrix and porous structure are formed.

Within the investigated mix-design and technological field, the strength of foam concrete cured under normal-humidity conditions varied from 1.1 to 4.4 MPa. Depending on the level of the other factors, activation of the mortar mixture led to an increase in strength of up to 325% compared with the control point of the experimental design. This result demonstrates the high efficiency of mechanochemical activation as a method for intensifying Portland cement hydration, improving the structure of the solid phase and increasing the strength potential of non-autoclaved foam concrete.

The results also show that temperature and humidity conditions during curing have a significant influence on the final strength of Portland cement-based non-autoclaved foam concrete. The most favourable conditions for strength development were normal-humidity curing at an ambient temperature of $20 \pm 2^{\circ}\text{C}$ and relative humidity of 98%. These conditions ensure more complete hydration of the binder, reduce the risk of premature moisture loss and create a more stable environment for the formation of the cellular concrete structure. Therefore, curing conditions should be considered one of the key technological parameters in the production of non-autoclaved foam concrete with predictable properties.

Foam concrete with an activated mortar component does not yield to autoclaved cellular concretes in terms of its physical and mechanical properties within the investigated strength range. This confirms the possibility of using activated non-autoclaved foam concrete in monolithic-frame housing construction as a wall material. The proposed technological approach may also expand the application of foam concrete from a predominantly thermal insulation material to a structural and thermal-insulating material suitable for enclosing structures and low-rise construction.

An important practical outcome of the study is the possibility of replacing part of expensive Portland cement with filler without reducing the required strength characteristics. The use of mechanochemical activation compensates for the decrease in binder content by increasing the efficiency of cement hydration and improving the structure-forming processes in the material. This creates technological prerequisites for reducing production cost, increasing mould turnover, lowering the energy intensity of manufacturing and improving the competitiveness of

non-autoclaved foam concrete in modern construction.

The theoretical significance of the obtained results lies in clarifying the role of mechanochemical activation in the formation of the structure and strength of non-autoclaved foam concrete. The study shows that the joint action of mechanical activation and a chemical hardening accelerator produces a synergistic effect, which changes the character of strength development and enables more effective control of the material's properties. This contributes to the further development of scientific approaches to the design of cellular concretes with regulated structure and performance characteristics.

At the same time, further research is required to verify the obtained patterns for other density classes, binder systems, filler types and chemical admixtures. It is also necessary to study the influence of mechanochemical activation on shrinkage, crack resistance, thermal conductivity, water resistance, durability and pore structure. Additional microstructural analysis and industrial-scale testing would make it possible to confirm the technological stability of the proposed approach and to develop practical recommendations for its implementation in production.

Overall, the study demonstrates that mechanochemical activation of the mortar component is an effective method for improving the strength and technological efficiency of non-autoclaved foam concrete. The obtained results provide a scientific and practical basis for producing stronger, more cost-effective and more widely applicable foam concrete for modern construction, particularly where a combination of low density, thermal efficiency and sufficient mechanical strength is required.

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Conflict of Interest

The author declares that there is no conflict of interest.

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Appendix

Table 1. Experimental design matrix and strength characteristics of foam concrete

№	Factors			Grade strength of foam concrete, MPa	Strength, as a percentage of vintage		
	X ₁	X ₂	X ₃		After HMT, % of grade strength	28th day of natural curing, % of grade strength	28th day after HMT, % of grade strength
	F	A	T				
1	-	-	-	1,2	58	83	108
2	+	-	-	1,1	45	73	100
3	-	+	-	3,4	47	62	82
4	+	+	-	1,9	37	47	63
5	-	-	+	2,7	52	81	89
6	+	-	+	2,6	58	69	100
7	-	+	+	4,1	63	80	100
8	+	+	+	2,4	63	75	79
9	-	0	0	3,7	62	81	97
10	+	0	0	2,7	59	78	111
11	0	-	0	1,8	50	72	100
12	0	+	0	2,9	48	79	86
13	0	0	-	1,7	47	65	76
14	0	0	+	3,0	47	80	97
15	0	0	0	2,7	48	74	89

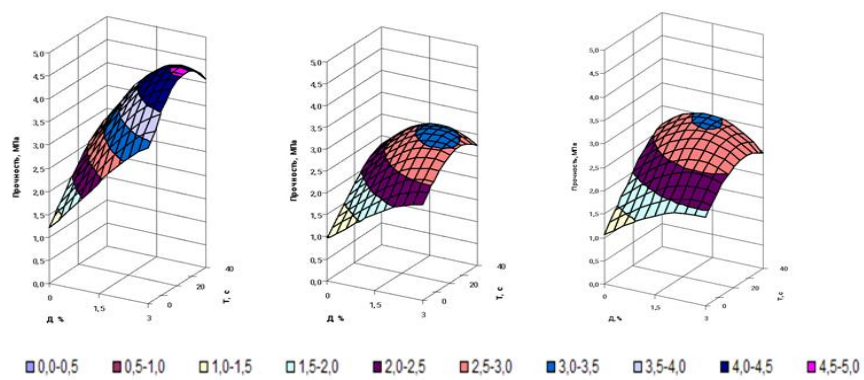


Figure 1. Isosurface strengths of foam concrete with filler content: a—0%;
b—15%; c—30%.

Implementation of Innovative Learning Technologies in the Training of Aviation Engineering Specialists: Experience and Prospect ^[22]

Abstract:

The modern modernization of the global aviation industry and the active implementation of Industry 4.0 concepts require a fundamental rethinking of engineer training methods in accordance with stringent international standards. The object of the study is the process of professional training of highly qualified specialists in aviation engineering in higher education institutions under conditions of intensive digitalization and production automation. The purpose of the work is the scientific substantiation and evaluation of the practical effectiveness of an integrated system for implementing innovative and digital learning technologies. To achieve this goal, a number of tasks were solved regarding the analysis of UAV design digitalization, the integration of advanced non-destructive testing methods and repair engineering into the educational process, as well as the design and approbation of objective assessment and feedback systems. The paper utilizes a complex of research methods: systematic analysis of standards and publications, parametric 3D modeling, finite element analysis (FEA) of the stress-strain state of structures, the method of analyzing real production cases, physical modeling of defectoscopy processes on laboratory test benches, and MCQ testing with subsequent statistical processing of the results. The theoretical framework of the study is based on the fundamental works of domestic and foreign scientists in the fields of innovative technical pedagogy, computer-aided design, and aviation diagnostics. The results of the study demonstrated that the use of modern computer modeling tools significantly develops spatial engineering thinking and allows for the topological optimization of UAV structures at early stages. The systematic integration of real operational defects into diagnostic and repair courses forms the professional responsibility of future engineers for ensuring flight safety. The implementation of automated MCQ testing based on LMS Google Classroom and anonymous feedback via Google Forms ensures high adaptability and flexibility of the educational process, while the proposed models of close partnership between universities and specialized enterprises open up effective ways to solve the problem of updating the material and technical base of universities.

Keywords: aviation engineering, 3D modeling, non-destructive testing, repair engineering, UAV, innovative learning technologies, digitalization of education.

Abbreviations:

AT is Aviation Technology

CAD is Computer-Aided Design

CAE is Computer-Aided Engineering

EASA is European Union Aviation Safety Agency

FAA is Federal Aviation Administration

FDM is Fused Deposition Modeling

FEA is Finite Element Analysis

HEI is Higher Education Institution

LMS is Learning Management System

MCQ is Multiple Choice Questions

NDT is Non-Destructive Testing

SLA is Stereolithography

UAV is Unmanned Aerial Vehicle

Introduction

The modern stage of development of the global aviation industry is characterised by a rapid change in technological paradigms, large-scale automation of production processes, the expansion of unmanned aerial vehicle technologies, the increasing use of composite materials and additive manufacturing, and the continuous strengthening of international aviation safety standards. These transformations create an urgent need for the fundamental modernisation of higher engineering education. Traditional pedagogical approaches oriented mainly towards the passive assimilation of theoretical material are no longer capable of fully providing the aviation industry with highly qualified specialists who can work effectively in a digital, automated and safety-critical professional environment.

The relevance of this study is determined by the growing discrepancy between the technological complexity of contemporary aviation engineering and the inertia of conventional educational models in higher education institutions. The contemporary labour market requires a new generation of specialists who are able not only to reproduce theoretical knowledge, but also to design complex unmanned aerial vehicle systems, use integrated CAD/CAE environments, perform finite element analysis, understand the principles of digital manufacturing, apply advanced non-destructive testing methods, and make justified repair engineering decisions in accordance with stringent international standards, including the requirements of EASA and FAA. In this context, the integration of Industry 4.0 concepts into aviation engineering education becomes not an optional pedagogical innovation, but a necessary condition for ensuring the professional readiness of future engineers.

The research problem lies in the insufficient correspondence between the content, methods and technological infrastructure of traditional aviation engineering education and the actual requirements of modern aircraft design, production, diagnostics and maintenance. Classical models of teaching often separate theoretical calculations from real engineering practice, two-dimensional drawing from parametric design, classroom study from industrial cases, and final assessment from continuous competence monitoring. As a result, graduates may possess formal academic knowledge but remain insufficiently prepared for multidisciplinary engineering tasks involving UAV design, composite structure diagnostics, repair documentation, airworthiness requirements and digital decision-making tools. This problem is intensified by the rapid moral obsolescence of university material and technical facilities, especially in the fields of CAD/CAE systems, non-destructive testing equipment and additive manufacturing technologies.

The hypothesis of the study is that the systematic implementation of an integrated model of innovative and digital learning technologies in aviation engineering education can significantly improve the quality of professional training. It is assumed that the combined use of parametric 3D modelling, CAD/CAE-based structural analysis, finite element simulation, real industrial case studies, laboratory non-destructive testing, LMS-supported MCQ assessment and anonymous digital feedback forms a more effective educational environment than traditional lecture-based instruction. Such an environment is expected to develop spatial engineering thinking, practical diagnostic skills, repair engineering judgement, professional responsibility for flight safety and the ability to adapt to the technological challenges of Industry 4.0.

The scientific novelty of the study consists in the substantiation of an integrated educational model that combines several complementary directions of innovative aviation engineering

training within a single methodological framework. Unlike approaches that consider digital design, non-destructive testing, repair engineering, assessment automation or university-industry cooperation separately, this study treats them as interconnected components of one competence-oriented system. The novelty also lies in demonstrating how CAD/CAE modelling of UAV structures, practical defectoscopy cases, digital assessment tools and feedback mechanisms may jointly support the formation of professional competences required by modern aviation engineering practice.

The object of the study is the process of professional training of future aviation engineering specialists in higher education institutions under conditions of intensive digitalisation of the academic space and the integration of Industry 4.0 concepts.

The subject of the study is the implementation of innovative and digital learning technologies in aviation engineering education, including CAD/CAE-based modelling, finite element analysis, practical non-destructive testing, repair engineering case studies, LMS-supported objective assessment and digital feedback systems.

The aim of the research is to provide scientific substantiation, develop and evaluate the practical effectiveness of an integrated model for implementing innovative technologies of design, computer modelling, technical diagnostics, repair engineering and digital assessment into the educational process of technical universities training aviation engineering specialists.

To achieve this aim, the following research tasks are set:

- to analyse the current challenges of aviation engineering education under conditions of digitalisation, production automation and Industry 4.0 transformation;
- to examine the possibilities of using advanced integrated CAD/CAE systems in modelling and optimising UAV structures;
- to determine the pedagogical potential of parametric 3D modelling and finite element analysis for developing spatial engineering thinking and design competence;
- to develop and approve a methodology for integrating practical non-destructive testing cases into lecture and laboratory courses;
- to evaluate the educational effectiveness of using real industrial defect and repair cases in the formation of diagnostic and repair engineering skills;
- to substantiate the role of objective MCQ testing and LMS-supported assessment in continuous monitoring of student knowledge;
- to analyse the potential of anonymous digital feedback for adapting the educational process to students' actual learning difficulties;
- to identify the prospects of university-industry cooperation and dual education mechanisms for overcoming the material and technical limitations of higher education institutions;
- to determine the theoretical and practical contribution of the proposed integrated model to the modernisation of aviation engineering training.

The methodological basis of the study includes systematic analysis of educational standards and scientific publications, comparative pedagogical analysis, computer three-dimensional modelling, parametric CAD design, finite element analysis of the stress-strain state of aviation structures, analysis of real industrial and diagnostic cases, physical modelling of defectoscopy processes on laboratory test benches, MCQ testing, sociological surveying of higher education

students and mathematical-statistical processing of empirical results. The theoretical framework of the study is based on the works of researchers in innovative technical education, computer-aided design, aviation safety, non-destructive testing, repair engineering, dual education and active learning strategies (*Brown, 2019; Green, 2021; Ivanov, 2021; Kovalenko, 2020; Moroz, 2023; Pavlenko, 2022; Shevchenko, 2023; Tkachenko, 2023*).

The theoretical significance of the study lies in deepening the understanding of innovative aviation engineering education as an integrated competence-forming system. The study contributes to the development of scientific approaches to technical pedagogy by showing that professional competences in aviation engineering are formed most effectively when digital modelling, engineering analysis, diagnostic practice, repair decision-making, assessment transparency and industrial cooperation are combined within one educational logic. It also clarifies the role of active learning, digital twins, case-based instruction and continuous feedback in preparing students for complex safety-critical engineering tasks.

The practical significance of the results lies in the possibility of applying the proposed educational model in aviation departments, technical universities, specialised training centres and professional development programmes for engineering and technical personnel. The developed approaches may be used by teachers of aviation engineering disciplines, guarantors and heads of educational programmes, methodologists of technical higher education institutions, and instructors of aviation enterprises. The integration of CAD/CAE tools, NDT laboratory practice, repair engineering cases, LMS-based assessment and anonymous feedback can make the educational process more practice-oriented, adaptive, transparent and aligned with real industry needs. In addition, the proposed model of cooperation between higher education institutions and specialised enterprises may help overcome the problem of outdated university equipment and provide students with access to modern industrial technologies.

Thus, the present study addresses one of the key challenges of modern aviation engineering education: how to train specialists who are capable of designing, analysing, diagnosing, repairing and maintaining aviation technology in accordance with the requirements of digital production and international aviation safety. The proposed integrated model of innovative learning technologies provides a methodological basis for transforming traditional engineering education into a more flexible, practice-oriented and industry-relevant system capable of preparing competitive aviation engineering specialists for the conditions of Industry 4.0.

Methods

This study employs a comprehensive mix of general scientific methods traditionally utilized in engineering education and applied systems analysis. Analytical methods were used to examine existing international educational standards (EASA/FAA) and to formulate the problem of aligning academic curricula with real-world industry requirements within the Industry 4.0 paradigm. Comparative pedagogical analysis was applied to contrast traditional lecture-based learning models with active "learning-by-doing" approaches, allowing for a systematic investigation of student motivation, knowledge retention, and practical skill acquisition.

Numerical modeling and CAD design served as primary tools for validating the proposed educational method within design and engineering courses. Parametric 3D modeling was applied within SolidWorks and Siemens NX environments using rigorous constraints to ensure

the reliable reproduction of complex aviation components and UAV assemblies. The finite element method (FEA/CAE) was subsequently used to calculate the stress-strain state of student-designed structures, enabling an objective evaluation of structural optimization, weight reduction, and load-bearing capacity without the immediate need for costly physical testing.

Among the specialized methods, case studies based on real industrial reports were used to bridge the gap between theoretical aircraft design and real-world diagnostics or repair engineering. This method allowed for the systematic extraction of failure modes, fatigue cracks, and composite delaminations from depersonalized aircraft accident investigation materials, offering students realistic engineering challenges under simulated conditions. Experimental non-destructive testing (NDT) methods were applied on physical laboratory test benches to evaluate the accuracy of defect detection. Specifically, ultrasonic thickness measurement and eddy current testing methods were used to locate artificially induced damage in aerospace alloys and composite materials.

Additionally, empirical evaluation and statistical analysis methods specific to modern educational systems were applied. Standardized multiple-choice questioning (MCQ) testing was implemented using the Google Forms platform integrated into the Google Classroom LMS for continuous objective knowledge monitoring, utilizing statistical metrics to ensure test reliability and item discriminative power. Qualitative survey and feedback methods via Google Forms were subsequently used to gather student insights regarding the implemented digital learning tools. Finally, the triangulation of qualitative and quantitative data ensured that the proposed pedagogical model aligns with both theoretical academic criteria and practical industrial competencies.

Literature Review

The vast majority of modern educational methods in the field of aviation engineering involve the integration of three fundamental directions: mastering computer modeling, studying failure physics, and implementing systems for objective knowledge quality assessment (*Ivanov, 2021; Kovalenko, 2020*). The works of Ivanov (*2021*) present a detailed analysis of global trends in the modernization of technical education, emphasizing the need to transition from passive learning to interactive forms, which serves to substantiate the general methodological concept of this study. The use of analytical models requires a number of assumptions; in particular, the geometric parameters of modeled objects are frequently simplified. Furthermore, the non-linear properties of aviation materials are often ignored, while development delays and interpolation errors remain unaddressed. Due to these limitations, significant design errors arise, making classical student training sub-optimal for modern production environments. The consequence of such a simplified approach is a gap between theoretical calculations and the actual aerodynamic characteristics of the product, which leads to deformation or even destruction of structural elements in promising aviation systems as early as the flight-testing stage.

Another approach to shaping the professional worldview of future specialists involves a detailed study of structural behavior under critical conditions. This direction is highly demanded for aviation safety disciplines (*Brown, 2019; Savchenko, 2022*) and relies on the analysis of real damage and defects in aircraft. The advantage of this method lies in the ability to investigate the operating conditions of components of any complexity level and the clarity of its

implementation. Some academic sources argue that working with real failure cases during classroom hours distracts from basic theoretical training. However, when the analysis of production situations is properly structured during experiments, this mode becomes fully balanced and safe for developing critical thinking (*Moroş, 2023; Petrov, 2022*). The work of Petrov (*2022*) describes the application of ultrasonic and capillary testing in education, which served as the direct reason for including this source to justify the choice of laboratory diagnostic methods. The practical mastery of NDT helps students transition from the abstract observation of graphs to understanding the physics of ultrasonic wave propagation in the heterogeneous environment of composite materials, enabling the preventive detection of dangerous microcracks.

Today, there is also a wide spectrum of commercial software products for 3D modeling and engineering analysis (*Taylor, 2020*). A typical educational CAD laboratory consists of computers running general-purpose operating systems with expensive licensed software installed. The designed object is integrated into a virtual development cycle, the system is tested for strength using a selected numerical method, and the obtained geometric characteristics are subsequently transferred to production equipment (*Davis, 2020; Johnson, 2021*). Due to user-friendly interfaces, significant computing power, and the absence of limitations on load identification algorithms, students have the opportunity to obtain design parameters that are as close to optimal as possible. The use of digital twin technology opens up new horizons for researching the service life of parts under various cyclic loads, which significantly reduces the time from concept development to material embodiment via additive manufacturing.

In addition to the works mentioned directly above, several fundamental studies cited in the references provide an important theoretical and practical foundation for this research. The work of Shevchenko (*2023*) offers a comprehensive analysis of innovative pedagogical strategies for technical disciplines, which allowed for the theoretical substantiation of the choice of active teaching methods at the Department of Aviation Engineering. Research by Green (*2021*) focuses on the practical aspects of active learning in engineering disciplines, demonstrating the positive impact of an interactive environment on the retention of complex material, which led to its inclusion in the literature review as a methodological guide. The implementation of project-oriented learning involves students in teamwork on complex tasks where everyone is responsible for a separate subsystem of an aviation structure, simulating the real framework of a design bureau.

The analysis of dual education systems outlined in the work of Pavlenko (*2022*) highlights the importance of cooperation between universities and business to overcome the depreciation of the material and technical base of HEIs. This work provides scientific confirmation of the effectiveness of utilizing certified laboratory facilities of enterprises for conducting classes. The work of Roberts (*2021*) describes in detail the aerodynamics and design of light UAVs, which allowed for the adaptation of 3D modeling tasks for students in accordance with current trends in aircraft manufacturing. This is important since the market for unmanned systems develops much faster than state standards of higher education are updated.

The study by Smith (*2022*) provides a structured overview of the evolution of unmanned systems manufacturing technologies, systematizing both classical and state-of-the-art production cycles. The author shows that the practical efficiency of aviation technology operation continues to largely depend on the quality of personnel training and the mastery of

rapid prototyping skills. For this study, this review is particularly important because it clearly identifies typical practical limitations of UAV operations, justifying the choice of corresponding educational modules in the curriculum. The work of Tkachenko (2023) serves as a methodological guide for constructing the discussion section, allowing for a systematic comparison between the proposed dual approaches and existing global models for integrating the academic and industrial sectors. Such integration helps eliminate the shortage of practical knowledge and enables educational institutions to involve leading industry practitioners in the co-supervision of students' graduation projects.

Results

The practical implementation of the educational process in the discipline “Fundamentals of 3D Modeling of Aviation Technology” has demonstrated the high efficiency of abandoning traditional two-dimensional drawings in favour of end-to-end parametric design. Students of the department are involved in the sequential execution of individual projects that start with the creation of conceptual sketches and progress to the construction of complex three-dimensional assemblies within SolidWorks, Siemens NX, and nTop environments. During group classes, future engineers develop critically important structural assemblies of UAVs, including fuselage frames, wing ribs, and spars of complex spatial shapes. The use of parameterization allows for the automatic updating of all connected part dimensions when changing basic geometric parameters or aircraft airframe dimensions (Johnson, 2021). Students actively apply advanced surface and hybrid modeling tools to construct aerodynamically clean fuselage fairings and profiled propeller blades, which requires a deep understanding of surface continuity by G2 class curvature.

The created models are integrated into built-in CAE modules for the analysis of the stress-strain state under the action of calculated aerodynamic and mass loads. Students independently configure boundary conditions: they assign constraints to motors, determine distributed thrust and lift forces, and perform discretization of the model using the finite element method (FEA), which requires adaptive mesh refinement in stress concentration zones. The analysis of the distribution of equivalent von Mises stresses and safety factors allows for an objective evaluation of structural reliability and the execution of its topological optimization—removing excess material in un-loaded zones by creating lightening cutouts and locally reinforcing weak sections by adding optimized stiffening ribs (Taylor, 2020). A separate stage of education is the preparation of designed parts for manufacturing on 3D printers, taking into account the anisotropy of material properties during the layer-by-layer deposition of plastics (FDM) and photopolymers (SLA). Students independently configure model slicing parameters: they choose the density and structure of the internal infill (honeycombs, gyroids), determine the orientation angles of the parts on the build platform to minimize the use of support structures, and account for the thermal shrinkage of polymers. Mastering the creation of such “digital twins” (Davis, 2020), higher education students learn to see a direct relationship between theoretical mechanics of materials, strength of materials, structural mechanics of aircraft, and the practical realization of a design idea in a physical product.

Thus, the implementation of CAD/CAE tools in the educational process reorients the training of aviation specialists from the passive copying of drawings to active engineering design.

The cloud-based environment allows students to experiment with shapes, lightweight materials, and UAV assembly schemes, instantly evaluating decisions through numerical modeling without the expense of physical testing. This eliminates the psychological barrier to error, forms dynamic design thinking, and prepares graduates for the challenges of digital aviation manufacturing of the Industry 4.0 class.

The specific feature of teaching the disciplines “Methods of Non-Destructive Testing of Aircraft Parts during Production and Repair” and “Fundamentals of Repair Engineering” is the shift from the abstract study of theoretical regulations toward the interactive analysis of real aviation defects (case-study). The educational process integrates materials from the actual defectoscopic practice of leading aviation enterprises, containing information on the occurrence of fatigue cracks in skin elements, corrosion degradation, and damage to the wing flap actuation assemblies of the Antonov series aircraft (*Savchenko, 2022*).

During laboratory sessions, students perform the full cycle of technical diagnostics on specially prepared full-scale specimens with pre-applied hidden defects of various types. Working with industrial ultrasonic thickness gauges and flaw detectors, students independently configure instrument sensitivity using standard calibration blocks V1 and V2, calibrate the time base, select optimal wave entry angles, and perform manual scanning of welded and bonded joint zones, interpreting the received echo signals (A-scans) on the instrument screen.

In parallel, eddy current probes are used to localize surface cracks in bolted joint zones, and high-sensitivity capillary (dye penetrant) testing is applied to detect defects on complex skin elements, which students perform step-by-step: from thorough surface preparation to the application of penetrant and developer (*Petron, 2022*). Based on the detected defects, students develop individual repair schemes and process sheets. They calculate rivet pitch and diameter, determine edge distances for installing reinforcing patches (doublers), justify repair sheet thickness taking into account fatigue strength and stress concentration, and select types of epoxy adhesive compositions and carbon fiber layup sequences to eliminate delaminations in composite UAV panels after hard operational landings (*Moroz, 2023*). This approach teaches students to independently evaluate the criticality of each specific defect using structural repair manuals and permissible damage charts, and to make qualified decisions regarding the possibility of further safe operation of the aircraft in accordance with airworthiness regulations.

Thus, the systematic integration of industrial case analysis and practical work with operating defectoscopic equipment ensures the applied nature of personnel training at the Department of Aviation Engineering. Students successfully complete a full professional cycle—from the physical detection of a hidden fatigue microcrack or composite delamination using ultrasound to designing a repair patch, calculating its strength, and processing technological documentation. This not only forms stable skills in high-precision diagnostics and aircraft reliability, but also fosters a deep understanding of the professional responsibility of an aviation engineer for preserving human life, instilling the habit of uncompromisingly ensuring flight safety at every stage of the technical lifecycle.

The transformation of education in complex engineering fields requires a transition to systems of continuous and transparent monitoring of student performance. Within the framework of this research, classic forms of term evaluation in aviation technology manufacturing and repair disciplines were successfully integrated into a cloud-based virtual

learning environment based on the Google Classroom LMS. The ongoing knowledge assessment was implemented using a step-by-step MCQ testing framework based on Google Forms, which allows for the automatic import of evaluation results directly into the course gradebook (Wilson, 2019). The effective interaction of cloud services allows for weekly short knowledge checks (express surveys), integrating them directly into the class schedule and creating a culture of continuous engagement without a significant increase in the psychological load on students. The created bank of test items was structured by difficulty levels, where each block of questions requires not just mechanical reproduction of terminology, but the solution of a specific applied problem: from determining the optimal non-destructive testing method for a multi-layered composite panel to calculating heat treatment parameters for structural alloys and determining optimal quenching temperatures for duralumin, taking into account subsequent natural aging. When solving test items, students are involved in quick calculations, for example, calculating the relative error of ultrasonic aircraft skin thickness measurement at different transducer vibration frequencies.

A systematic analysis of testing results in Google Forms, including automatically generated analytical summaries and histograms of correct answer distributions, allowed the instructor to promptly optimize the test database by identifying oversimplified or incorrectly formulated questions. The use of an integrated Google Sheets results table simplifies the calculation of classic testometric indicators: the item difficulty index and item discriminative power, enabling continuous calibration of tests. Furthermore, at the end of each content module within the Google Classroom environment, links to anonymous surveys in Google Forms were published to gather student feedback. Students anonymously evaluated the complexity of the lecture material, the utility of laboratory works, and independently highlighted topics that caused the greatest difficulties (such as the interpretation of ultrasonic signals or the design of repair patches). The cloud-based analysis of the received feedback allows the instructor to identify the so-called “bottlenecks” in course comprehension in a timely manner and to dynamically introduce changes into the next week's lecture plan, expanding or duplicating complex topics. The availability of the Google Classroom mobile application allowed students to receive instant notifications about new assignments and complete testing at a convenient time directly from portable devices, which significantly accelerated test completion time and minimized the risks of delayed task execution. The obtained survey data were mathematically summarized by the cloud service in real time, allowing the instructor to immediately make adjustments to the structure of subsequent classes.

Thus, the comprehensive digitalization of assessment based on the cloud environment of the Google Classroom LMS and Google Forms allows for the construction of a highly adaptive, flexible, and student-centered model of aviation engineer training. Continuous performance monitoring combined with instant feedback eliminates subjectivity in evaluation due to automated cloud-based answer verification, which noticeably reduces students' academic stress levels through absolute transparency of criteria. At the same time, detailed analytics provide the instructor with clear, well-founded indicators for the immediate optimization of methodological support for complex technical disciplines and flexible reorientation of instructional time in favour of topics requiring additional review.

Discussion

The findings of this study confirm that the training of aviation engineering specialists can no longer be effectively organised within the limits of traditional lecture-centred instruction alone. The aviation industry is undergoing a rapid transition towards digital manufacturing, unmanned systems, data-driven diagnostics, additive production, and stricter international safety requirements. Under these conditions, the professional competence of an aviation engineer should be formed not only through the acquisition of theoretical knowledge, but also through continuous involvement in design, simulation, diagnostics, repair decision-making, and objective assessment. The integrated educational model analysed in this study demonstrates that innovative learning technologies can serve as a practical mechanism for reducing the gap between academic training and real industrial expectations.

One of the central results of the study is the pedagogical value of integrating CAD/CAE tools into the training of aviation engineering students. The transition from two-dimensional drawing to end-to-end parametric three-dimensional modelling changes the nature of engineering education. Students are not limited to reproducing standard graphical solutions; instead, they become involved in the full cycle of digital design, from conceptual geometry to finite element analysis and preparation for additive manufacturing. This approach is consistent with the broader trend towards active and project-oriented learning in engineering education, where knowledge is acquired through solving complex technical tasks rather than through passive memorisation of theoretical content (*Ivanov, 2021; Green, 2021*).

The use of CAD/CAE environments is especially important in UAV-related training because unmanned aerial systems require the integration of aerodynamics, structural mechanics, materials science, electronics, and manufacturing technologies. Parametric modelling allows students to understand how changes in geometry affect mass, stiffness, strength, manufacturability and aerodynamic form. Finite element analysis further strengthens this connection by demonstrating the physical consequences of design decisions. When students observe stress concentration zones, safety factors and deformation fields, theoretical courses in mechanics of materials and aircraft structural mechanics acquire applied meaning. This contributes to the development of spatial engineering thinking and supports the formation of design responsibility at an early stage of training.

The results also show that numerical simulation has a strong didactic function. In a conventional educational model, students often encounter a separation between theoretical calculations and the physical behaviour of aircraft structures. By contrast, CAD/CAE-based learning provides an opportunity to test design hypotheses in a virtual environment before moving to physical prototyping. This reduces the psychological barrier to experimentation and encourages students to compare alternative engineering solutions. At the same time, virtual modelling should not be interpreted as a complete substitute for physical testing. It is most effective when used as part of a broader educational system that combines simulation, laboratory verification and analysis of real operational cases.

Another important outcome is the effectiveness of integrating real industrial cases into the study of non-destructive testing and repair engineering. Aviation safety depends not only on the ability to design aircraft structures, but also on the ability to identify hidden defects, interpret diagnostic signals and make justified decisions regarding further operation or repair. The use of

depersonalised materials from real defectoscopic practice creates a learning environment in which students face realistic engineering uncertainty. They must not only apply theoretical knowledge, but also evaluate defect criticality, select diagnostic methods, design repair schemes and prepare technological documentation. This approach supports the formation of professional judgement, which is one of the most difficult competences to develop in purely theoretical instruction.

The inclusion of ultrasonic, eddy-current and capillary testing methods in laboratory work is particularly significant for aviation engineering education. These methods allow students to move from abstract descriptions of damage mechanisms to direct interaction with diagnostic equipment and physical specimens. The interpretation of echo signals, calibration of measuring devices, detection of surface cracks and evaluation of composite delamination create a direct link between materials science, aircraft maintenance and flight safety. This is consistent with studies emphasising the importance of practical non-destructive testing in the professional preparation of aviation specialists (*Petrov, 2022; Savchenko, 2022*).

The results indicate that the case-study approach in repair engineering also has an important ethical and professional dimension. Aviation engineering decisions are safety-critical: an error in detecting a defect, calculating a repair patch or interpreting permissible damage may have serious operational consequences. Therefore, the educational process must form not only technical skills, but also a stable understanding of professional responsibility. By working with realistic defect scenarios, students learn to perceive aircraft maintenance as a complex engineering process where each diagnostic and repair decision contributes to the preservation of airworthiness and human life. This is one of the strongest advantages of integrating industrial cases into the curriculum.

The digitalisation of assessment through Google Classroom and Google Forms represents another relevant result of the study. Continuous MCQ testing integrated into an LMS environment makes assessment more systematic, transparent and manageable. In complex technical disciplines, delayed assessment often prevents the instructor from identifying learning difficulties in time. By contrast, weekly or modular digital testing provides rapid information about students' understanding of key concepts and allows the instructor to adjust the teaching strategy. The use of automated scoring and test analytics reduces subjectivity and increases the transparency of evaluation criteria, which is important for maintaining student trust in the assessment process.

However, the effectiveness of MCQ testing depends on the quality of test design. In aviation engineering education, multiple-choice questions should not be limited to terminology reproduction. The study demonstrates the importance of applied test items that require interpretation, quick calculation, diagnostic reasoning or selection of an appropriate technical solution. In this form, MCQ testing becomes not merely an administrative assessment instrument, but also a pedagogical tool for consolidating engineering thinking. The use of item difficulty and discriminative power indicators further supports the reliability of the testing system and enables continuous improvement of the question bank (*Wilson, 2019*).

Anonymous feedback through Google Forms also strengthens the adaptability of the educational process. In technical disciplines, students may not always openly indicate difficulties during class, especially when the material concerns complex topics such as ultrasonic signal

interpretation, finite element modelling or repair documentation. Anonymous feedback allows instructors to identify conceptual “bottlenecks” and adapt lectures and laboratory sessions to actual learning needs. This supports a student-centred educational model while preserving academic rigour and professional standards. At the same time, feedback should be interpreted carefully: student perceptions are valuable for course improvement, but they should be combined with objective performance data and expert evaluation of achieved competences.

The study also raises a strategically important issue: the material and technical base of higher education institutions often develops more slowly than aviation technologies themselves. Industrial CAD/CAE systems, NDT equipment, additive manufacturing devices and digital diagnostic technologies are expensive and require regular updating. This creates a structural gap between university resources and industry standards. The problem is particularly acute in aviation engineering, where outdated equipment may limit students’ access to the tools and procedures used in real production and maintenance environments. Therefore, the sustainability of innovative engineering education depends not only on internal pedagogical reform, but also on external institutional cooperation.

In this context, university-industry partnership appears to be one of the most promising solutions. The dual education model allows theoretical and methodological training to remain within the university, while advanced practical sessions can be organised at certified laboratories and specialised enterprises. Such cooperation may provide students with access to modern diagnostic equipment, real production cases and industry mentors without requiring universities to independently maintain the full range of expensive technological infrastructure. This corresponds to the concept of dual education discussed in previous studies and reflects the need to integrate academic and industrial environments in technical training (*Parlenko, 2022; Tkachenko, 2023*).

The proposed model also has implications for curriculum design. Aviation engineering programmes should be structured as integrated competence systems rather than as isolated disciplinary blocks. CAD/CAE modelling, UAV design, non-destructive testing, repair engineering, additive manufacturing, LMS-supported assessment and industrial internships should reinforce one another. Such integration is essential because real aviation engineering practice does not separate design from manufacturing, diagnostics, maintenance and safety regulation. A graduate who understands only one segment of the aircraft lifecycle may be insufficiently prepared for the multidisciplinary nature of modern aviation technology.

The results support the conclusion that the development of innovative learning technologies should be understood as a systemic transformation rather than as the isolated introduction of individual digital tools. A CAD programme, an LMS platform or an MCQ test bank cannot independently modernise aviation engineering education. Their effectiveness emerges only when they are incorporated into a coherent pedagogical model based on active learning, real engineering cases, competence-based assessment and industry cooperation. The value of the proposed approach therefore lies in its integrative character: it connects digital design, diagnostic practice, repair decision-making and adaptive feedback within one educational logic.

From a theoretical perspective, the study contributes to the development of innovative technical pedagogy by demonstrating how digital tools can be aligned with professional

engineering competences. It confirms that the use of virtual modelling and automated assessment is most productive when connected with practical tasks and real industrial contexts. From a practical perspective, the study offers a model that may be adapted by aviation departments, technical universities and training centres involved in the preparation or retraining of aviation engineering personnel. It is particularly relevant for educational institutions seeking to modernise curricula under limited financial resources and rapidly changing technological requirements.

Nevertheless, several limitations should be acknowledged. First, the study mainly presents the experience of implementing selected technologies within a specific educational context, which may limit the generalisability of the findings to other institutions, countries or aviation specialisations. Secondly, although the study describes the effectiveness of CAD/CAE modelling, NDT cases and LMS-based assessment, further quantitative evidence is needed to measure long-term learning outcomes, competence retention and graduates' performance in industrial settings. Thirdly, the use of commercial software and cloud platforms may create dependence on licensing conditions, institutional digital infrastructure and students' access to devices and stable internet connectivity. Fourthly, the implementation of dual education requires strong administrative coordination, legal agreements and shared responsibility between universities and enterprises.

Future research should therefore focus on empirical validation of the proposed model across several cohorts and institutions. It would be useful to compare student performance before and after the introduction of integrated CAD/CAE, NDT and LMS-supported modules using standardised competence indicators. Longitudinal studies could examine whether graduates trained through such models adapt faster to industrial workplaces and demonstrate higher readiness for real maintenance, repair and design tasks. Additional research should also evaluate the effectiveness of VR/AR simulators in teaching defectoscopy, aircraft maintenance procedures and cockpit or hangar-based workflows. Such tools may become a cost-effective complement to physical laboratories, especially where access to certified industrial equipment is limited.

Further development of the topic should also include the creation of shared digital repositories of aviation engineering cases. These repositories could contain anonymised defect scenarios, UAV design tasks, repair engineering problems, FEA models, NDT signal examples and assessment templates. If developed jointly by universities and aviation enterprises, such repositories would support standardisation of practical training and improve the comparability of learning outcomes. They could also accelerate the updating of educational content in response to technological changes in UAV manufacturing, composite materials, additive production and aircraft maintenance.

Overall, the discussion demonstrates that innovative learning technologies are not supplementary elements of aviation engineering education, but necessary instruments for preparing specialists capable of working in the Industry 4.0 environment. The combination of CAD/CAE modelling, real industrial diagnostic cases, non-destructive testing laboratories, LMS-based assessment, anonymous feedback and university-industry cooperation creates a more practice-oriented, adaptive and professionally responsible educational system. Such a system can help higher education institutions overcome the gap between academic training and

aviation industry requirements, while ensuring that future engineers are prepared to design, diagnose, repair and operate aviation technologies in accordance with international safety expectations.

Conclusion

Summarizing the results of the conducted analysis, it can be confidently asserted that the implementation of innovative and digital technologies is an un-alternative and most promising path for the systemic development of modern aviation education. The interim results of the study have fully proven the high pedagogical and engineering effectiveness of the proposed approaches at each stage of the comprehensive training of future specialists. In particular, the active use of advanced CAD/CAE systems within the framework of the core discipline of 3D modeling allowed students to transition from static abstract drawing to the design of full-fledged digital twins of complex UAV assemblies. The calculation of stress-strain states (FEA) taught students to see the direct physical consequences of the selected geometry, which significantly reduces the time for design iterations and fosters a culture of designing with consideration for weight limits, rigidity, and the load-bearing capacity of structures.

The integration of a comprehensive analysis of real industrial failure cases in non-destructive testing and repair engineering courses allowed students not only to successfully master the skills of instrumental defectoscopic diagnostics on laboratory test benches but also to develop full-fledged airframe repair process sheets. This directly formed a stable psychological responsibility for the safety of future flights and instilled a basic culture of aviation reliability, where every measurement or calculation error has real critical consequences. Teamwork on defectoscopy cases successfully eliminates dry academicism and brings the learning process closer to the real conditions of operational units of aircraft repair enterprises. In turn, regular MCQ testing based on the Google Classroom LMS and anonymous feedback surveys via Google Forms allowed instructors to promptly evaluate the quality of knowledge retention and flexibly adapt the presentation of complex technical material to the current comprehension level of the audience, making the learning process manageable, individualized, and minimally stressful for higher education students, while ensuring automated collection of objective performance statistics.

The overall result of the study convincingly demonstrates that the future of training competitive specialists in aviation engineering lies in the dimension of deep integration of virtual modeling, interactive augmented reality (VR/AR), widespread use of cloud-based feedback technologies, and dual forms of education. Cooperative work of higher education institutions with the aviation industry and the direct involvement of students in solving real production tasks at aviation enterprises is the key to overcoming the material and technical gap. Only under the condition of continuous dynamic modernization of discipline content and the development of a sustainable partnership between the academic and industrial sectors can a high quality of training be ensured for the new generation of engineers capable of instantly adapting to the challenges of Industry 4.0 and maintaining a high level of aviation transport safety at the international level.

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Conflict of Interest

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Online Fuzzy Clusterization of Distorted Data Streams [23]

Abstract:

Modern computational intelligence technologies are widely used to solve complex problems that often lack an exact analytical solution. A special place among them is held by artificial neural networks, which are widely used in signal processing, optimization, adaptive control, pattern recognition, object identification, time-series forecasting, and many other areas. On this basis, effective systems for computer vision, technical and medical diagnostics, aerospace object management, analysis of financial processes, energy systems, transport flows, and military equipment have been created. The list of applications for these technologies is continually expanding due to their high efficiency and ability to handle complex data. Currently, a significant amount of information has been accumulated about the activities of enterprises, institutions, organizations, and socio-economic systems. Such data reflect various aspects of their functioning and may contain valuable patterns and relationships. In particular, these may be indicators of inflation, population income, household expenditure structure, the cost of housing and communal services, the state of industrial and agricultural production, employment levels, and the timeliness of wage and pension payments. Analysis of such information is difficult due to its substantial volume, multidimensionality, and nonlinear cause-and-effect relationships. That is why there is a need to use modern methods of intelligent data analysis and machine learning that can automatically detect hidden patterns and generate forecasts. An important problem when analyzing empirical data is the presence of missing values, which may arise from errors in data collection, transmission, or storage. The presence of omissions reduces the quality of subsequent analysis and can undermine the accuracy of the constructed models. Despite significant research in missing data recovery, approaches based on computational intelligence methods, in particular artificial neural networks and fuzzy systems, are of particular interest. Such methods can account for complex nonlinear dependencies between features and achieve high accuracy in reconstructing lost observations, making them an effective tool for processing incomplete data sets. Modern methods for recovering missing data are effective mainly for static data sets whose structure does not change during processing. In many practical tasks, information must arrive in real time, requiring adaptive analysis methods. To solve such tasks, artificial neural networks, fuzzy systems, and neuro-fuzzy systems are widely used and, due to their ability to learn and approximate nonlinear dependencies, effectively work with streaming data. Of particular importance are the processes by which evolving systems form their structure and determine the parameters governing their functioning. However, the latest approaches focus on batch processing, which limits their applicability to online analysis of time series and data streams. Additional problems include gaps and anomalous outputs, which significantly reduce the efficiency of traditional processing and clustering algorithms. Among the methods of data mining, fuzzy clustering plays an important role, allowing you to capture the uncertainty and ambiguity of information. However, most known algorithms are ineffective in the simultaneous presence of missing values, outliers, and streaming data. Therefore, the development of new adaptive methods for clustering and data analysis that operate in real time is relevant. Significant contributions to the development of data recovery methods, fuzzy clustering, and evolving intelligent systems have been made by scientists such as T. Kohonen, J. Bezdek, R. Krishnapuram, L. Rutkowski, and T. Marwala, as well as others whose work laid the theoretical foundations of modern intelligent data analysis systems.

Keywords: Data Streams, distorted data, clustering, online mode, adaptive method, optimal expansion strategy.

Abbreviations:

ANNs are artificial neural networks,

PD is partial distance,
WTM is “winner-takes-more”.

Introduction

In recent years, computational intelligence technologies have become one of the most effective tools for solving complex problems that often lack analytical solutions. Among these technologies, ANNs have gained particular importance due to their ability to model nonlinear relationships, learn from data, and adapt to changing environments. Today, ANNs are successfully applied in signal processing, optimization, adaptive control, pattern recognition, identification, time-series forecasting, and many other fields. Their practical applications include image processing and computer vision systems, aerospace control systems, medical and technical diagnostics, economic and financial analysis, energy management, transportation systems, military technologies, forensic science, and various signal analysis tasks. The range of applications continues to expand as new computational methods and intelligent systems are developed.

At present, vast amounts of information describing the activities of enterprises, healthcare institutions, financial organizations, and other complex systems are continuously accumulated. These data contain valuable information about the behavior and performance of the corresponding objects and processes. When properly analyzed, they can reveal objective patterns and hidden relationships that characterize the underlying phenomena. Examples include economic indicators such as inflation rates, household income levels, expenditure structures, utility costs, industrial and agricultural production statistics, employment rates, and social welfare indicators. Due to the large volume of available information and the presence of complex nonlinear dependencies, manual analysis of such data is often impractical or impossible.

As a result, there is a growing demand for advanced data analysis and forecasting techniques capable of automatically discovering hidden patterns in large datasets. Machine learning and computational intelligence methods provide powerful tools for addressing these challenges by extracting useful knowledge from empirical observations and supporting decision-making processes.

One of the major difficulties encountered in real-world data analysis is the presence of missing values. In many data mining and knowledge discovery tasks, empirical observations may be incomplete because of measurement errors, data transmission failures, equipment malfunctions, or human-related factors. Missing information can significantly reduce the accuracy and reliability of analytical models. Consequently, the problem of recovering missing observations has attracted considerable research attention. Among the existing approaches, methods based on computational intelligence, particularly artificial neural networks and fuzzy systems, have demonstrated high effectiveness in reconstructing incomplete data. Their ability to capture complex nonlinear relationships and uncertainty makes them especially suitable for restoring missing observations and improving the quality of subsequent data analysis.

Clustering is one of the most important tasks in data analysis and pattern recognition. Unlike classification, clustering is performed without prior knowledge of the underlying data structure, making it a challenging unsupervised learning problem. The main difficulty lies in the

absence of additional information about the data, which requires the algorithm to independently identify hidden patterns and group similar observations into meaningful clusters.

An additional challenge arises in online learning environments, where data are received sequentially and must be processed in real time. In such scenarios, traditional clustering algorithms often require retraining whenever new observations become available. For large-scale datasets, repeated retraining significantly increases computational costs and processing time, limiting the applicability of these methods in real-world systems.

To ensure efficient and accurate clustering, it is necessary to develop methods that automatically select the most appropriate clustering solution based on predefined quality criteria. Therefore, the development of adaptive clustering approaches that can dynamically adjust their parameters and structure during operation is of considerable practical and scientific interest.

Despite the substantial number of studies devoted to clustering and data analysis, several important challenges remain unresolved. In particular, existing methods often demonstrate limited effectiveness when processing distorted or incomplete data containing missing values and outliers. Furthermore, there is a growing need for clustering techniques capable of handling fuzzy, overlapping clusters, in which an object may belong to multiple clusters simultaneously with varying degrees of membership. Equally important is the ability of such methods to operate in real time, adapting to continuously arriving data streams without requiring complete retraining. These requirements motivate the development of new adaptive fuzzy clustering algorithms designed for dynamic and uncertain data environments.

Methods

This study was designed as a theoretical and algorithmic investigation aimed at developing an adaptive method for online fuzzy clusterization of distorted data streams. The methodological focus was placed on data streams represented by object–property tables in which incoming observations may contain both missing values and anomalous outliers. Since conventional clustering algorithms are usually designed for complete static datasets processed in batch mode, the study develops a sequential framework capable of updating cluster prototypes, membership levels and recoverable data components in real time.

The methodological basis of the research combines fuzzy clustering, neuro-fuzzy modelling, self-organising Kohonen-type learning, recurrent optimisation procedures, partial-distance computation, optimal completion of missing observations and robust similarity-based clustering. The general logic of the proposed approach is to transform classical fuzzy clustering algorithms into recurrent online procedures and then adapt them to distorted streams by introducing mechanisms for handling incomplete and abnormal data.

The initial data model assumes that the processed dataset is represented by a sequence of n -dimensional feature vectors. Each observation is denoted as an input vector belonging to an n -dimensional feature space. Before clustering, all incoming variables are centred and standardised so that the values of each feature lie within the interval $[-1, 1]$. This normalisation is necessary to ensure comparability of feature scales, to prevent domination of variables with larger numerical ranges, and to make the subsequent use of distance- and similarity-based measures methodologically consistent.

The clustering task is formulated as an unsupervised partitioning problem. The purpose is to divide the incoming data stream into a predefined or adaptively updated number of clusters, while assigning each observation a degree of membership in every cluster. Unlike crisp clustering, fuzzy clustering allows an observation to belong to several clusters simultaneously with different membership levels. This property is important for real-world data streams, where cluster boundaries may be uncertain, overlapping or dynamically changing.

As a baseline, the study uses the general fuzzy c-means framework. In this framework, each cluster is represented by a prototype or centroid, while each observation is characterised by membership levels that satisfy probabilistic constraints. The classical objective function minimises the weighted sum of distances between observations and cluster prototypes. Membership levels are controlled by a fuzzifier parameter, which determines the degree of blurring of boundaries between clusters. When the fuzzifier is set to the standard value and the Euclidean metric is used, the procedure corresponds to Bezdek's fuzzy c-means algorithm.

To make fuzzy clustering suitable for online processing, the batch optimisation scheme is rewritten in recurrent form. In the recurrent version, observations are processed sequentially as they arrive. At each time step, the algorithm calculates current membership levels for the new observation and updates the corresponding cluster prototypes using a learning-rate parameter. This procedure makes it possible to avoid full retraining of the model after each new observation and therefore substantially reduces computational costs in streaming environments. If the data flow is high-frequency, the method performs a single recurrent update per incoming observation; if the flow is lower-frequency, several accelerated internal iterations can be carried out between consecutive real-time observations.

The recurrent fuzzy clustering procedure is interpreted as a neuro-fuzzy extension of Kohonen-type self-organisation. In this interpretation, cluster prototypes correspond to adaptive weight vectors, and the update mechanism follows a winner-takes-more learning principle. Unlike the winner-takes-all rule, in which only one prototype is substantially updated, the winner-takes-more principle allows several prototypes to be updated according to their fuzzy membership values. This makes the procedure more appropriate for overlapping clusters and uncertain data distributions.

A separate methodological stage is devoted to the processing of data with missing values. To describe incomplete observations, the input data array is divided into available and unavailable components. For each observation, a binary indicator is introduced to distinguish observed feature values from missing ones. Instead of the standard Euclidean metric, the method uses a partial-distance strategy. The partial distance is calculated only over the available components of the observation and is normalised with respect to the number of observed features. This enables the algorithm to estimate the distance between an incomplete observation and a cluster prototype without preliminary imputation.

On the basis of the partial-distance strategy, the standard fuzzy c-means objective function is modified. The modified objective function minimises distances computed only over the available feature components. The corresponding optimisation procedure yields updated membership levels and cluster prototypes that are calculated with regard to the pattern of missingness in each observation. This approach allows incomplete data streams to be processed

directly in online mode and avoids the systematic bias that may arise from deleting incomplete observations or replacing missing values by simple statistical estimates.

The partial-distance fuzzy clustering algorithm is then reformulated as a recurrent learning procedure. In this recurrent form, each cluster prototype is updated only through the available components of the incoming observation, while the missing components do not directly contribute to the prototype correction. The resulting algorithm can be implemented within the architecture of a neuro-fuzzy Kohonen network. In this setting, the partial-distance computation defines the current membership levels, while the winner-takes-more update rule provides adaptive correction of the cluster prototypes in online mode.

Since the partial-distance strategy may become insufficient when the number of missing values is high, the study additionally introduces an optimal completion strategy. Under this strategy, missing feature values are treated as additional unknown variables to be estimated simultaneously with clustering. The algorithm alternates between three operations: calculation of fuzzy membership levels, recalculation of cluster prototypes and estimation of missing observations. Missing values are estimated by minimising the clustering objective function with respect to the unknown components of the data vector. Thus, the method performs clustering and data recovery as parts of a single optimisation process.

To organise the optimal completion strategy in online mode, two-time scales are introduced. The first scale is real time, corresponding to the sequential arrival of observations in the data stream. The second scale is accelerated computational time, during which internal iterations are performed between two consecutive real-time observations. Within accelerated time, the algorithm refines membership levels and estimates missing values; within real time, it updates cluster prototypes using the recurrent winner-takes-more learning rule. This two-scale organisation makes it possible to combine real-time operation with a more accurate recovery of missing observations.

The study also considers the limitations of probabilistic fuzzy clustering. In probabilistic clustering, the membership levels of each observation across all clusters must sum to unity. Although this condition is mathematically convenient, it may become restrictive in the presence of outliers and atypical observations. To address this limitation, the methodology includes possibilistic fuzzy clustering, in which membership levels are not constrained by the requirement of summing to one. In the possibilistic formulation, an additional scale parameter is introduced for each cluster, defining the distance at which the membership level equals 0.5. This makes the algorithm less sensitive to the forced redistribution of membership among clusters and more suitable for distorted data.

The possibilistic clustering objective function is minimised with respect to membership levels, cluster prototypes and cluster-specific scale parameters. The resulting expressions are also converted into recurrent online form. As in the probabilistic case, the procedure can be interpreted as a self-learning Kohonen-type rule with Cauchy functions acting as neighbourhood functions. This interpretation provides a unified neuro-fuzzy framework for both probabilistic and possibilistic clustering of streaming data.

To improve robustness in the presence of anomalous outliers, the study replaces purely distance-based criteria with similarity-based measures. A similarity measure is introduced as a function satisfying weaker conditions than a metric, since it does not require the triangle

inequality. The proposed similarity measure is based on a Cauchy-type function with a width parameter controlling the influence of distant observations. By selecting this parameter appropriately, observations located at the edges of the normalised interval can be down-weighted, thereby reducing the effect of outliers on prototype updates. This robustification cannot be achieved by the Euclidean metric alone, since large distances generated by outliers may strongly distort the clustering process.

The similarity-based objective function is constructed by replacing distance minimisation with similarity maximisation. Under probabilistic constraints, the corresponding Lagrange optimisation problem is formulated and solved to obtain updated membership levels and prototype correction rules. The resulting robust fuzzy clustering algorithm is then adapted to incomplete data by using a partial similarity measure based on partial distance. This allows the method to handle missing values and outliers simultaneously.

The final methodological framework consists of a group of adaptive online fuzzy clustering algorithms. The first group includes probabilistic fuzzy clustering procedures for complete data streams. The second group extends these procedures to incomplete observations using the partial-distance strategy. The third group applies the optimal completion strategy to estimate missing values during clustering. The fourth group introduces possibilistic clustering to reduce the limitations of probabilistic membership constraints. The fifth group incorporates robust similarity-based measures to suppress the influence of outliers. Together, these procedures form an adaptive neuro-fuzzy approach for online clusterization of distorted data streams.

Algorithmic implementation follows a sequential processing logic. At each real-time step, a new observation is received and normalised if necessary. The algorithm identifies available and missing components, calculates partial distances or partial similarities, determines fuzzy or possibilistic membership levels, updates missing-value estimates where required, and corrects cluster prototypes according to the winner-takes-more rule. When accelerated internal iterations are enabled, membership levels and missing-value estimates are refined before prototype updating. The process continues for the full data stream without requiring complete retraining on the accumulated dataset.

The stopping and control conditions depend on the difference between successive prototype updates, the threshold accuracy parameter and the maximum number of accelerated internal iterations. In batch-derived procedures, the calculation continues until the norm of the difference between successive cluster prototypes becomes smaller than the predefined threshold. In online processing, this condition is adapted to sequential operation by controlling the magnitude of prototype correction and by limiting the number of accelerated iterations between consecutive observations.

The proposed methodology was evaluated at the theoretical and algorithmic level through consistency with known fuzzy clustering principles, compatibility with Kohonen-type self-organisation and the ability to process incomplete and distorted observations without batch recomputation. The key methodological criteria were online applicability, capacity to process missing values, robustness to outliers, reduction of memory requirements due to the absence of summation over the full historical sample in recurrent updates, and suitability for numerical implementation by adaptive linear associators.

The methodological contribution of the study lies in combining several previously separate approaches into one coherent framework: fuzzy c-means clustering, partial-distance processing, optimal estimation of missing values, possibilistic membership modelling, similarity-based robustification and neuro-fuzzy Kohonen learning. This combination enables real-time clusterization of data streams in situations where observations are incomplete, noisy and affected by abnormal outputs. The proposed methodology is therefore suitable for applications in which data are continuously received and must be processed under uncertainty, distortion and changing statistical conditions.

Literature Review

The problem of data sets described by vector-image clustering often arises in many applications associated with Data Mining (*Höppner et al., 1999, Bezdek, 2013*), where a processed vector-image with varying levels of probability, possibility, or membership can belong to more than one class.

However, there are situations when the data sets contain missing values. In this situation, it is more effective to use the mathematical apparatus of Computational and, first of all, artificial neural networks (*Marwala, 2009*), which solve the task of restoring the lost observations and modifications of the popular method of fuzzy c-means (*Hathaway & Bezdek, 2001*), which solves the problem of clustering without recovery of data.

Existing approaches for data processing with missing values (*Bodyanskiy et al., 2012*) are efficient when the mass of the original observations is provided in batch form and remains constant during processing. At the same time, there is a wide class of problems in which the data arriving for processing takes the form of a sequence, fed in real time as it occurs, as in the training of Kohonen self-organizing maps (*Kohonen & Maps, 1995*) or their modifications (*Gorshkov et al., 2009*). In this regard, we have introduced (*Bodyanskiy et al., 2012*) the adaptive neuro-fuzzy Kohonen network to address the problem of clustering data with gaps, based on the partial-distance strategy (PDS FCM). However, in situations where the number of such missing values is too big, the strategy of partial distances may not be effective, and therefore, it may be necessary, along with the solution of fuzzy clustering, to simultaneously estimate the missing observations. In this situation, a more efficient approach is based on the optimal expansion strategy (OCS FCM) (*Hathaway & Bezdek, 2001*).

Results

Baseline information for solving clustering tasks in batch mode is a sample of observations consisting of n -dimensional feature vectors $X = \{x_1, x_2, \dots, x_N\} \subset R^n, x_k \in X, k = 1, 2, \dots, N$. The result of clustering is the partition of original data set into m classes ($1 \leq m \leq N$) with some levels of membership $U_q(k)$ of k -th feature vector to the q -th cluster ($1 \leq q \leq m$). Incoming data are centered and standardized for all features, so that all observations lie within the hypercube $[-1, 1]^n$. Therefore, the data for clustering form array $\tilde{X} = \{\tilde{x}_1, \dots, \tilde{x}_k, \dots, \tilde{x}_N\} \subset R^n$, $\tilde{x}_k = (\tilde{x}_{k1}, \dots, \tilde{x}_{ki}, \dots, \tilde{x}_{kn})^T$, $-1 \leq \tilde{x}_{ki} \leq 1$, $1 < m < N$, $1 \leq q \leq m$, $1 \leq i \leq n$, $1 \leq k \leq N$.

Introducing the objective function of clustering

$$E(U_q(k), w_q) = \sum_{k=1}^N \sum_{q=1}^m U_q^\beta(k) D^2(\tilde{x}_k, w_q)$$

with constraints $\sum_{q=1}^m U_q(k) = 1$, $0 < \sum_{k=1}^N U_q(k) < N$ and solving the nonlinear programming problem, we get the probabilistic fuzzy clustering algorithm (*Höppner et al., 1999, Bezdek, 2013*)

$$\left\{ \begin{array}{l} U_q^{(\tau+1)}(k) = \frac{(D^2(\tilde{x}_k, w_q^{(\tau)}))^{\frac{1}{1-\beta}}}{\sum_{l=1}^m (D^2(\tilde{x}_k, w_l^{(\tau)}))^{\frac{1}{1-\beta}}}, \\ w_q^{(\tau+1)} = \frac{\sum_{k=1}^N (U_q^{(\tau+1)})^\beta \tilde{x}_k}{\sum_{k=1}^N (U_q^{(\tau+1)}(k))^\beta}, \end{array} \right. \quad (1)$$

where

w_q is prototype (centroid) of q -th cluster,

$\beta > 1$ is parameter that is called fuzzyfier and defines “blurring” the boundaries between classes,

$D^2(\tilde{x}_k, w_q)$ is the distance between $\tilde{x}_k$ and w_q in adopted metric,

$\tau = 0, 1, 2, \dots$ is index of epoch information processing which is organized as a sequence of $w_q^{(0)} \rightarrow U_q^{(1)} \rightarrow w_q^{(1)} \rightarrow U_q^{(2)} \rightarrow \dots$.

The calculation process continues until satisfy the condition

$$\|w_q^{(\tau+1)} - w_q^{(\tau)}\| \leq \varepsilon \quad \forall 1 \leq q \leq m$$

where

ε is defines threshold of accuracy.

Choosing $\beta = 2$ and taking the Euclidean distance, we get a popular algorithm of Bezdek’s fuzzy c-means (FCM)

$$\left\{ \begin{array}{l} U_q^{(\tau+1)}(k) = \frac{\|\tilde{x}_k - w_q^{(\tau)}\|^{-2}}{\sum_{l=1}^m \|\tilde{x}_k - w_l^{(\tau)}\|^{-2}}, \\ w_q^{(\tau+1)} = \frac{\sum_{k=1}^N (U_q^{(\tau+1)}(k))^2 \tilde{x}_k}{\sum_{k=1}^N (U_q^{(\tau+1)}(k))^2}. \end{array} \right.$$

The process of fuzzy clustering can be organized in on-line mode as sequentially processing. At this situation batch algorithm (1) can be rewritten in recurrent form (*Bodyanskiy et al., 2005*)

$$\begin{cases} U_q(k+1) = \frac{(D^2(\tilde{x}_{k+1}, w_q^{(k)}))^{\frac{1}{1-\beta}}}{\sum_{l=1}^m (D^2(\tilde{x}_{k+1}, w_l(k)))^{\frac{1}{1-\beta}}}, \\ w_q(k+1) = w_q(k) + \eta(k+1)U_q^\beta(k+1)(\tilde{x}_{k+1} - w_q(k)) \end{cases} \quad (2)$$

(here $\eta(k+1)$ is learning rate parameter), which is a generalization of the clustering gradient procedure of Park-Dagher and the learning algorithm of Chung-Lee (*Chung & Lee, 1994*). If the data are fed to the processing with high-frequency, recalculation of epochs is not made, if this frequency is low, between the instants k and $k+1$ it is possible to organize several epochs in an accelerated time.

It should be noted that the first expression in (2) can be rewritten in the form

$$\begin{aligned} U_q(k+1) &= \frac{(D^2(\tilde{x}_k, w_q(k)))^{\frac{1}{1-\beta}}}{\sum_{l=1}^m (D^2(\tilde{x}_k, w_l(k)))^{\frac{1}{1-\beta}}} = \frac{(D^2(\tilde{x}_k, w_q(k)))^{\frac{1}{1-\beta}}}{(D^2(\tilde{x}_k, w_q(k)))^{\frac{1}{1-\beta}} + \sum_{\substack{l=1 \\ l \neq q}}^m (D^2(\tilde{x}_k, w_l(k)))^{\frac{1}{1-\beta}}} = \\ &= \frac{1}{1 + (D^2(\tilde{x}_k, w_q(k)))^{\frac{1}{\beta-1}} \sum_{\substack{l=1 \\ l \neq q}}^m (D^2(\tilde{x}_k, w_l(k)))^{\frac{1}{1-\beta}}} \end{aligned}$$

for the Euclidean metric and $\beta = 2$ taking the form of the Cauchy density distributionfunction with a parameter of width σ^2 :

$$\begin{aligned} U_q(k+1) &= \frac{1}{1 + \frac{\|\tilde{x}_k - w_q(k)\|^2}{\sigma^2}}, \\ \sigma^2 &= \left(\sum_{\substack{l=1 \\ l \neq q}}^m \|\tilde{x}_k - w_l(k)\|^{-2} \right)^{-1}. \end{aligned}$$

This fact allows us to rewrite the second expression in (2) with $\beta = 2$ in the form

$$w_q(k+1) = w_q(k) + \eta(k+1)U_q^2(k+1)(\tilde{x}_{k+1} - w_q(k)) = w_q(k) + \eta(k+1)\varphi_q(k+1)(\tilde{x}_{k+1} - w_q(k))$$

where $U_q^2(k+1) = \varphi_q(k+1)$ is the bell-shaped neighborhood function of neuro-fuzzy Kohonen network (*Gorshkov et al., 2009*) designed for solving the fuzzy clustering task (*Shafrenenko, et al., 2018*) using the principle WTM.

In the situation if the data in the array $\tilde{X}$ contain gaps, the approach discussed above should be modified accordingly. For example, in (*Hathaway & Bezdek, 2001*) it was proposed the modification of the FCM-procedure based on partial distance strategy (PDS FCM). Thus introducing, additional arrays:

$$\begin{aligned} X_F &= \{\tilde{x}_k \in \tilde{X} \mid \tilde{x}_k \text{- vector containing all components}\}; \\ X_P &= \{\tilde{x}_{ki}, 1 \leq i \leq n, 1 \leq k \leq N \mid \text{values } \tilde{x}_k, \text{ available in } \tilde{X}\}; \\ X_G &= \{\tilde{x}_{ki} = ?, 1 \leq i \leq n, 1 \leq k \leq N \mid \text{values } \tilde{x}_k, \text{ absent in } \tilde{X}\} \end{aligned}$$

and using instead of the traditional Euclidean metric PD:

$$D_p^2(\tilde{x}_k, w_q) = \frac{n}{\delta_{k\Sigma}} \sum_{i=1}^n (\tilde{x}_{ki} - w_{qi})^2 \delta_{ki},$$

the objective function of clustering

$$E(U_q(k), w_q) = \sum_{k=1}^N \sum_{q=1}^m U_q^\beta(k) \frac{n}{\delta_{k\Sigma}} \sum_{i=1}^n (\tilde{x}_{ki} - w_{qi})^2 \delta_{ki}$$

$$(\text{here } \delta_{ki} = \begin{cases} 0 & \tilde{x}_{ki} \in X_G, \\ 1 & \tilde{x}_{ki} \in X_F, \end{cases} \quad \delta_{k\Sigma} = \sum_{i=1}^n \delta_{ki})$$

and solving nonlinear programming problem, we obtain the algorithm

$$\begin{cases} U_q^{(\tau+1)} = \frac{(D_p^2(\tilde{x}_k, w_q^{(\tau)}))^{\frac{1}{1-\beta}}}{\sum_{l=1}^m (D_p^2(\tilde{x}_k, w_q^{(\tau)}))^{\frac{1}{1-\beta}}}, \\ w_{qi}^{(\tau+1)} = \frac{\sum_{k=1}^N (U_q^{(\tau+1)}(k))^\beta \delta_{ki} \tilde{x}_{ki}}{\sum_{k=1}^N (U_q^{(\tau+1)}(k))^\beta \delta_{ki}} \end{cases} \quad (3)$$

which is a generalization of the standard FCM-procedure (1).

Algorithm (3) can be rewritten in recurrent form

$$\begin{cases} U_q(k+1) = \frac{(D_p^2(\tilde{x}_{k+1}, w_q(k)))^{\frac{1}{1-\beta}}}{\sum_{l=1}^m (D_p^2(\tilde{x}_{k+1}, w_q(k)))^{\frac{1}{1-\beta}}}, \\ w_{qi}(k+1) = w_{qi}(k) + \eta(k+1) U_q^\beta(k+1) (\tilde{x}_{k+1,i} - w_{qi}(k)) \delta_{ki} \end{cases} \quad (4)$$

with the second relation (4) that can be represented as learning algorithm for neuro-fuzzy Kohonen network:

$$w_q(k+1) = w_q(k) + \eta(k+1) \phi_q(k+1) (\tilde{x}_{k+1} - w_q(k)) \square \delta_k \quad (5)$$

where $\phi_q(k+1) = U_q^\beta(k+1)$ - bell-shaped neighborhood function, $\delta_k = (\delta_{k1}, \dots, \delta_{kn})^T$, $\square$ - symbol of direct product.

Thus, using a standard Kohonen network architecture and algorithm of its tuning (5) in online mode, it is possible to solve the problem of fuzzy clustering data with gaps.

The main disadvantage of probabilistic algorithms is connected with the constraints on membership levels whose sum has to be equal unity. This reason has led to the creation of possibilistic fuzzy clustering algorithms (*Bezdek et al., 1999*).

In possibilistic clustering algorithms the objective function has the form

$$E(U_q(k), w_q, \mu_q) = \sum_{k=1}^N \sum_{q=1}^m U_q^\beta(k) D^2(\tilde{x}_k, w_q) + \sum_{q=1}^m \mu_q \sum_{k=1}^N (1 - U_q(k))^\beta \quad (6)$$

where the scalar parameter $\mu \geq 0$ determines the distance at which level of membership equals to 0.5, i.e. if $D^2(\tilde{x}_k, w_q) = \mu_q$, then $w_q(k) = 0.5$.

Minimizing (6) relatively $U_q(k)$, w_q and μ_q we get the solution

$$\left\{ \begin{array}{l} U_q^{(\tau+1)}(k) = \frac{1}{1 + \left(\frac{D^2(\tilde{x}_k, w_q^{(\tau)})}{\mu_q^{(\tau)}} \right)^{\frac{1}{\beta-1}}}, \\ w_q^{(\tau+1)} = \frac{\sum_{k=1}^N (U_q^{(\tau+1)}(k))^{\beta} \tilde{x}_k}{\sum_{k=1}^N (U_q^{(\tau+1)}(k))^{\beta}}, \\ \mu_q^{(\tau+1)} = \frac{\sum_{k=1}^N (U_q^{(\tau+1)}(k))^{\beta} D^2(\tilde{x}_k, w_q^{(\tau+1)})}{\sum_{k=1}^N (U_q^{(\tau+1)}(k))^{\beta}} \end{array} \right. \quad (7)$$

which with $\beta = 2$ and Euclidean metric has the form

$$\left\{ \begin{array}{l} U_q^{(\tau+1)}(k) = \frac{1}{1 + \frac{\|\tilde{x}_k - w_q^{(\tau)}\|^2}{\mu_q^{(\tau)}}}, \\ w_q^{(\tau+1)} = \frac{\sum_{k=1}^N (U_q^{(\tau)}(k))^2 \tilde{x}_k}{\sum_{k=1}^N (U_q^{(\tau)}(k))^2}, \\ \mu_q^{(\tau+1)} = \frac{\sum_{k=1}^N (U_q^{(\tau)}(k))^2 \|\tilde{x}_k - w_q^{(\tau+1)}\|^2}{\sum_{k=1}^N (U_q^{(\tau)}(k))^2}. \end{array} \right. \quad (8)$$

Information processing in the on-line mode (7), (8) can be written as (Bodyanskiy et al., 2012; Shafrenenko et al., 2018)

$$\left\{ \begin{array}{l} U_q(k+1) = \frac{1}{1 + \left(\frac{D^2(\tilde{x}_{k+1}, w_q(k))}{\mu_q(k)} \right)^{\frac{1}{\beta-1}}}, \\ w_q(k+1) = w_q(k) + \eta(k+1) U_q^{\beta}(k+1) (\tilde{x}_{k+1} - w_q(k)), \\ \mu_q(k+1) = \frac{\sum_{p=1}^{k+1} U_q^{\beta}(p) D^2(\tilde{x}_p, w_q(k+1))}{\sum_{p=1}^{k+1} U_q^{\beta}(p)} \end{array} \right. \quad (9)$$

and

$$\left\{ \begin{array}{l} U_q(k+1) = \frac{1}{1 + \frac{\|\tilde{x}_k - w_q(k)\|^2}{\mu_q(k)}}, \\ w_q(k+1) = w_q(k) + \eta(k+1)U_q^2(k+1)(\tilde{x}_{k+1} - w_q(k)), \\ \mu_q(k+1) = \frac{\sum_{p=1}^{k+1} U_q^2(p) \|\tilde{x}_p - w_q(k+1)\|^2}{\sum_{p=1}^k U_q^2(p)}. \end{array} \right. \quad (10)$$

It's easily to see that relations (9), (10) are the Kohonen's self-learning WTM-rule with Cauchy functions as a neighborhood ones.

Adopting instead of Euclidean metric partial distance (PD), we can write the goal function of the type (6) as

$$E(U_q(k), w_q, \mu_q) = \sum_{k=1}^N \sum_{q=1}^m U_q^\beta(k) \frac{n}{\delta_{k\Sigma}} \sum_{i=1}^n (\tilde{x}_{ki} - w_{qi})^2 \delta_{ki} + \sum_{q=1}^m \mu_q \sum_{k=1}^N (1 - U_q(k))^\beta$$

and then solving the equations system

$$\left\{ \begin{array}{l} \frac{\partial E(U_q(k), w_q, \mu_q)}{\partial U_q(k)} = 0, \\ \frac{\partial E(U_q(k), w_q, \mu_q)}{\partial \mu_q} = 0, \\ \nabla_{w_q} E(U_q(k), w_q, \mu_q) = \vec{0}, \end{array} \right.$$

get the procedure of type (9), which can be rewritten in the recurrent form

$$\left\{ \begin{array}{l} U_q(k) = \frac{1}{1 + \left(\frac{D_p^2(\tilde{x}_{k+1}, w_q(k))}{\mu_q(k)} \right)^{\frac{1}{\beta-1}}}, \\ w_{qi}(k+1) = w_{qi}(k) + \eta(k+1)U_q^\beta(k+1)(\tilde{x}_{k+1,i} - w_{qi}(k))\delta_{ki}, \\ \mu_q(k+1) = \frac{\sum_{p=1}^{k+1} U_q^\beta(p) D_p^2(\tilde{x}_p, w_q(k+1))}{\sum_{p=1}^{k+1} U_q^\beta(p)}. \end{array} \right.$$

The second relation can be rewritten too as

$$w_q(k+1) = w_q(k) + \eta(k+1)U_q^\beta(k+1)(\tilde{x}_{k+1} - w_q(k)) \square \delta_k$$

coinciding with the learning procedure (7).

Thus, the process of fuzzy possibilistic clustering of data with gaps can also be implemented using a neuro-fuzzy Kohonen network.

An optimal expansion strategy is to treat the elements of the sub-array as additional variables, which are estimated by minimizing the goal function E . Thus, in parallel with clustering (optimization E by $U_q(k)$ and w_q), estimation of missing observations is made (optimization E by $\tilde{x}_{ki} \in X_G$). In this case, the algorithm of fuzzy c-means based on the optimal expansion strategy can be written as the following sequence of steps (*Hathaway & Bezdek, 2001*):

1. Setting the initial conditions for the algorithm: $\beta > 0$; $1 < m < N$; $\varepsilon > 0$
; $w_q^{(0)}$; $1 \leq q \leq m$; $\tau = 0, 1, 2, \dots, Q$; $X_G^{(0)} = \{-1 \leq \hat{x}_{ki}^{(0)} \leq 1\}$, where
 $X_G^{(0)} - N_G (1 \leq N_G \leq (n-1)N)$ arbitrary initial estimates $\hat{x}_{ki}^{(0)}$ of missing values
 $\tilde{x}_{ki} \in X_G$;

2. Calculation of membership levels by solving the optimization problem:

$$U_q^{(\tau+1)}(k) = \arg \min_{U_q(k)} E(U_q(k), w_q^{(\tau)}, X_G^{(\tau)}) = \frac{(D^2(\hat{x}_k^{(\tau)}, w_q^{(\tau)}))^{\frac{1}{1-\beta}}}{\sum_{l=1}^m (D^2(\hat{x}_k^{(\tau)}, w_l^{(\tau)}))^{\frac{1}{1-\beta}}} = \frac{(\|\hat{x}_k^{(\tau)} - w_q^{(\tau)}\|^2)^{\frac{1}{1-\beta}}}{\sum_{l=1}^m (\|\hat{x}_k^{(\tau)} - w_l^{(\tau)}\|^2)^{\frac{1}{1-\beta}}}$$

(here vector $\hat{x}_k^{(\tau)}$ differs from $\tilde{x}_k$ by replacing missing values $\tilde{x}_{ki} \in X_G$ by estimates $\hat{x}_{ki}^{(\tau)}$ that are calculated for the τ -th epoch of data processing);

3. Calculate the centroids of clusters:

$$w_q^{(\tau+1)} = \arg \min_{w_q} E(U_q^{(\tau+1)}(k), w_q, X_G^{(\tau)}) = \frac{\sum_{k=1}^N (U_q^{(\tau+1)}(k))^{\beta} \hat{x}_k^{(\tau)}}{\sum_{k=1}^N (U_q^{(\tau+1)}(k))^{\beta}};$$

4. Checking the stop conditions:

if $\|w_q^{(\tau+1)} - w_q^{(\tau)}\| < \varepsilon \forall 1 \leq q \leq m$ or $\tau = Q$, then the algorithm terminates, otherwise go to step 5;

5. Estimation of missing observations by solving the optimization problem:

$$X_G^{(\tau+1)} = \arg \min_{X_G} E(U_q^{(\tau+1)}(k), w_q^{(\tau+1)}, X_G)$$

or, equivalently

$$\frac{\partial E(U_q^{(\tau+1)}(k), w_q^{(\tau+1)}, X_G)}{\partial \hat{x}_{ki}} = 0.$$

That leads to the final expression

$$\hat{x}_{ki}^{(\tau+1)} = \frac{\sum_{q=1}^m (U_q^{(\tau+1)}(k))^{\beta} w_{qi}^{(\tau+1)}}{\sum_{q=1}^m (U_q^{(\tau+1)}(k))^{\beta}}.$$

Information processing with this algorithm is organized as a sequence

$$w_q^{(0)} \rightarrow U_q^{(1)} \rightarrow \hat{x}_{ki}^{(1)} \rightarrow w_q^{(1)} \rightarrow U_q^{(2)} \rightarrow \dots \rightarrow w_q^{(\tau)} \rightarrow U_q^{(\tau+1)} \rightarrow \hat{x}_{ki}^{(\tau+1)} \rightarrow w_q^{(\tau+1)} \rightarrow \dots \rightarrow w_q^{(Q)}$$

thus, it is possible to organize online clustering by type of procedure (2). For this purpose, we introduce two-time scales: real time $k=1,2,...,N,...$, and accelerated computing time $\tau=0,1,2,...,Q$. Here, we assume that between two instants of real time k and $k+1$ implemented Q iterations of accelerated time.

Then we can write a procedure

$$\left\{ \begin{array}{l} U_q^{(\tau+1)}(k+1) = \frac{(\|\hat{x}_{k+1}^{(\tau)} - w_q(k)\|^2)^{\frac{1}{1-\beta}}}{\sum_{l=1}^m (\|\hat{x}_{k+1}^{(\tau)} - w_l(k)\|^2)^{\frac{1}{1-\beta}}}, \\ \hat{x}_{k+1,i}^{(\tau+1)} = \frac{\sum_{q=1}^m (U_q^{(\tau+1)}(k+1))^\beta w_{qi}(k)}{\sum_{q=1}^m (U_q^{(\tau+1)}(k+1))^\beta}, \\ w_q(k+1) = w_q(k) + \eta(k+1)(U_q^{(Q)}(k+1))^\beta (\hat{x}_{k+1}^{(Q)} - w_q(k)), \end{array} \right. \quad (11)$$

which shows that the memberships and missing observations are calculated in accelerated time, and centroids are calculated in real time by the WTM self-learning rule.

Of course, centroids can be recalculated in accelerated time too:

$$\left\{ \begin{array}{l} U_q^{(\tau+1)}(k+1) = \frac{(\|\hat{x}_{k+1}^{(\tau)} - w_q^{(\tau)}(k+1)\|^2)^{\frac{1}{1-\beta}}}{\sum_{l=1}^m (\|\hat{x}_{k+1}^{(\tau)} - w_l^{(\tau)}(k)\|^2)^{\frac{1}{1-\beta}}}, \\ w_q^{(0)}(k+1) = w_q^{(Q)}(k), \\ w_q^{(\tau+1)}(k+1) = w_q^{(\tau)}(k+1) + \eta(k+1)(U_q^{(\tau+1)}(k+1))^\beta (\hat{x}_{k+1}^{(\tau)} - w_q^{(\tau)}(k+1)), \\ \hat{x}_{k+1,i}^{(\tau+1)} = \frac{\sum_{q=1}^m (U_q^{(\tau+1)}(k+1))^\beta w_{qi}^{(\tau+1)}(k+1)}{\sum_{q=1}^m (U_q^{(\tau+1)}(k+1))^\beta}, \end{array} \right. \quad (12)$$

in this case anyway, both in (11) and (12) operation of summation about k is absent, that for large N can involve a lot of memory.

As already mentioned, to address the problem of fuzzy clustering of data containing outliers, special objective functions of the form (*Bezdek, 2013; Yang & Tseng, 1996*) can be used; however, these anomalies are overwhelming, and the problem itself is associated with minimizing these functions. From a practical point of view, it is more convenient to use, instead of the objective functions, based on the metrics, the so-called measures of similarity (SM) (*Hathaway et al., 2002*), which are subject to milder conditions than metrics:

$$\left\{ \begin{array}{l} S(\tilde{x}_k, \tilde{x}_p) \geq 0, \\ S(\tilde{x}_k, \tilde{x}_p) = S(\tilde{x}_p, \tilde{x}_k), \\ S(\tilde{x}_k, \tilde{x}_k) = 1 \geq S(\tilde{x}_k, \tilde{x}_p) \end{array} \right.$$

(no triangle inequality), and clustering problem can be “tied” to maximize these measures. If the data are transformed so that $-1 \leq \tilde{x}_{ki} \leq 1$ the measure of similarity can be structured so as to suppress data lying at the edges of interval $[-1, 1]$.

Figure 1 illustrates the use of similarity measure as the Cauchy density distribution function with different parameter widths $\sigma^2 < 1$

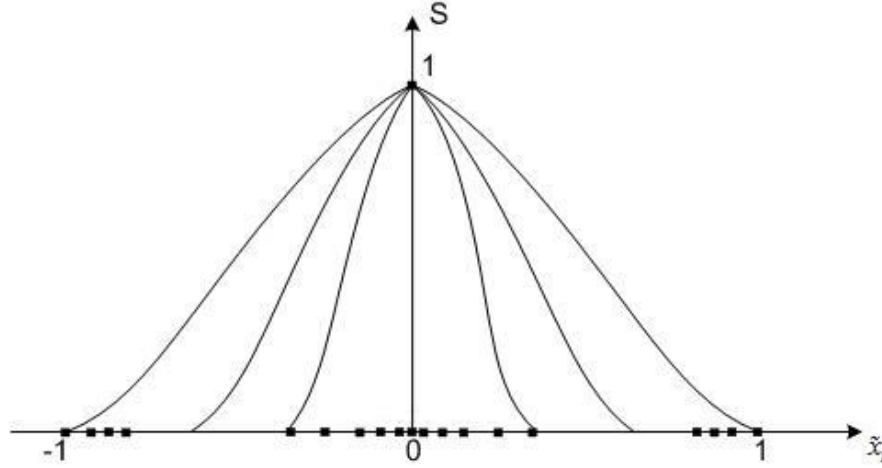


Figure 1 - Similarity measure based on the Cauchy probability distribution

Picking up the width parameter σ^2 functions

$$S(\tilde{x}_k, w_q) = \frac{1}{1 + \frac{\|\tilde{x}_k - w_q\|^2}{\sigma^2}} = \frac{\sigma^2}{\sigma^2 + \|\tilde{x}_k - w_q\|^2} = \frac{\sigma^2}{\sigma^2 + D^2(\tilde{x}_k, w_q)} \quad (13)$$

it's possible to exclude the effect outliers, which in principle can not be done using the Euclidean metric

$$D^2(\tilde{x}_k, w_q) = \|\tilde{x}_k - w_q\|^2. \quad (14)$$

Further, by introducing the objective function based on similarity measure (13)

$$E_S(U_q(k), w_q) = \sum_{k=1}^N \sum_{q=1}^m U_q^\beta(k) S(\tilde{x}_k, w_q) = \sum_{k=1}^N \sum_{q=1}^m \frac{U_q^\beta(k) \sigma^2}{\sigma^2 + \|\tilde{x}_k - w_q\|^2},$$

probabilistic constraints

$$\sum_{q=1}^m U_q(k) = 1,$$

Lagrange function

$$L_S(U_q(k), w_q, \lambda(k)) = \sum_{k=1}^N \sum_{q=1}^m \frac{U_q^\beta(k) \sigma^2}{\sigma^2 + \|\tilde{x}_k - w_q\|^2} + \sum_{k=1}^N \lambda(k) \left(\sum_{q=1}^m U_q(k) - 1 \right) \quad (15)$$

(here $\lambda(k)$ is indefinite Lagrange multipliers) and solving the system of Karush-Kuhn-Tucker equations, we arrive at the solution

$$\left\{ \begin{array}{l} U_q(k) = \frac{(S(\tilde{x}_k, w_q))^{\frac{1}{1-\beta}}}{\sum_{l=1}^m (S(\tilde{x}_k, w_l))^{\frac{1}{1-\beta}}}, \\ \lambda(k) = -(\sum_{l=1}^m (\beta S(\tilde{x}_k, w_l))^{\frac{1}{1-\beta}})^{1-\beta}, \\ \nabla_{w_q} L_S(U_q(k), w_q, \lambda(k)) = \sum_{k=1}^N U_q^\beta(k) * \\ * \frac{\tilde{x}_k - w_q}{(\sigma^2 + \|\tilde{x}_k - w_q\|^2)^2} = \vec{0}. \end{array} \right. \quad (16)$$

The last equation (16) has no analytic solution, so to find a saddle point of the Lagrangian (15), we can use the procedure of Arrow-Hurwitz-Uzawa, as a result of which we obtain the algorithm

$$\left\{ \begin{array}{l} U_q(k+1) = \frac{(S(\tilde{x}_{k+1}, w_q))^{\frac{1}{1-\beta}}}{\sum_{l=1}^m (S(\tilde{x}_{k+1}, w_l))^{\frac{1}{1-\beta}}}, \\ w_q(k+1) = w_q(k) + \eta(k+1) U_q^\beta(k+1) * \\ * \frac{\tilde{x}_{k+1} - w_q}{(\sigma^2 + \|\tilde{x}_{k+1} - w_q\|^2)^2} = \\ = w_q(k) + \eta(k+1) \varphi_q(k+1) (\tilde{x}_{k+1} - w_q) \end{array} \right. \quad (17)$$

where

$$\varphi_q(k+1) = \frac{\tilde{x}_{k+1} - w_q}{(\sigma^2 + \|\tilde{x}_{k+1} - w_q\|^2)^2}$$

neighbourhood robust functions of WTM-self-learning rule.

Assuming the fuzzifier value as $\beta = 2$, we arrive at a robust variant of FCM:

$$\left\{ \begin{array}{l} U_q(k+1) = \frac{(S(\tilde{x}_{k+1}, w_q))}{\sum_{l=1}^m (S(\tilde{x}_{k+1}, w_l))}, \\ w_q(k+1) = w_q(k) + \eta(k+1) \frac{U_q^2(k+1)}{(\sigma^2 + \|\tilde{x}_{k+1} - w_q\|^2)^2}. \end{array} \right.$$

Further, using the concept of accelerated time, it is possible to introduce robust adaptive probabilistic fuzzy clustering procedure in the form

$$\left\{ \begin{array}{l} U_q^{(\tau+1)}(k) = \frac{(S(\tilde{x}_k, w_q^{(\tau)}(k)))^{\frac{1}{1-\beta}}}{\sum_{l=1}^m (S(\tilde{x}_k, w_l^{(\tau)}))^{\frac{1}{1-\beta}}}, \\ w_q^{(Q)}(k) = w_q^{(0)}(k+1), \\ w_q^{(\tau+1)}(k+1) = w_q^{(\tau)}(k+1) + \eta(k+1) * \\ * \frac{(U_q^{(Q)}(k))^\beta}{(\sigma^2 + \|\tilde{x}_{k+1} - w_q^{(\tau)}(k+1)\|^2)^2} * \\ * (\tilde{x}_{k+1} - w_q^{(\tau)}(k+1)). \end{array} \right. \quad (18)$$

Similarly, it is possible to synthesize a robust adaptive algorithm for possibilistic ([Hathaway et al., 2002](#)) fuzzy clustering using criterion

$$E_S(U_q(k), w_q, \mu_q) = \sum_{k=1}^N \sum_{q=1}^m U_q^\beta(k) S(\tilde{x}_k, w_q) + \sum_{q=1}^m \mu_q \sum_{k=1}^N (1 - U_q(k))^\beta.$$

Solving the task of optimization, we obtain the solution:

$$\left\{ \begin{array}{l} U_q(k+1) = \left(1 + \left(\frac{S(\tilde{x}_{k+1}, w_q(k))}{\mu_q(k)} \right) \right)^{-1}, \\ w_q(k+1) = w_q(k) + \eta(k+1) U_q^\beta(k+1) \frac{\tilde{x}_{k+1} - w_q(k)}{(\sigma^2 + \|\tilde{x}_{k+1} - w_q(k)\|^2)^2}, \\ \mu_q(k+1) = \frac{\sum_{p=1}^{k+1} U_q^\beta(p) S(\tilde{x}_p, w_q(k+1))}{\sum_{p=1}^{k+1} U_q^\beta(p)}, \end{array} \right. \quad (19)$$

receiving at $\beta = 2$ the form

$$\left\{ \begin{array}{l} U_q(k+1) = \frac{1}{1 + \frac{S(\tilde{x}_{k+1}, w_q(k))}{\mu_q(k)}}, \\ w_q(k+1) = w_q(k) + \eta(k+1) \frac{U_q^2(k+1)}{(\sigma^2 + \|\tilde{x}_{k+1} - w_q(k)\|^2)^2} (\tilde{x}_{k+1} - w_q(k)), \\ \mu_q(k+1) = \frac{\sum_{p=1}^{k+1} U_q^2(p) S(\tilde{x}_p, w_q(k+1))}{\sum_{p=1}^{k+1} U_q^2(p)}. \end{array} \right.$$

And, finally, introducing the accelerated time we obtain the procedure

$$U_q^{(\tau+1)}(k) = \frac{1}{1 + \left(\frac{S(\tilde{x}_k, w_q^{(\tau)}(k))}{\mu_q^{(\tau)}(k)} \right)^{\frac{1}{\beta-1}}}, \quad (20a)$$

$$w_q^{(Q)}(k) = w_q^{(0)}(k+1), \quad (20b)$$

$$w_q^{(\tau+1)}(k+1) = w_q^{(\tau)}(k+1) + \eta(k+1) \frac{(U_q^{(Q)}(k))^{\beta}}{(\sigma^2 + \|\tilde{x}_{k+1} - w_q^{(\tau)}(k+1)\|^2)^2} (\tilde{x}_{k+1} - w_q^{(\tau)}(k+1)), \quad (20c)$$

$$\mu_q^{(\tau+1)}(k) = \frac{\sum_{p=1}^k (U_q^{(\tau+1)}(p))^{\beta} S(\tilde{x}_p, w_q^{(\tau+1)}(k))}{\sum_{p=1}^k (U_q^{(\tau+1)}(p))^{\beta}}. \quad (20d)$$

Nearest prototype strategy (NFS), proposed in (*Hathaway & Bezdek, 2001*), is a modification of FCM-algorithm and leads to the replacement of missing components of the vector observations $\tilde{x}_{ki} \in X_G$ by estimates of the corresponding component prototypes (centroids) of the clusters computed using FCM. Thus, for each $\tilde{x}_{ki} \in X_G$ it's possible to find the prototype $w_q = (w_{q1}, \dots, w_{qi}, \dots, w_{qn})^T$ nearest to $\tilde{x}_k$ in the sense of the partial distance (PD)

$$D_p^2(\tilde{x}_k, w_q) = \frac{n}{\delta_{k\Sigma}} \sum_{i=1}^n (\tilde{x}_{ki} - w_{qi})^2 \delta_{ki} \quad (21)$$

where

$$\delta_{ki} = \begin{cases} 0 & | \tilde{x}_{ki} \in X_G, \\ 1 & | \tilde{x}_{ki} \in X_F, \end{cases}$$

$$\delta_{k\Sigma} = \sum_{i=1}^n \delta_{ki},$$

$w_q^{(\tau+1)} = \arg \min_q \{D_p^2(\tilde{x}_k, w_1^{(\tau+1)}), \dots, D_p^2(\tilde{x}_k, w_m^{(\tau+1)})\}$, then instead $\tilde{x}_{ki} \in X_G$ input estimate

$\hat{x}_{ki} \in w_{qi}$ used in place of the missing components.

In (*Shafrotenko et al, 2018*) adaptive fuzzy clustering procedure based on the NPS was introduced:

$$\left\{ \begin{array}{l} U_q^{(\tau+1)}(k) = \frac{(\|\hat{x}_k^{(\tau)} - w_q^{(\tau)}(k)\|^2)^{\frac{1}{1-\beta}}}{\sum_{l=1}^m (\|\hat{x}_k^{(\tau)} - w_l(k)\|^2)^{\frac{1}{1-\beta}}}, \\ \hat{x}_{ki}^{(\tau)} = w_{qi}^{(\tau)}(k), \quad w_q^{(\tau)}(k) = \arg \min_q \{D_p^2(\tilde{x}_k, w_1^{(\tau)}(k)), \dots, D_p^2(\tilde{x}_k, w_m^{(\tau)}(k))\}, \\ w_q^{(Q)}(k) = w_q^{(0)}(k+1), \\ w_q^{(\tau+1)}(k+1) = w_q^{(\tau)}(k+1) + \eta(k+1) (U_q^{(Q)}(k))^{\beta} (\hat{x}_k^{(\tau)} - w_q^{(\tau)}(k+1)). \end{array} \right. \quad (22)$$

To address the problem of robust data clustering with missing values, let's introduce the partial similarity measure (PCM), a hybrid of the partial distance (PD) (21) and a similarity measure (SM). It is easy to see that such a PSM has the form

$$S_p(\tilde{x}_k, w_q) = \frac{\sigma^2}{\sigma^2 + D_p^2(\tilde{x}_k, w_q)}, \quad (23)$$

that allows to obtain the desired properties of algorithms based on procedures described above.

So, on the basis of the procedures (23) and (20) we can introduce the robust adaptive probabilistic fuzzy clustering algorithm for data with missing values:

$$\left\{ \begin{array}{l} U_q^{(\tau+1)}(k) = \frac{(S_p(\hat{x}_k^{(\tau)}, w_q^{(\tau)}(k)))^{\frac{1}{\beta-1}}}{\sum_{l=1}^m (S_p(\hat{x}_k^{(\tau)}, w_l^{(\tau)}(k)))^{\frac{1}{\beta-1}}}, \\ \hat{x}_{ki}^{(\tau)} = w_{qi}^{(\tau)}, w_q^{(\tau)}(k) = \arg \max_q \{S_p(\tilde{x}_k^{(\tau)}, w_1^{(\tau)}(k)), \dots, S_p(\tilde{x}_k^{(\tau)}, w_m^{(\tau)}(k))\}, \\ w_q^{(Q)}(k) = w_q^{(0)}(k+1), \\ w_q^{(\tau+1)}(k+1) = w_q^{(\tau)}(k+1) + \eta(k+1) \frac{(U_q^{(Q)}(k))^\beta}{(\sigma^2 + \|\hat{x}_{k+1}^{(\tau)} - w_q^{(\tau)}(k+1)\|^2)^2} (\hat{x}_{k+1}^{(\tau)} - w_q^{(\tau)}(k+1)), \end{array} \right. \quad (24)$$

based on procedures (24) and (19), we can also write a robust adaptive algorithm for possibilistic fuzzy clustering of data with missing values:

$$\left\{ \begin{array}{l} U_q^{(\tau+1)}(k) = \frac{1}{1 + \left(\frac{S^{-1}(\hat{x}_k^{(\tau)}, w_q^{(\tau)}(k))}{\mu_q^{(\tau)}(k)} \right)^{\frac{1}{\beta-1}}}, \\ \hat{x}_{ki}^{(\tau)} = w_{qi}^{(\tau)}, w_q^{(\tau)}(k) = \arg \max_q \{S_p(\tilde{x}_k^{(\tau)}, w_1^{(\tau)}(k)), \dots, S_p(\tilde{x}_k^{(\tau)}, w_m^{(\tau)}(k))\}, \\ w_q^{(Q)}(k) = w_q^{(0)}(k+1), \\ w_q^{(\tau+1)}(k+1) = w_q^{(\tau)}(k+1) + \eta(k+1) \frac{(U_q^{(Q)}(k))^\beta}{(\sigma^2 + \|\hat{x}_{k+1}^{(\tau)} - w_q^{(\tau)}(k+1)\|^2)^2} (\hat{x}_{k+1}^{(\tau)} - w_q^{(\tau)}(k+1)), \\ \mu_q^{(\tau+1)}(k) = \frac{\sum_{p=1}^k (U_q^{(\tau+1)}(p))^\beta S_p^{-1}(\hat{x}_p^{(\tau+1)}, w_q^{(\tau+1)}(k))}{\sum_{p=1}^k (U_q^{(\tau)}(p))^\beta}. \end{array} \right. \quad (25)$$

Thus, the use of a partial similarity measure based on partial distance (21) allows us to solve the problem of fuzzy clustering of data containing both missing values and outliers.

Discussion

The results of the study demonstrate that online fuzzy clusterization of distorted data streams should be considered not merely as a modification of classical clustering procedures,

but as a separate methodological problem requiring the simultaneous treatment of three complicating factors: sequential data arrival, missing feature values and anomalous observations. Classical fuzzy clustering methods were originally developed for complete datasets processed in batch mode. In contrast, many applied systems in economics, engineering diagnostics, technical monitoring, transport, energy management, medicine and socio-economic analysis operate with continuously arriving observations whose structure may be incomplete, noisy and dynamically changing. This makes the transition from batch clustering to adaptive online neuro-fuzzy procedures theoretically and practically significant.

The proposed approach extends the conventional fuzzy c-means framework by transforming it into recurrent online learning procedures. This transformation is important because repeated recalculation of the entire clustering model after each new observation becomes computationally inefficient for large data streams. By updating membership levels and cluster prototypes sequentially, the method reduces memory requirements and enables real-time processing. The use of a Kohonen-type neuro-fuzzy architecture provides an additional advantage because cluster prototypes can be interpreted as adaptive weight vectors, while the update mechanism follows a self-learning logic. This interpretation connects fuzzy clustering with neural network learning and makes the proposed approach suitable for evolving intelligent systems.

A significant methodological contribution of the study lies in the use of the “winner-takes-more” principle instead of the stricter “winner-takes-all” rule. In distorted and uncertain data environments, an incoming observation cannot always be unambiguously assigned to a single cluster. The fuzzy membership mechanism allows several prototypes to be updated with different intensities, reflecting the degree to which the observation is associated with each cluster. This is especially important for overlapping clusters and transitional states in multidimensional data streams. Therefore, the proposed recurrent procedure preserves the flexibility of fuzzy partitioning while ensuring the adaptivity required for online processing.

The treatment of missing values is one of the central issues addressed in the study. In many practical datasets, omissions arise from measurement errors, transmission failures, incomplete registration, sensor malfunction or human-related factors. Traditional strategies such as deleting incomplete observations or replacing missing values with mean or median estimates may distort the cluster structure and reduce analytical reliability. The partial-distance strategy used in the study is more appropriate for online clustering because it allows incomplete observations to be processed directly, using only the available components of each vector. This makes it possible to avoid preliminary imputation and maintain the continuity of data stream processing.

At the same time, the study correctly recognises that the partial-distance strategy has limitations when the proportion of missing components becomes too large. In such cases, the available information may be insufficient for reliable membership estimation, and therefore the optimal expansion strategy becomes necessary. Treating missing values as additional variables estimated during clustering is a stronger methodological solution because data recovery and cluster formation are performed within a single optimisation process. This makes the clustering procedure more internally coherent: missing values are not restored independently from the clustering model, but are inferred from the same prototype and membership structure that defines the data partition.

The introduction of two-time scales—real time and accelerated computational time—is particularly important for online implementation. Real time corresponds to the arrival of new observations, while accelerated time allows several internal iterations to be performed between two incoming data points. This construction gives the method a flexible computational organisation. If the stream arrives rapidly, the algorithm can perform minimal updates; if time permits, it can refine memberships and missing-value estimates before updating prototypes. Such a design is highly relevant for real-world systems where data rates may vary and where the balance between computational accuracy and processing speed must be dynamically controlled.

The study also addresses the limitations of probabilistic fuzzy clustering. In probabilistic algorithms, the sum of membership levels for each observation must equal one. This assumption is useful for mathematically well-structured cluster partitions, but it may be restrictive when data contain outliers or observations that do not naturally belong to any existing cluster. The incorporation of possibilistic fuzzy clustering weakens this restriction and makes the model more robust to atypical observations. Possibilistic membership reflects the absolute compatibility of an observation with a cluster rather than its relative distribution among all clusters. This is especially valuable in distorted data streams, where abnormal outputs may otherwise force artificial redistribution of membership levels and distort cluster prototypes.

The use of similarity measures based on the Cauchy distribution further strengthens the robustness of the proposed approach. Distance-based objective functions are sensitive to outliers because large deviations may dominate the optimisation process and shift cluster centroids in undesirable directions. Similarity-based measures operate differently: they can suppress the influence of remote or edge observations by assigning them lower similarity values. The width parameter of the Cauchy-type function becomes a control mechanism regulating the sensitivity of the algorithm to deviations. This makes the clustering procedure more stable in the presence of abnormal outputs and provides a practical alternative to purely metric-based clustering.

An important advantage of the proposed methodology is that missing values and outliers are not treated as separate problems. In many applied systems, incomplete observations and anomalous values occur simultaneously. Methods designed only for omissions may be unstable in the presence of outliers, while robust methods designed for anomalies may not handle missing feature values. The partial similarity measure based on partial distance creates a unified mechanism for processing both types of distortion. This makes the proposed framework more applicable to real data streams, where data quality problems are usually mixed rather than isolated.

From a theoretical perspective, the study contributes to the development of evolving neuro-fuzzy systems by combining several methodological lines: fuzzy c-means clustering, partial-distance strategies, optimal completion of missing observations, possibilistic membership modelling, similarity-based robustification and Kohonen-type recurrent learning. The strength of this contribution lies not in proposing a single isolated algorithm, but in constructing a family of related adaptive procedures that can be selected depending on the type and degree of data distortion. This modularity increases the methodological flexibility of the approach and allows it to be adapted to different application contexts.

From a computational perspective, the proposed algorithms are promising because they avoid repeated summation over the entire historical dataset during recurrent updates. This is particularly relevant for large-scale data streams, where storing and reprocessing all previous observations may be impractical. The representation of the neuro-system as a set of adaptive linear associators also supports fast numerical implementation. Such computational simplicity is important for embedded systems, monitoring platforms and online decision-support tools, where available memory and processing time may be limited.

The practical significance of the study is broad. Online fuzzy clusterization of distorted data streams can be used in technical diagnostics, where sensor data may contain missing values and abnormal measurements; in financial and socio-economic monitoring, where indicators may arrive irregularly and contain reporting gaps; in medical data analysis, where incomplete patient records and atypical observations are common; and in transport, energy and military systems, where real-time adaptation is essential. The ability to process incomplete and anomalous observations without interrupting the clustering procedure makes the proposed approach suitable for operational environments where delayed batch preprocessing is impossible.

Nevertheless, several limitations should be acknowledged. The study is primarily theoretical and algorithmic. Although the proposed procedures are mathematically grounded, their empirical performance should be further evaluated on benchmark datasets and real data streams. Future validation should include comparisons with classical fuzzy c-means, possibilistic fuzzy c-means, Kohonen self-organising maps, robust clustering algorithms and modern online clustering methods. Such comparison should be based on clustering accuracy, stability of prototype updates, reconstruction quality for missing values, robustness to outliers, computational complexity and memory consumption.

Another limitation concerns the selection of algorithmic parameters. The fuzzifier, learning rate, accuracy threshold, number of clusters, number of accelerated internal iterations, scale parameters in possibilistic clustering and width parameter of the Cauchy similarity function may significantly influence the quality of clustering. The article provides the mathematical framework for these procedures, but further research should develop adaptive parameter-selection strategies. In particular, it would be useful to investigate mechanisms for automatic adjustment of the learning rate and similarity-function width depending on the observed level of noise, missingness and outlier intensity in the data stream.

The issue of cluster number selection also remains important. Many practical data streams are non-stationary: new clusters may emerge, old clusters may disappear, and existing clusters may change their position or shape over time. The present framework provides mechanisms for updating prototypes and membership levels, but further development may include evolving structure adaptation, where the number of clusters is not fixed in advance. Such an extension would bring the proposed method closer to fully evolving clustering systems capable of adapting not only parameters, but also model structure.

Future studies should also examine the behaviour of the proposed algorithms under different missingness mechanisms. Missing data may be missing completely at random, missing at random, or missing not at random. The effectiveness of partial-distance and optimal expansion strategies may differ depending on the mechanism that produces omissions. Similarly, the type of outliers should be considered: isolated point anomalies, contextual anomalies and

collective anomalies may affect cluster prototypes in different ways. A systematic simulation study could clarify the robustness boundaries of the proposed methods.

Another promising direction is the integration of the proposed online fuzzy clustering procedures with forecasting, classification and anomaly detection systems. Since clustering can reveal hidden structure in streaming data, the resulting membership levels and prototype dynamics may serve as additional features for downstream predictive models. In diagnostic systems, changes in membership patterns may indicate early-stage abnormal behaviour. In socio-economic monitoring, evolving clusters may reflect changes in the structure of regional or institutional indicators. Therefore, the proposed methods may become part of broader intelligent decision-support systems.

Overall, the study provides a coherent algorithmic basis for online fuzzy clusterization of distorted data streams. Its main value lies in the simultaneous consideration of online operation, fuzzy uncertainty, missing observations and outlier robustness. By combining partial-distance processing, optimal expansion, possibilistic membership and similarity-based robustification within a neuro-fuzzy Kohonen framework, the proposed approach addresses several limitations of classical clustering algorithms. The method therefore has strong potential for applications in dynamic environments where data arrive sequentially, are incomplete or distorted, and must be analysed without full batch retraining.

Conclusion

The problem of clustering data in object-property tables, with gaps in the mode of sequential receipt of this data for processing.

An adaptive neural network method is proposed that enables online clustering of damaged data with constant correction of recoverable table elements and cluster centroids. The introduced neuro-system consists of a set of adaptive linear associators, characterized by high speed and ease of numerical implementation.

Methods of probabilistic and probabilistic fuzzy online data clustering with gaps based on the partial distance strategy are proposed, and it is shown that it can be solved on the basis of the Kohonen self-organizing neuro-fuzzy network and the proposed self-learning algorithm, which is a hybrid of the “winner gets more” rule and recurrent fuzzy clustering algorithms.

A group of adaptive robust fuzzy methods is proposed for clustering, allowing online processing of distorted data containing both omissions and abnormal outliers. The proposed methods are based on the classical procedures of fuzzy c-means J. Bezdek, self-training map T. Kohonen, as well as a specially introduced measure of similarity, allowing you to work with distorted information. The considered methods are simple to implement numerically, being essentially gradient-based procedures for optimizing objective functions of a special type.

Data clustering methods based on recurrent optimization of a special type of objective functions, while the missing observations are replaced by estimates also obtained in the process of solving the optimization problem.

Methods of probabilistic and probabilistic adaptive fuzzy clustering of distorted data streams are proposed, based on the strategy of the closest prototype centroid. The developed approach is computationally simple, and the processing can be organized around a self-organizing Kohonen map.

The methods of probabilistic and probabilistic fuzzy adaptive clustering for data containing an unknown number of a priori gaps, based on the optimal expansion strategy, are proposed.

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Conflict of Interest

The author declares that there is no conflict of interest.

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Synthesis of Hydroxyapatite Using Recycled Wash Water ^[24]

Abstract:

Hydroxyapatite is a biocompatible calcium-phosphate material widely used in medicine, pharmacy, and advanced biomaterials engineering. At the same time, its synthesis by homogeneous precipitation is associated with the generation of significant amounts of wash water containing residual nitrogen- and phosphorus-containing compounds. In the context of circular economy and low-waste chemical production, the valorization and recycling of such water streams represent an important technological challenge. This work investigates the synthesis kinetics of Hydroxyapatite using calcium saccharate as a calcium precursor and urea as an *in situ* source of ammonium hydroxide under conditions approximating a Continuous Stirred-Tank Reactor (CSTR). The formation of Hydroxyapatite was confirmed by infrared spectroscopy and X-ray phase analysis. Kinetic studies based on turbidity measurements established that the rational precipitation time is 50–60 min, which ensures the completion of nucleation and crystal growth processes. The purification of the resulting Hydroxyapatite precipitate requires no fewer than seven consecutive centrifugal washing cycles, leading to the generation of substantial volumes of wash water. It was shown that these water fractions contain residual ammonium phosphates, urea, and organic saccharate compounds, making them suitable for secondary valorization. Two utilization pathways are proposed: conversion into a suspended mineral-organic NP fertilizer and concentration by membrane technologies, particularly reverse osmosis, followed by permeate recycling into the synthesis process. The proposed approach may enable the integration of Hydroxyapatite synthesis with nutrient recovery and wash water recycling, significantly improving process sustainability and supporting the principles of zero-waste chemical technology.

Keywords: hydroxyapatite, calcium saccharate, homogeneous precipitation, recycled wash water, NP-fertilizer, reverse osmosis, circular economy.

Abbreviations:

CSTR is Continuous Stirred-Tank Reactor.

Introduction

Under modern conditions of the development of advanced low-tonnage industrial synthesis methods for chemical materials, the implementation of resource-saving and low-waste approaches is becoming increasingly relevant. One of the key directions in the realization of sustainable development principles is the reuse of process water within industrial cycles. In certain cases, the source of such wastewater is the technological washing of target products after filtration or centrifugation.

A similar situation is observed in the synthesis of hydroxyapatite by the homogeneous precipitation method (*Serhiienko et al., 2021*).

Hydroxyapatite ($\text{Ca}_5(\text{PO}_4)_3\text{OH}$ або $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$) belongs to the calcium phosphate mineral family forming the hard tissues of vertebrate organisms (*Kumar et al. 2022; Precious et al., 2024*). Synthetic hydroxyapatite is a biocompatible material with promising potential in 3D-printing technologies (*Serhiienko et al., 2022*).

The development of industrial low-tonnage hydroxyapatite synthesis technologies using recycled wash water corresponds to modern trends in the progressive greening of chemical

production, as well as to the principles of the circular economy and the concept of zero-waste production.

Of particular importance is the establishment of the regularities governing the influence of the composition of recycled wash water on the physicochemical properties of the resulting product. Equally significant is the possibility of valorizing wash or wastewater into secondary-value products, such as complex fertilizers.

The study aims to investigate the possibility of Hydroxyapatite synthesis using recycled wash water and to develop proposals for water reuse with the simultaneous production of a liquid NP fertilizer formulation, as well as to substantiate the prospects for implementing such an approach in low-waste technologies for the production of calcium phosphate materials.

To achieve this purpose, the study focuses on several interrelated research tasks:

- to obtain hydroxyapatite by homogeneous precipitation using calcium saccharate, diammonium phosphate and urea as initial reagents;
- to determine the kinetics of hydroxyapatite formation by monitoring changes in the light transmittance of the reaction medium;
- to identify the rational duration of precipitation required for the completion of nucleation and crystal growth;
- to confirm the phase composition of the obtained precipitate by infrared spectroscopy and X-ray phase analysis;
- to evaluate the technological necessity of repeated centrifugal washing for removing residual impurities;
- to analyse the composition and potential value of the resulting wash water and primary centrifugate;
- to propose possible schemes for integrating wash water recycling, membrane concentration and nutrient recovery into the hydroxyapatite production process.

The theoretical significance of the study lies in the clarification of the relationship between homogeneous precipitation conditions, urea hydrolysis, pH generation, precipitation kinetics and the formation of hydroxyapatite as the dominant calcium-phosphate phase. The work contributes to the scientific understanding of hydroxyapatite synthesis under conditions close to ideal mixing, where urea acts as an internal precursor of ammonium hydroxide and provides a more uniform increase in alkalinity throughout the reaction volume. In addition, the study develops the theoretical basis for considering wash water not merely as a technological waste stream, but as a secondary resource containing residual nitrogen- and phosphorus-bearing compounds that may be involved in further material or nutrient recovery cycles.

The practical significance of the results is associated with the possibility of improving the environmental and technological efficiency of low-tonnage hydroxyapatite production. The determination of a rational precipitation time of 50–60 minutes can be used for process optimisation and future scale-up. The confirmation that no fewer than seven centrifugal washing cycles are required for effective purification provides a practical basis for designing the washing stage and estimating water consumption. At the same time, the proposed utilisation pathways for wash water—conversion into a suspended mineral-organic NP fertiliser or concentration by membrane technologies with subsequent permeate recycling—may reduce wastewater

discharge, increase material efficiency and support the transition towards low-waste and circular chemical production.

Thus, the study is aimed not only at obtaining hydroxyapatite as a valuable biocompatible calcium-phosphate material, but also at developing a more sustainable technological concept in which the synthesis process is integrated with wash water recycling, nutrient recovery and secondary product formation. Such an approach corresponds to the principles of circular economy, resource conservation and zero-waste chemical technology.

Methods

The study was based on the method of homogeneous precipitation of hydroxyapatite from a mixture of aqueous solutions of calcium saccharate, diammonium phosphate, and urea, followed by heating to a temperature of 60°C and above without mandatory reactor thermostating (*Serhiienko et al., 2021*).

At the preparation stage, an aqueous solution of calcium saccharate was separately obtained. The calcium saccharate solution was prepared by the interaction of calcium oxide (0.53 g) with an aqueous sucrose solution (3 g of sucrose, 97 g of distilled water).

Subsequently, aqueous solutions of calcium saccharate, ammonium hydrogen phosphate, and urea were mixed in distilled water within a laboratory-scale CSTR, followed by heating of the resulting homogeneous reaction medium to a temperature not lower than 80°C or at the boiling point (in our case 103°C). Hydroxyapatite synthesis was carried out under constant stirring for 1.5 hours.

As a result, a white precipitate was formed, while the reaction medium became viscous. After completion of the synthesis, the reaction mixture was cooled, the Hydroxyapatite precipitate was washed with distilled water and separated from the liquid phase using a laboratory centrifuge. The washed Hydroxyapatite precipitate was dried in a forced-convection drying oven at 60°C.

During the precipitation process, turbidity measurements were carried out to determine the completion time of Hydroxyapatite precipitation kinetics.

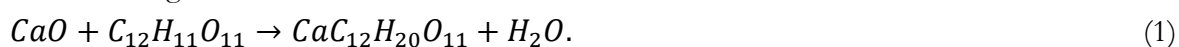
Literature Review

The homogeneous precipitation method makes it possible to control the particle size of precipitates, ranging from highly dispersed to conventional dimensions. Under such conditions, a large number of crystallization centers are formed, leading to the generation of highly dispersed precipitate particles.

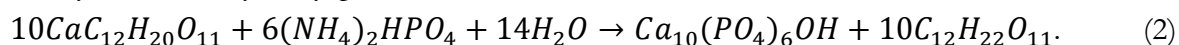
To a certain extent, this model is close to the CSTR concept (*Fedenko et al., 2026*). In this model, instantaneous and complete mixing of the entire reaction volume is assumed, resulting in uniform concentrations of reactants, products, and temperature throughout the reactor.

In the case of hydroxyapatite precipitation, the following chemical interactions occur:

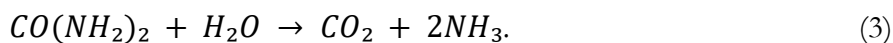
obtaining calcium saccharate for reaction



synthesis of Hydroxyapatite



To create an alkaline medium ($\text{pH} \geq 8$) for the implementation of reaction (2), any alkali, even a weak one, is suitable. However, the use of ammonium hydroxide is expedient, since it is volatile and can be easily removed from the hydroxyapatite precipitate during drying. The sources of ammonium hydroxide are gaseous ammonia introduced into the reaction medium during stirring or aqueous ammonia solution. If ammonium hydroxide is introduced in the form of gaseous ammonia or aqueous ammonia, inevitable local supersaturation with alkali occurs at the point of reagent introduction. Instantaneous and uniform distribution of alkali throughout the entire reactor volume requires forced and rather complex programmed hydrodynamic conditions (*Rashid et al., 2020*). Such a regime does not guarantee uniform alkali distribution in the reactor within an almost zero-time interval. The introduction of gaseous ammonia or aqueous ammonia therefore does not correspond to conditions close to those of an ideal mixing reactor. The problem lies in the fact that aqueous solutions of calcium saccharate and diammonium phosphate are first mixed to form a homogeneous mixture, and only then the alkaline reagent is added. It is precisely at this stage that concentration heterogeneity arises and the correspondence to the ideal mixing reactor conditions is violated. An alternative source of ammonium hydroxide is the well-known hydrolysis reaction of urea upon heating (*Sigurdarson et al., 2018; Mazzei et al., 2020*).



If an aqueous urea solution is introduced at room temperature into the reaction mixture consisting of aqueous calcium saccharate and diammonium phosphate solutions and then mixed, the reaction mixture becomes homogeneous. Under such conditions, reaction (2) does not proceed immediately. Upon subsequent heating and stirring of the homogeneous mixture of aqueous calcium saccharate, diammonium phosphate, and urea solutions at 60°C , urea hydrolysis according to reaction (3) begins, resulting in ammonia formation and the release of hydroxide groups. Even under moderate stirring, uniform temperature throughout the reactor volume is established very rapidly. Likewise, the concentration of hydroxide groups in the reactor is established almost instantaneously. Thus, the use of urea in hydroxyapatite synthesis by the homogeneous precipitation method largely corresponds to the conditions of an ideal mixing reactor. It is specifically urea that enables the formation of hydroxyapatite in nanosized form.

A drawback of using urea is that even under boiling conditions of the reaction mixture it does not decompose completely; therefore, it must be used in a certain excess. In addition, in the case of nanosized hydroxyapatite formation, additional volumes of wash water are required to obtain hydroxyapatite free from residual impurities of the precursor substances. This raises the issue of wash water utilization. In (*Serhiienko et al., 2021*), neither the multiplicity of washing cycles nor the utilization of wash water was considered. Likewise, the kinetics of hydroxyapatite formation by the homogeneous precipitation method were not addressed. The present work examines the precipitation rate of hydroxyapatite, the rational number of washing cycles, and proposals for wash water recycling.

The issue of wash water recycling is directly related to the fact that these waters contain dissolved residual diammonium phosphate and urea, both of which are fertilizers. Considering that saccharates also remain in solution, such a composition can be classified as mineral-organic

fertilizer. This classification makes it possible to consider the utilization of wash water as a fertilizer product.

Wash waters generated during Hydroxyapatite synthesis by precipitation and containing residual concentrations of Ammonium phosphate and Urea may therefore be regarded as a by-product liquid fertilizer, namely a complex binary nitrogen-phosphorus fertilizer.

Residual ammonium phosphates represent a biologically available form of phosphorus readily assimilated by plants, as well as a source of ammonium nitrogen. Residual urea represents a biologically available and prolonged amide form of nitrogen for root uptake. The combination of ammonium phosphates and urea forms a balanced nutrient system, namely:

- readily available phosphorus for plants;
- immediate ammonium nitrogen;
- prolonged nitrogen release from urea;
- possible enhancement of the utilization coefficient of N and P due to synergistic effects.

Such a composition is functionally close to liquid NP-fertilizers.

From a technological perspective, the use of urea as an internal source of ammonium hydroxide ensures a more uniform increase of local pH throughout the entire reaction volume, which is fundamentally important for achieving conditions close to those of a Continuous Stirred-Tank Reactor (CSTR). This minimizes local supersaturation zones and promotes the formation of a large number of homogeneous nucleation centers. Such a mechanism is particularly important for the formation of finely dispersed Hydroxyapatite, since the uniform generation of OH^- directly affects the morphology, particle size distribution, and crystallinity of the precipitate.

Results

The results of measuring by spectrophotometer Unico101 light transmittance (%) in the reaction medium during Hydroxyapatite precipitation are presented in Table 1.

The kinetic studies make it possible to recommend 50–60 minutes as the rational time required for complete Hydroxyapatite precipitation according to reactions 1–3. During this period, crystallization centers are formed and Hydroxyapatite crystals grow.

The unwashed Hydroxyapatite precipitate obtained in the experiments was studied by infrared spectroscopy using a Shimadzu IRAffinity-15 spectrometer (*Figure 1*).

The unwashed Hydroxyapatite precipitate contains impurities of organic calcium complexes, ammonium phosphates, and urea (*Linstrom & Mallard, 2025; John Wiley & Sons, 2025*).

Separately, the composition of the Hydroxyapatite precipitate subjected to seven consecutive centrifugal washing cycles was studied by infrared spectroscopy (*Figure 2*).

The spectral profiles are consistent, and the dominant crystalline phase is Hydroxyapatite.

The washed Hydroxyapatite precipitate was further investigated by X-ray phase analysis (*Figure 3*).

The interpretation of the data was carried out based on (*ICDD Powder Diffraction File (PDF-4+ / PDF-2), Crystallography Open Database (COD)*).

The obtained infrared spectroscopy and X-ray phase analysis data are consistent with the results previously reported in (*Serhiienko et al., 2021*). The precipitate obtained and washed at least seven times is Hydroxyapatite.

Discussion

The results of the kinetic studies make it possible to recommend 50–60 minutes as the rational time required for the complete precipitation of hydroxyapatite from homogeneous solutions according to reactions 1–3.

During this period, the formation of crystallization centers and the growth of hydroxyapatite crystals take place.

The investigation of the crystal-chemical composition was not the objective of this study. The examination of the chemical composition by means of X-ray phase analysis and infrared spectroscopy demonstrates that the dominant solid phase is hydroxyapatite. A challenging stage of the synthesis is the purification of this precipitate from all residual reagent impurities present in the reaction solution. For effective precipitate separation, the use of a centrifuge and no fewer than seven consecutive washing cycles is required.

The washing process is inevitably accompanied by the formation of a significant amount of wastewater. These waters should also include the first fugate, which represents the reaction solution remaining after the separation of the hydroxyapatite precipitate. The problem of generating substantial volumes of wastewater and wash water requires the development of appropriate approaches for its resolution.

Conclusions

The wastewater generated during the synthesis and washing stages of Hydroxyapatite production may be effectively utilized by several technological approaches.

A. One possible route is the conversion of the obtained Hydroxyapatite into a suspended mineral-organic NP fertilizer. Such a fertilizer is characterized by the prolonged release of its phosphate component and may be applied in closed-soil systems for precision plant nutrition. This approach is functionally attractive due to the combined fertilizing effect of Hydroxyapatite, residual ammonium phosphates, and urea. Hydroxyapatite itself may serve as a slow-release phosphorus source, while the dissolved ammonium phosphate and urea components provide immediately available and prolonged nitrogen nutrition. Thus, the resulting system may function as a binary NP fertilizer with combined short-term and long-term nutrient release effects. However, this approach should be considered rather palliative, since it does not fully solve the problem of obtaining chemically pure Hydroxyapatite as an independent product. In addition, maintaining the long-term colloidal stability of the Hydroxyapatite suspension requires additional investigation and optimization of stabilizing systems. Among the promising stabilizing agents are polyhexamethylene guanidine succinate compounds, which may improve suspension stability while preserving the fertilizing functionality of the product (*Natiazhnyi et al., 2023*).

B. A more technologically attractive and industrially scalable route is the integration of all generated water fractions, including wash water and the primary centrifugate, followed by their homogenization and membrane treatment, particularly by reverse osmosis. Such an approach

can potentially provide concentration of dissolved residual compounds by at least 5–7 times (Tyvonenko, A. et al., 2023). In the performed experiments, depending on reactor loading, 1 to 3 g of Hydroxyapatite were obtained, while the total collected wastewater volume reached no less than 700 ml. Under such conditions, membrane concentration may yield approximately 100–200 ml of concentrate and 500–600 ml of purified permeate. Based on mass-balance estimation, the concentrate may theoretically be regarded as a non-standardized liquid NP fertilizer containing 8–12% N and up to 5% P_2O_5 . This route not only minimizes wastewater discharge but also increases the overall material efficiency of the process through nutrient recovery.

The kinetic investigations performed in this work make it possible to recommend 50–60 minutes as the rational duration of homogeneous precipitation for complete Hydroxyapatite formation under the studied conditions. Within this period, the formation of crystallization centers and subsequent crystal growth reach practical completion. The obtained kinetic parameters may be considered as a basis for scaling up the process and for developing automated process control systems based on turbidity measurements.

The performed infrared spectroscopy and X-ray phase analysis confirmed that the dominant solid phase after synthesis and repeated washing is Hydroxyapatite. The obtained analytical data demonstrate the feasibility of Hydroxyapatite synthesis under homogeneous precipitation conditions and confirm the applicability of the CSTR model as an adequate approximation of the hydrodynamic conditions in the reactor. The use of urea as an internal precursor of ammonium hydroxide ensures uniform pH generation throughout the reaction medium, minimizes local supersaturation zones, and promotes the formation of highly dispersed Hydroxyapatite particles.

A critical technological stage of the process is the purification of Hydroxyapatite from residual reaction components. Experimental results show that no fewer than seven consecutive centrifugal washing cycles are required to achieve sufficient purity of the target product. However, this stage is directly associated with the generation of considerable amounts of wash water, which creates an additional environmental and technological challenge.

In general, industrial Hydroxyapatite production by the homogeneous precipitation method from calcium saccharate under conditions approximating a CSTR may consist of the following technological stages:

- synthesis of calcium saccharate;
- preparation of diammonium phosphate solution;
- preparation of urea solution;
- mixing of calcium saccharate, diammonium phosphate, and urea solutions in a stirred and heated reactor;
- heating of the homogeneous reaction medium to a temperature not lower than 60°C, preferably 80–100°C;
- maintaining the reaction medium at the selected temperature for 50–60 minutes until completion of Hydroxyapatite precipitation;
- cooling of the reaction medium;
- centrifugation and separation of the Hydroxyapatite precipitate;

- addition of purified water followed by repeated centrifugal washing of the precipitate for 6–7 cycles, with separate collection of wash water after each cycle;
- drying of the completely washed Hydroxyapatite precipitate;
- homogenization and purification of the accumulated wash water by membrane separation methods;
- concentration of nutrient-containing wastewater fractions;
- conditioning and packaging of the concentrate as a liquid NP fertilizer product;
- return of the permeate to the stages of calcium saccharate, diammonium phosphate, and urea solution preparation.

Thus, the proposed technological concept combines Hydroxyapatite synthesis with an integrated wash water recycling strategy and simultaneous recovery of a secondary-value fertilizer product. Such an approach corresponds to the principles of circular economy, resource conservation, nutrient recovery, and zero-waste chemical synthesis. The obtained experimental data confirm the technological feasibility of integrating Hydroxyapatite synthesis with internal water recycling without compromising the formation of the target calcium-phosphate phase.

Further studies should be focused on the detailed investigation of long-term wash water recycling effects, impurity accumulation in the closed-loop system, membrane concentration efficiency, and the agronomic properties of the resulting NP fertilizer concentrate. Particular attention should also be paid to the influence of recycled wash water composition on the physicochemical characteristics, phase purity, and morphology of Hydroxyapatite obtained in subsequent synthesis cycles.

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Conflict of Interest

The author declares that there is no conflict of interest.

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Not applicable.

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Appendix

Table 1. Kinetics of changes in the percentage of light transmittance during hydroxyapatite formation.

Time, min	0,5	3	5	10	20	30	45	60	75	90
Percentage of transmittance	92	91	49	42	40	36	35	34	34	34

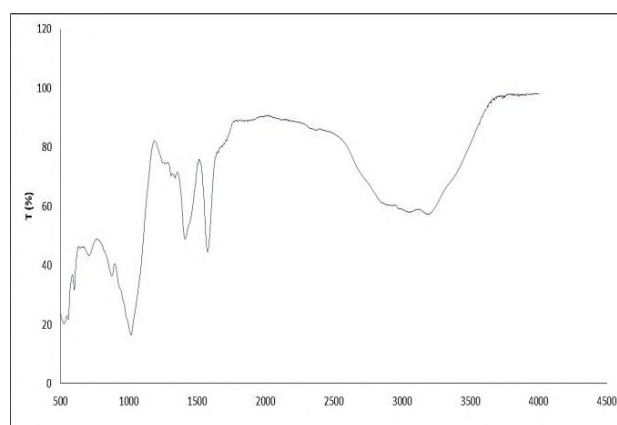


Figure 1. Infrared spectrum of unwashed hydroxyapatite

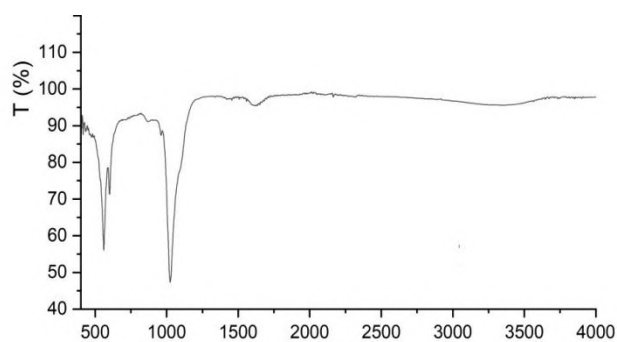


Figure 2. Infrared spectrum of washed hydroxyapatite

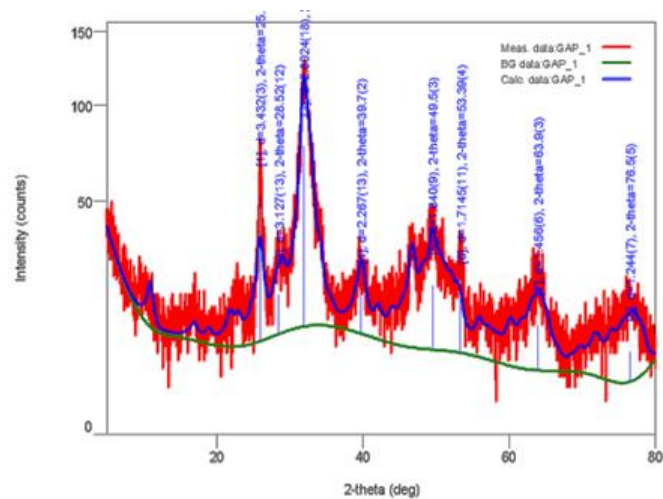


Figure 3. Results of X-ray phase analysis of the hydroxyapatite precipitate

Regularities of Sorption-based Removal of Petroleum Products from Model Aqueous Solutions using Saponite Clay of Ukrainian Origin ^[25]

Abstract:

Industrial wastewater contains petroleum products, heavy metal ions, and a wide range of chemical compounds. Harmful chemical elements and substances enter water bodies, degrading their sanitary condition; therefore, thorough treatment is necessary before the water can be used for domestic, drinking, and certain industrial purposes. Many the most obvious trends in changes to the quality of natural waters under the influence of human economic activity can be identified. Petroleum products entering the environment negatively impact the “water body–soil–flora and fauna–human” ecosystem and are among the most dangerous components of wastewater pollution. They have a harmful effect on biochemical and physiological processes in living organisms. The use of natural minerals, such as saponite clay, for sorption-based wastewater treatment to remove petroleum products is acceptable from both environmental and economic perspectives; however, such materials often lack the necessary sorption properties and require chemical modification. The modification allows for the production of sorbents, whose surface differs from that of the original mineral and combines the beneficial properties of the source material and synthetic sorbents. In this study, the influence of various factors on the efficiency of sorption-based removal of petroleum products using native saponite clay samples was investigated, since their use (without prior modification) is more economically feasible. The influence of parameters such as sorbent dose, pH, temperature, and concentration of petroleum products on the efficiency of sorption extraction of petroleum products was analysed. Optimal conditions for the sorption process were established.

Keywords: sorption, petroleum products, saponite clay, recovery rate, optimal conditions.

Introduction

Petroleum refining waste (oil sludge) consists of amphoteric or fine-crystalline masses containing 20–80% water. The chemical composition of oil sludge is extremely complex and includes aliphatic and aromatic hydrocarbons, carboxylic acids, asphaltenes, tar, metal ions, mechanical impurities, and radioactive elements.

A significant portion of petroleum products and a wide range of organic compounds originate from lubricating and cooling fluids (oil-based and water-miscible) and degreasing solutions.

Oil-based coolants consist of mineral oils (70–90%) with or without additives serving various functional purposes. Water-miscible coolants include three types: emulsifiable, semi-synthetic, and synthetic (*Kosheleva et al., 2022*).

Emulsifiable coolants (emulsions) are specially formulated (balanced) mixtures of mineral oils, emulsifiers, binding agents (water, alcohols, glycols, etc.), corrosion inhibitors, biocides, defoamers, and various additives. So-called water-miscible coolants—semi-synthetic (containing insignificant amounts of petroleum oils) and synthetic (containing no petroleum oils)—are finding increasingly widespread use in addition to emulsions; these mix well with water and form stable colloidal emulsions or solutions.

The most important components of coolants are vegetable oils (rapeseed, coriander, castor, and cottonseed), animal fats, and fat substitutes (synthetic fatty acids, naphthenic acids) (*Maia Cardoso et al., 2021*).

Modern coolants contain additives with various functional purposes (0.5–15%). These are primarily anti-wear, anti-seize, and antioxidant additives. The additives used include phosphates and dialkyl phosphates, dialkyldithiophosphates and dialkyldithiocarbamates of metals, salts of amines and amides of dialkylphosphoric acids, sulfurized fats, organic sulphides and polysulfides, chlorinated paraffins, antioxidants such as aromatic amines, alkanolamines, and polydimethylsiloxane fluids (anti-foaming additives).

Biocides are added to coolants to protect them from microbiological degradation. Triazines are used as biocides in coolants; oxazolines, thiazolines, formalin, fibracillin, hexachlorophene, vasin, and others are also recommended. All components of coolants can have a negative impact on the environment (*Bingari et al., 2024*).

The classification of waste by hazard class is based on indicators characterizing the impact of toxic pollutants on ecosystems, including humans: toxicity, cumulative effects, and the ability to cause long-term effects.

Petroleum hydrocarbons belong to hazard class III. Some substances in the coolant belong to class IV (triethanolamine, carbamol, oleic acid) (*Emerike et al., 2022; Zamparas et al., 2020*).

Methods

Natural samples of saponite clay from the Varvarivskyi deposit (Ukraine) were used as the subject of the study.

The sorption properties of saponite clay were studied using model aqueous solutions (emulsions) of petroleum products with concentrations, mg/L: 20, 50, 100, 200, 250, 500. The dependence of the degree of petroleum product removal on the following parameters was investigated: sorbent dose (0,1; 0,5; 1; 1,5; 2; 2,5 g), pH (3, 5, 6, 7, 9), temperature (20, 25, 30, 35, 40°C).

The content of petroleum products in water was determined by IR spectroscopy using an IRAffinity-1S (Shimadzu) IR spectrophotometer in accordance with MBB Method No. 081/12-0877-13 “Reclaimed, surface, and groundwater”.

The determination of the content of petroleum products in water consists of four stages according to the methodology:

1. Extraction: Petroleum products are extracted from the water sample using a nonpolar solvent (e.g., carbon tetrachloride, tetrachloroethylene, or hexane).
2. Purification: The extract is passed through a column containing a sorbent (aluminum oxide or silica gel) to separate petroleum products from polar compounds, such as natural fats and vegetable oils.
3. Measurement: The purified solution is placed in an IR spectrometer or infrared photometer. The instrument records the degree of light absorption at a wavelength of approximately 3.4 μm (2930 cm^{-1}), which corresponds to the valence vibrations of C-H bonds.

Calculation: The concentration is determined using a calibration curve constructed from standard solutions of reference petroleum products.

Literature Review

Wastewater Treatment at Oil Refineries. Effective treatment of wastewater containing petroleum products is an essential step in refinery production cycles, as water is used as:

- a coolant for equipment, units, and finished products;
- a source of condensate and steam;
- a solvent for mixing reagents (*Melnykov et al., 2026*).

After water is used in these processes, the wastewater may have varying degrees of contamination and differ in the composition of pollutants. It may contain:

- urea and ammonium ions;
- cyclic organic hydrocarbons and phenol;
- surfactants and paraffins;
- fatty acids, petroleum products, sulphates, and other contaminants (*Chruszcz-Lipska, 2024*).

Installing oil separators or wastewater treatment systems for petroleum products allows the wastewater to be treated to a safe condition. Afterward, it can be discharged into sewer systems, onto the ground, into water bodies, or reused.

Technologies for Removing Oil Products from Water. There are two main technologies for treating oil-contaminated wastewater:

- mechanical.
- physicochemical (*Bekchanov et al., 2023; Lach et al., 2023*).

Mechanical removal of petroleum products from wastewater. This method of treating wastewater from oil refineries allows for the removal of up to 65% of contaminants from the effluent. The mechanical wastewater treatment process involves settling in oil separators. Wastewater is placed in tanks, where it is treated to remove petroleum products over a period of 6–24 hours. These tanks can be either static or dynamic. In the former case, the wastewater remains stationary; in the latter, it moves vertically or horizontally (*Tekeyeh et al., 2025; Zaker et al., 2025*).

Physicochemical treatment of wastewater from oil refineries. This technology removes suspended solids and water-soluble impurities from the effluent. The most effective methods for removing petroleum products from water are:

1. Flotation is removal of colloidal and dispersed contaminants from the medium using gas bubbles.
2. Sorption is adsorption of contaminants from the medium by the surfaces of adsorbents (solid materials). The following can be used for this purpose: activated carbon, alumogel, silica gel, zeolites.
3. Ion exchange is ion-exchange materials remove ions from the medium, replacing them with an equal number of ions from the ionite.
4. Hyperfiltration is treatment of oil-containing wastewater using reverse osmosis systems. The wastewater is fed under high pressure through semipermeable membranes, which purify the water at the molecular level.
5. Neutralization is removal of alkalis and acids from the treated medium.
6. Extraction is the redistribution of contaminants in a mixture of two mutually insoluble liquids.
7. Evaporation is a method of treating wastewater from oil refineries by passing steam heated to 100°C through the contaminated medium (*Hrynysbyn & Znak, 2024*).

Sorption is one of the most promising methods for removing petroleum products from water, both in terms of cost and efficiency.

Saponite is one of the most promising natural sorbents. The removal of petroleum products from water using saponite is based on its unique natural properties: it is a magnesium aluminosilicate that acts as a powerful adsorbent and ion exchanger. The mineral effectively binds hydrocarbons, heavy metals, and toxins, but has its own technological characteristics.

How saponite works?

Purification mechanism: Oil product molecules adhere to the highly developed internal and external surfaces of the mineral (adsorption).

Form of application: It is used in powder form (saponite flour) for treating stains, or as a filter media in industrial and local treatment facilities.

Advantage over other clays: Saponite forms a denser and more easily collectable sediment, thanks to its layered structure and lack of significant swelling in water (unlike bentonite).

Water purification methods:

1. Filtration method (for wastewater): Water is passed through multi-layer filters, where saponite acts as the main sorption layer. Once saturated, the filter is regenerated.
2. Direct application (for open water bodies/oil spills): The powder is sprayed over the water's surface, binds oil products into flakes, and settles to the bottom for subsequent mechanical collection (*Romanovsky et al., 2025*).

Limitations and challenges are following. Water absorption. Saponite must be as dry as possible before being introduced into water like many natural clays. Otherwise, its pores will be blocked by its own moisture molecules, which will reduce its oil-holding capacity. Waste disposal. Spent mineral saturated with oil products is classified as hazardous waste. It cannot simply be discarded; it must be disposed of in accordance with environmental regulations (for example, incineration at specialized landfills, since the clay has refractory properties). Difficult regeneration. It is much more difficult to extract oil from saponite for reuse unlike some synthetic or carbon-based sorbents.

Results

The first experiment was devoted to investigating the dependence of the removal degree of oil product removal on the sorbent dose. Initial conditions: duration—15 min, pH 7, oil product solution concentration—100 mg/L, temperature 20°C, volume of the model aqueous solution—100 mL.

It was found that as the sorbent dose increased from 0.1 g to 2 g, the degree of oil product removal increased from 10% to 96%. The degree of oil product removal remained practically constant (not exceeding 97%) with a further increase in the sorbent dose (up to 2.5 g) (*Figure 1*).

The second experiment was devoted to investigating the dependence of the removal degree of oil product removal on the pH of the model aqueous solution. Initial conditions: duration – 15 min, oil product solution concentration—100 mg/L, temperature 20°C, volume of the model aqueous solution—100 mL, sorbent dose—2 g.

It was found that as the pH increased from 3 to 7, the degree of oil product removal increased from 21% to 96%. The degree of oil product removal decreased significantly (to 47%) with a further increase in pH (from 7 to 9) (*Figure 2*).

The third experiment was devoted to investigating the dependence of the removal degree of oil product removal on the temperature of the model aqueous solution. Initial conditions: duration—15 min, oil product solution concentration—100 mg/L, pH 7, volume of the model aqueous solution—100 mL, sorbent dose—2 g.

It was found that as the temperature increased from 20 to 40°C, a significant decrease in the degree of oil product removal was observed (from 99% to 38%) (*Figure 3*).

The fourth experiment was devoted to investigating the dependence of the degree of oil product removal on their concentration in the model aqueous solution. Initial conditions: duration—15 min, temperature 20°C, pH 7, volume of the model aqueous solution—100 mL, sorbent dose—2 g.

It was found that as the concentration of petroleum products increased from 20 mg/L to 500 mg/L, the degree of petroleum product removal decreased (from 99.9% to 72%) (*Figure 4*).

Thus, based on the studies conducted and the patterns identified, it can be concluded that the optimal conditions for the removal of petroleum products from model aqueous solutions are as follows: pH 7; sorbent dose—2 g per 100 mL of solution (further increases are impractical due to the extremely negligible increase in the degree of oil product removal); sorption process temperature—20°C (at higher temperatures, desorption processes evidently begin); concentration of petroleum products—100 mg/L (further increases require a proportional increase in the dose of saponite adsorbent).

Discussion

The following explanations for the observed patterns can be provided, based on the studies conducted.

The degree of petroleum product removal increases from 10% to 97% as the sorbent dose increases from 0.1 to 25 g per 100 mL of solution, which is due to an insufficient amount of sorbent in the range of 0.1 to 1.5 g per 100 mL of solution for effective removal of petroleum products. When the sorbent dose is increased to 2 g per 100 mL of solution, the removal efficiency increases to 96%. The extraction efficiency remains virtually unchanged, reaching 97% with a further increase in the sorbent dose to 2.5 g per 100 mL of solution. This indicates that adding more than 2 g of sorbent per 100 mL of solution is economically unfeasible.

The degree of oil product removal also increases, reaching 96% as the pH of the solution increases from 3 to 7. However, the degree of oil product removal drops sharply and is 47% at pH 9 as the pH shifts toward the alkaline side. This is because acidic and, especially, neutral pH values contribute to the saponite surface acquiring a high affinity for petroleum products (the effect of a positively charged surface). The saponite surface apparently becomes negatively charged, preventing petroleum products from adhering to it at alkaline pH.

The degree of oil product removal decreases from 99% to 38% as the temperature increases from 20 to 40°C, which is associated with the predominance of desorption processes as the temperature rises (a well-known fact of the inversely proportional dependence of adsorption on temperature).

The degree of petroleum product removal remains nearly unchanged (98–99%) as the concentration of model aqueous solutions of petroleum products increases from 20 mg/L to 100 mg/L; however, it begins to decrease as the concentration of petroleum products continues

to rise. This indicates that at petroleum product concentrations exceeding 100 mg/L, a sorbent dose of 2 g per 100 mL of solution is insufficient and must be increased in proportion to the rise in petroleum product concentration.

Conclusion

A literature review was conducted on the relevance of various methods for removing petroleum products from water. A comparative analysis revealed that sorption processes are among the most promising and effective methods for removing petroleum products from water, based on the literature review. The most promising sorbents, particularly from an economic standpoint, are natural clay minerals (e.g., saponite), which are abundant in Ukraine's subsoil.

A study was conducted on the effectiveness of sorption-based removal of petroleum products from model aqueous solutions using samples of natural saponite clay as a sorbent. The use of native saponite samples is motivated by the search for the most cost-effective method of removing petroleum products from large volumes of domestic and industrial wastewater. In addition, pre-modification of saponite clay leads to an increase in both the duration of the process and the need for additional reagents, which affect the cost of treated water and may be a source of secondary contamination.

It was established that to optimize sorption conditions, the following recommendations must be followed: the concentration of petroleum product solutions should not exceed 100 mg/L; the pH should be neutral; the process temperature should be as low as possible (at least 20°C); and the sorbent dosage should be 2 g per 100 mL of solution.

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Conflict of Interest

The author declares that there is no conflict of interest.

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Appendix

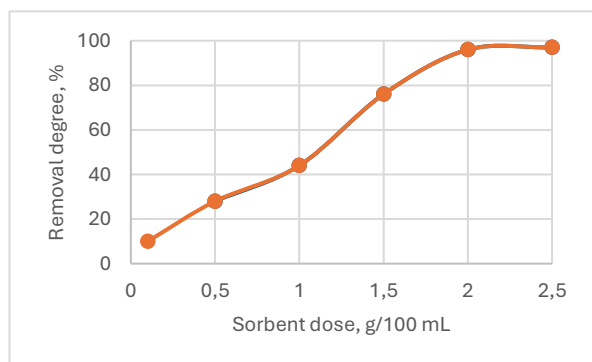


Figure 1. Dependence of the degree of petroleum product removal on the sorbent dose

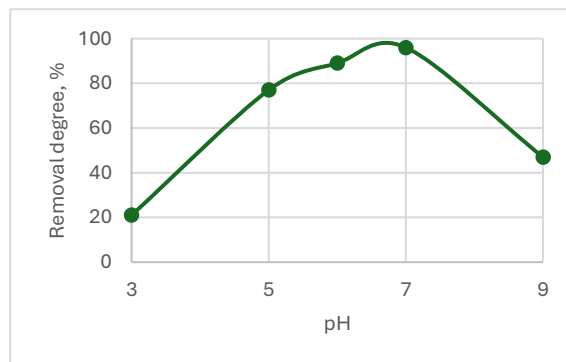


Figure 2. Dependence of the degree of oil product removal on the pH of the model aqueous solution

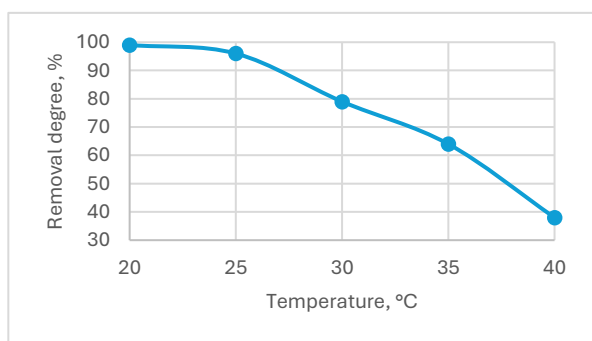


Figure 3. Dependence of the degree of oil product removal on the temperature of the model aqueous solution

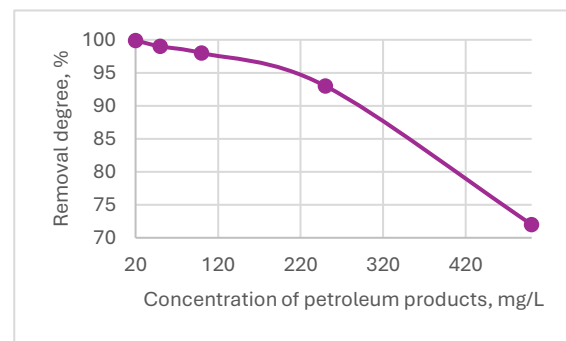


Figure 4. Dependence of the degree of oil product removal on the concentration of oil products

Waveform Optimization for Enhanced Target Coordinate Estimation in Multistatic Radar Systems ^[26]

Abstract:

The relevance of this study is determined by the rapid development of modern air attack means, including unmanned aerial vehicles, cruise missiles and other small aerial objects, which significantly increases the requirements for airspace surveillance and target localisation systems. The research problem lies in the fact that the accuracy of target coordinate estimation in multistatic radar systems depends not only on the spatial configuration of transmitting and receiving positions, but also on the structure, bandwidth and correlation properties of the probing waveform. The scientific novelty of the study consists in a comparative simulation-based assessment of conventional pulse, linear frequency modulated and phase-coded probing signals under identical multistatic radar conditions, with a focus on their influence on ranging accuracy and coordinate estimation error. The object of the study is the process of target coordinate estimation in multistatic radar systems using the ranging method. The aim of the research is to evaluate how probing waveform characteristics affect target localisation accuracy and to determine which waveform types provide the most effective reduction of coordinate estimation errors. The methodology is based on mathematical and simulation modelling of a three-position multistatic radar system in MATLAB, Monte Carlo experiments, correlation-based signal delay estimation, range measurement modelling and statistical analysis of target coordinate estimation errors. The investigated waveforms include conventional rectangular pulses, linear frequency modulated signals with different frequency deviations, and phase-coded modulation signals, including Barker-coded and long Frank-coded waveforms. The results show that conventional pulse signals provide the lowest localisation accuracy because of their limited bandwidth and insufficient range resolution. Linear frequency modulated signals significantly improve coordinate estimation accuracy due to pulse compression and increased effective bandwidth, while long phase-coded waveforms also demonstrate high performance owing to favourable autocorrelation properties and a large time-bandwidth product. The study confirms that waveform optimisation is one of the most effective ways to improve ranging-based localisation in multistatic radar systems without changing the radar network geometry. The obtained findings may be used in the design and modernisation of radar systems intended for the detection, tracking and localisation of small aerial targets under complex airspace surveillance conditions.

Keywords: multistatic radar system, target localization, coordinate estimation accuracy, probing signal, ranging method, unmanned aerial vehicle, airspace surveillance.

Abbreviations:

LFM is linear frequency modulated,
OFDM is orthogonal frequency-division multiplexing,
PCM is phase-coded modulation,
UAV is unmanned aerial vehicle.

Introduction

In recent years, the rapid development of air attack means, particularly UAVs, cruise missiles and other small aerial objects, has created new challenges for radar surveillance systems. The reliable detection of such targets and the accurate determination of their spatial coordinates are essential for ensuring effective airspace monitoring and supporting decision-making processes in air defence systems. The increasing complexity of the air environment, combined with the widespread use of low-observable, small-sized and manoeuvring aerial targets, requires

continuous improvement of radar technologies, target localisation algorithms and signal processing methods.

The relevance of this study is determined by the growing need to improve the accuracy of target coordinate estimation under conditions of complex airspace surveillance. Modern air defence and air traffic monitoring systems must operate in an environment characterised by high target manoeuvrability, reduced radar cross-section, electronic countermeasures and limited reaction time. Under such conditions, even moderate coordinate estimation errors may reduce the effectiveness of tracking, classification, engagement asset allocation and interception. Therefore, improving the accuracy and reliability of target localisation is a critical scientific and engineering task for contemporary radar systems.

One of the key factors affecting the effectiveness of target interception and tracking is the accuracy of coordinate information. High-precision target localisation enables more efficient use of available engagement assets and improves the overall performance of air defence systems. In this context, multistatic radar systems represent a promising technological direction. Due to the spatial distribution of transmitting and receiving modules, multistatic radar systems provide additional target observation opportunities, improved resistance to jamming, enhanced system survivability and better geometric diversity compared with conventional monostatic radar systems (*Cherniak, 1998; Griffiths et al., 2019; Willis, 2005*).

The research problem lies in the fact that, although multistatic radar systems can improve target observability due to distributed geometry, the accuracy of coordinate estimation remains strongly dependent on the quality of range measurements. In ranging-based localisation, target coordinates are determined from measured signal propagation delays. Therefore, any error in delay estimation is transformed into range error and subsequently into coordinate estimation error. The magnitude of this error depends not only on radar position geometry and measurement noise, but also on the structure and characteristics of the probing waveform, including pulse duration, bandwidth, modulation type, correlation properties and time-bandwidth product (*Levanon & Mozeson, 2004; Richards, 2014; Skolnik, 2008*).

Traditional pulse signals are relatively simple to implement but have limited range resolution because their resolution is directly related to pulse duration and effective bandwidth. Shorter pulses may improve range resolution, but they also reduce transmitted energy, which may adversely affect detection performance. Modern radar systems therefore increasingly employ wideband and coded waveforms, including linear frequency modulated signals and phase-coded signals, which provide improved range resolution, processing gain and more favourable correlation characteristics. However, the comparative influence of different waveform types on ranging-based coordinate estimation accuracy in multistatic radar systems requires additional quantitative analysis.

The hypothesis of the study is that optimisation of probing waveform parameters can significantly improve target coordinate estimation accuracy in multistatic radar systems without changing the spatial configuration of radar positions. It is assumed that signals with larger effective bandwidth, higher time-bandwidth product and more favourable autocorrelation properties provide more accurate delay and range measurements, which in turn reduce the spatial dispersion of estimated target coordinates. Accordingly, wideband linear frequency

modulated waveforms and long phase-coded waveforms are expected to outperform conventional rectangular pulse signals in multistatic localisation tasks.

The scientific novelty of the study consists in a comparative simulation-based evaluation of the influence of probing waveform characteristics on target coordinate estimation accuracy in a multistatic radar system using the ranging method. Unlike approaches that analyse radar waveforms primarily from the standpoint of detection or range resolution alone, the present study focuses on the full localisation chain: waveform structure, delay estimation, range measurement error and resulting coordinate estimation accuracy. The study compares conventional rectangular pulses, linear frequency modulated waveforms and phase-coded modulation signals under identical simulation conditions, thereby allowing their localisation performance to be assessed within the same multistatic geometry.

The object of the study is the process of target coordinate estimation in multistatic radar systems using the ranging method.

The subject of the study is the influence of probing waveform parameters, including bandwidth, modulation type and correlation properties, on range measurement accuracy and target localisation error in a distributed radar configuration.

The study aims to evaluate the influence of different probing waveforms on target coordinate estimation accuracy in a multistatic radar system and to determine which waveform types provide the most effective reduction of localisation errors when the ranging method is used.

To achieve this aim, the following research tasks are set:

- to analyse the role of multistatic radar systems in improving airspace surveillance and target localisation accuracy;
- to identify the main factors affecting coordinate estimation accuracy when the ranging method is applied;
- to examine the influence of probing waveform structure on delay and range measurement accuracy;
- to develop a simulation model of a three-position multistatic radar system operating within a common information-processing framework;
- to compare conventional rectangular pulses, linear frequency modulated signals and phase-coded modulation signals under identical modelling conditions;
- to evaluate the spatial distribution of target coordinate estimates obtained through Monte Carlo simulation experiments;
- to determine the relationship between signal bandwidth, time-bandwidth product, correlation properties and localisation accuracy;
- to identify waveform types that provide the most favourable balance between coordinate estimation accuracy, implementation feasibility and operational applicability.

The methodological basis of the study includes mathematical modelling, simulation modelling, correlation-based signal delay estimation, Monte Carlo experiments and statistical analysis of coordinate estimation errors. A three-position multistatic radar system is considered, in which several spatially separated radar positions jointly perform target localisation using independent range measurements. The simulation model reproduces range estimation errors

and uncertainties associated with signal processing. The comparative assessment is carried out for conventional pulse signals, linear frequency modulated signals with different frequency deviations and phase-coded waveforms, including Barker-coded and long Frank-coded signals.

The theoretical significance of the study lies in clarifying the relationship between probing waveform characteristics and coordinate estimation accuracy in multistatic radar systems. The research contributes to radar signal processing theory by showing how waveform bandwidth, modulation structure and autocorrelation properties influence not only range resolution, but also the final spatial localisation accuracy of a distributed radar system. The study also develops the theoretical understanding of the multiplicative effect of range measurement improvement in multistatic configurations, where reductions in individual ranging errors can lead to a substantial decrease in overall coordinate uncertainty.

The practical significance of the results lies in the possibility of using the obtained findings for the design, modernisation and optimisation of multistatic radar systems intended for airspace surveillance, detection and tracking of small aerial objects. The results may support the selection of probing waveforms for radar systems operating against UAVs, cruise missiles and other low-observable aerial targets. In practical terms, the study indicates that wideband linear frequency modulated waveforms may provide the most advantageous balance between localisation accuracy, energy efficiency and technological maturity, while long phase-coded waveforms may be useful where improved correlation properties and interference resistance are required.

Thus, the present study addresses an important problem of modern radar engineering: how to improve target coordinate estimation accuracy in multistatic radar systems through rational waveform selection and optimisation. The results are expected to contribute to the development of more accurate, reliable and operationally effective radar systems for complex airspace surveillance and air defence applications.

Methods

The research was conducted using mathematical and simulation modeling methods to evaluate the influence of probing signal parameters on the accuracy of target coordinate estimation in a multistatic radar system. The considered consisted of several spatially separated radar positions operating within a common information-processing framework and jointly performing target localization using the ranging method.

The coordinate estimation process was based on independent range measurements obtained from multiple radar positions. The target location was determined by combining distance measurements from different observation points and calculating the most probable target coordinates. This approach allows the influence of measurement errors to be reduced and improves localization accuracy compared with conventional single-position radar systems.

To investigate the influence of probing signal characteristics, a simulation model was developed in MATLAB. The model reproduced the operation of a multistatic radar system under realistic measurement conditions, including range estimation errors and uncertainties associated with signal processing. The simulation environment enabled repeated experiments under identical conditions while varying only the parameters of the transmitted signal.

The studied radar configuration included three radar positions arranged in a distributed geometry with overlapping coverage areas. A target was placed within the common surveillance region, and range measurements from all radar positions were used to estimate its coordinates. The localization process was repeated multiple times to obtain statistically reliable results and to evaluate the distribution of coordinate estimation errors.

Several signal types commonly used in radar systems were considered. These included conventional rectangular pulses, LFM signals, and PCM signals with different bandwidths and coding structures. The selected signals represent different approaches to improving radar performance through increased bandwidth and signal time-bandwidth product.

For each signal type, a series of Monte Carlo simulation experiments was performed. The received signal delay was estimated using correlation-based processing techniques, and the corresponding range measurements were used for coordinate estimation. The accuracy of target localization was evaluated by analyzing the spatial distribution of estimated target positions and the corresponding coordinate errors.

The comparative assessment focused on the relationship between signal characteristics and localization performance. Particular attention was paid to the influence of signal bandwidth, modulation type, and correlation properties on range measurement accuracy and, consequently, on the overall coordinate estimation accuracy of the multistatic radar system.

Literature Review

Multistatic radar systems have attracted considerable attention in recent years due to their potential to improve target detection, tracking, and localization performance. The spatial separation of radar positions provides additional geometric diversity, increases system survivability, and enhances resistance to electronic countermeasures compared with conventional monostatic radar systems.

A significant number of studies have focused on target localization methods in multistatic radar networks. Among the available approaches, ranging-based methods remain one of the most widely used because of their relatively simple implementation and suitability for distributed radar architectures. In such systems, localization accuracy is primarily determined by the precision of range measurements and the geometric configuration of radar positions.

Previous research has shown that the characteristics of the probing signal strongly influence range estimation accuracy. Conventional unmodulated pulse signals are characterized by simple implementation; however, their range resolution is limited by pulse duration and available bandwidth. As a result, the achievable coordinate estimation accuracy may be insufficient for the detection and tracking of small aerial targets.

To overcome these limitations, modern radar systems increasingly employ wideband waveforms with intrapulse modulation. LFM signals have become one of the most common solutions due to their ability to provide pulse compression, improved range resolution, and high energy efficiency. Several studies report that increasing signal bandwidth significantly improves range measurement accuracy while maintaining sufficient detection performance.

PCM signals have also been extensively investigated in radar applications. Their advantages include improved correlation properties and enhanced resistance to interference. The

localization performance of PCM signals depends on code length and waveform design, with longer codes generally providing better range estimation accuracy.

Recent studies have additionally considered advanced waveform designs, including OFDM and other wideband radar signals. Although these approaches offer promising localization capabilities, their practical implementation often requires increased computational complexity and strict synchronization requirements.

Despite extensive research on radar waveforms and multistatic radar architectures, limited attention has been paid to the combined influence of probing signal characteristics and ranging-based coordinate estimation accuracy in multistatic radar systems. In particular, the quantitative relationship between waveform parameters, range measurement accuracy, and resulting target localization performance requires further investigation.

Therefore, this study focuses on evaluating the impact of different probing signal types on coordinate estimation accuracy in a multistatic radar system employing the ranging method. Special attention is devoted to comparing conventional pulse signals, linear frequency modulated signals, and phase-coded waveforms under identical simulation conditions.

Results

The simulation study was conducted to evaluate the influence of probing waveform characteristics on target coordinate estimation accuracy in a multistatic radar system employing the ranging method. The investigated waveforms included conventional pulse signals, LFM signals, and PCM signals. For each waveform type, multiple Monte Carlo simulation runs were performed, and the resulting coordinate estimates were analyzed statistically.

The results obtained for conventional pulse signals confirmed the expected relationship between pulse duration and range resolution. A pulse duration of 2 μs produced a relatively large uncertainty region due to limited signal bandwidth. The estimated target positions exhibited considerable spatial dispersion, indicating insufficient ranging accuracy for high-precision localization tasks. Reducing the pulse duration to 1 μs improved the range resolution and reduced the spread of estimated target coordinates. However, the achieved accuracy remained limited compared with modern wideband waveforms.

The use of LFM signals resulted in a significant improvement in localization performance. For an LFM waveform with a frequency deviation of 400 kHz, the estimated coordinate distribution became substantially more concentrated than in the case of conventional pulse signals. The reduction of coordinate dispersion demonstrated the positive effect of increased signal bandwidth on ranging accuracy. Further improvement was achieved when the frequency deviation was increased to 50 MHz. Under these conditions, the uncertainty region surrounding the true target position decreased considerably, and the majority of coordinate estimates were clustered close to the actual target location.

PCM waveforms also demonstrated improved ranging performance compared with conventional pulse signals. The Barker-coded waveform provided a noticeable reduction in coordinate estimation errors due to its favorable autocorrelation properties. The improvement became even more pronounced when a long phase-coded waveform based on a 169-element Frank code was employed. The resulting coordinate estimates formed a compact cluster around

the true target position, indicating high localization accuracy and stable operation of the ranging algorithm.

The simulation results confirmed that increasing signal bandwidth and time-bandwidth product leads to improved delay estimation accuracy and, consequently, more accurate coordinate determination (*Figure 1*). Figure-based analysis showed a progressive reduction in the coordinate uncertainty region when moving from conventional pulse signals to LFM and long PCM waveforms.

A comparison of the investigated signal types revealed that the largest coordinate estimation errors were associated with conventional pulse signals, while the smallest errors were obtained for wideband LFM and long PCM waveforms. These findings indicate that waveform design plays a critical role in determining the overall performance of multistatic radar systems.

Overall, the obtained results demonstrate that advanced probing waveforms can substantially improve ranging accuracy and reduce target localization uncertainty. The observed improvement was particularly evident for signals possessing large effective bandwidths and favorable correlation characteristics.

Discussion

The obtained results demonstrate that the performance of a multistatic radar system is strongly dependent on the characteristics of the probing waveform. Since the ranging method relies entirely on accurate delay estimation, any factor influencing range measurement accuracy directly affects the quality of target coordinate estimation.

The relatively poor performance of conventional pulse signals can be explained by their limited bandwidth. In pulse radar systems, range resolution is determined primarily by pulse duration. Improving resolution therefore requires shorter pulses, which simultaneously reduces transmitted energy and may negatively affect detection performance. This fundamental limitation restricts the applicability of conventional pulse waveforms in systems requiring both long detection ranges and high localization accuracy.

The superior performance of LFM waveforms is associated with the pulse compression principle. By introducing frequency modulation within the pulse, it becomes possible to transmit a long-duration, high-energy signal while achieving the range resolution characteristics of a much shorter pulse after matched filtering. Consequently, LFM signals provide a favorable compromise between energy efficiency and ranging accuracy. The simulation results clearly indicate that increasing the frequency deviation leads to a significant reduction in coordinate estimation errors, confirming theoretical predictions reported in previous radar signal processing studies.

PCM waveforms demonstrated comparable advantages due to their favorable correlation properties. The Barker-coded signal exhibited lower sidelobe levels than conventional pulse waveforms, resulting in more reliable delay estimation. The long Frank-coded waveform further improved performance because of its larger time-bandwidth product and enhanced processing gain. These characteristics contribute to more accurate range measurements and reduced coordinate uncertainty.

An important observation is that improvements in range estimation accuracy produce a greater overall effect in multistatic radar systems than in conventional monostatic radars. In a

multistatic configuration, target coordinates are determined from the intersection of multiple range measurements. Consequently, even moderate improvements in individual range estimates lead to a substantial reduction in the resulting localization error. This effect becomes increasingly important when tracking small aerial targets, where precise coordinate information is required for reliable target classification and engagement.

The results also highlight the practical trade-off between localization accuracy and implementation complexity. Although wideband LFM and long PCM waveforms provide superior performance, their implementation requires more sophisticated signal generation, synchronization, and digital signal processing capabilities. Increasing signal bandwidth places additional requirements on analog-to-digital converters, waveform generators, processing hardware, and system synchronization. Therefore, waveform selection should consider both desired localization performance and available technological resources.

From an operational perspective, the obtained findings suggest that wideband LFM waveforms represent the most practical solution for modern multistatic radar systems. They provide high ranging accuracy, good energy efficiency, and relatively mature implementation technology. Long PCM waveforms may be particularly attractive in applications requiring improved interference resistance and enhanced correlation properties. Conventional pulse signals remain relevant for simple and low-cost radar systems but are less suitable for applications demanding high coordinate estimation accuracy.

Therefore, the conducted study confirms that waveform optimization is one of the most effective approaches for improving target localization performance in multistatic radar systems. The achieved results demonstrate that the use of wideband LFM and long phase-coded signals can significantly reduce coordinate estimation errors and enhance the overall effectiveness of ranging-based target localization.

Conclusions

This study investigated the influence of probing waveform characteristics on target coordinate estimation accuracy in a multistatic radar system employing the ranging method. The conducted analysis, mathematical modeling, and simulation experiments made it possible to evaluate the relationship between waveform parameters, range measurement accuracy, and the resulting localization performance of the radar system.

The literature review demonstrated that target coordinate estimation accuracy in multistatic radar systems is determined not only by the geometric configuration of radar positions but also by the characteristics of the transmitted waveform. Modern radar systems increasingly employ wideband and coded waveforms to overcome the limitations of conventional pulse signals and to achieve higher ranging precision. However, the combined influence of waveform properties and ranging-based coordinate estimation in multistatic radar architectures remains insufficiently investigated.

A simulation model of a multistatic radar system was developed to assess the localization performance of different probing waveform types under identical operating conditions. The model incorporated range estimation based on signal delay measurements and target coordinate determination using measurements obtained from multiple spatially distributed radar positions.

This approach enabled a comparative evaluation of waveform effectiveness with respect to coordinate estimation accuracy.

The obtained results confirmed that conventional pulse signals provide the lowest localization performance among the investigated waveform types. Their limited bandwidth results in relatively poor range resolution and consequently larger coordinate uncertainty regions. Although reducing pulse duration improves localization accuracy, the achievable performance remains significantly lower than that of modern modulated waveforms.

The study demonstrated that linear frequency modulated (LFM) signals provide substantial improvements in ranging and localization accuracy. Increasing the signal bandwidth through frequency modulation significantly reduces range estimation errors and decreases the spatial dispersion of estimated target coordinates. Among the investigated waveforms, wideband LFM signals exhibited the highest localization accuracy due to their large effective bandwidth and favorable pulse-compression properties.

PCM signals also demonstrated high effectiveness in multistatic radar applications. Barker-coded and Frank-coded waveforms provided improved correlation characteristics and reduced coordinate estimation errors compared with conventional pulse signals. Long phase-coded waveforms with large time-bandwidth products achieved localization performance comparable to that of wideband LFM signals while additionally offering improved sidelobe suppression and interference resistance.

The conducted analysis confirmed that signal bandwidth and time-bandwidth product are the primary factors influencing ranging accuracy in multistatic radar systems. Increasing these parameters leads to more accurate delay estimation, narrower correlation peaks, and reduced target localization uncertainty. Consequently, waveform optimization represents one of the most effective methods for improving coordinate estimation performance without requiring changes to the geometric configuration of the radar network.

An important finding of the study is that improvements in range measurement accuracy have a multiplicative effect on localization performance in multistatic radar systems. Since target coordinates are determined from multiple independent range measurements, even moderate reductions in individual ranging errors result in a significant decrease in the overall coordinate estimation error. This characteristic makes waveform optimization particularly valuable for multistatic radar architectures.

From a practical perspective, the results indicate that wideband LFM waveforms provide the most advantageous balance between localization accuracy, energy efficiency, implementation feasibility, and technological maturity. Long phase-coded signals constitute a promising alternative for applications requiring enhanced correlation properties and increased resistance to interference. Conversely, conventional pulse waveforms are suitable primarily for low-complexity radar systems with moderate localization accuracy requirements.

Therefore, the research confirms that the application of advanced probing waveforms can significantly enhance the effectiveness of multistatic radar systems employing the ranging method. The obtained results may be used in the design and modernization of future radar systems intended for the detection, tracking, and localization of small aerial objects. Future research should focus on the investigation of adaptive waveform design, hybrid LFM-PCM

signals, OFDM-based radar waveforms, and the influence of synchronization errors and electronic countermeasures on coordinate estimation accuracy in multistatic radar networks.

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Conflict of Interest

The author declares that there is no conflict of interest.

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Appendix

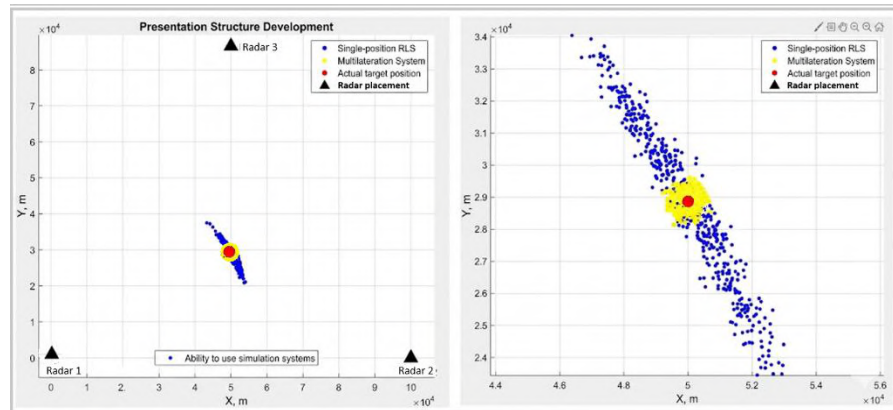


Figure 1. Results of modeling the process of determining the coordinates of the target in a three-position system with the location of the true target location in the center of the triangle (Source: compiled by the author)

Water Territories: Urban Planning Term and Concept ^[27]

Abstract:

The current paradigm shift in the perception of natural water bodies has intensified the need to adapt urban planning and landscape design to the realities of climate change, sea-level rise, extreme precipitation, and recurrent flooding. At the same time, the continuing concentration of population and infrastructure in coastal zones requires not only new technical and environmental solutions, but also a clearer conceptual and terminological framework for planning spaces situated at the interface between land and water. The article addresses this problem by analysing, comparing, and systematising terms related to the aquatic environment as used in national legislation, international maritime law, geographical and hydrological sciences, urban planning regulations, and architectural and landscape studies. The research applies a qualitative conceptual and terminological methodology based on documentary analysis, comparative interpretation, systematisation, and inductive-deductive generalisation. The study demonstrates that existing terms such as “territorial waters”, “internal waters”, “water fund lands”, “coastal waters”, “aquatorium”, “water protection zone”, and “coastal protection strip” describe legal, geographical, hydrological, or environmental phenomena, but do not adequately define water spaces as independent objects of urban planning and architectural-landscape design. In response to this conceptual gap, the article proposes the term “water territories” as an urban planning concept. Water territories are defined as territories covered by the waters of natural water bodies and including the water surface, the water column, and the submerged part of the shore, considered as objects of planning, design, development, and environmental regulation. The article identifies their components, boundaries, and main types: lake, river, marine, and oceanic water territories. The proposed concept provides a theoretical basis for integrating water spaces into contemporary urban planning practice, particularly in relation to coastal adaptation, floating architecture, artificial islands, recreational water zones, ecological infrastructure, and future models of human habitation in aquatic environments.

Keywords: water territories (or areas), lake, river, and marine water areas, the boundaries of water territories.

Introduction

The beginning of the twenty-first century has been marked by a significant transformation in the perception of natural water bodies within urban planning, landscape architecture, and environmental design. Water is no longer considered only as a natural boundary, a resource, or an element of visual and recreational value. In contemporary planning practice, it increasingly becomes a spatial, functional, ecological, and infrastructural component of the urban environment. This shift is closely connected with climate change, sea-level rise, the increasing frequency of extreme weather events, heavy rainfall, coastal erosion, and flooding, all of which directly affect areas of human habitation located in the immediate vicinity of seas, rivers, lakes, and other natural water bodies.

The relevance of this problem is intensified by the persistent global tendency towards population concentration in coastal zones. The demographic attractiveness of coastal territories, which became especially visible in the second half of the twentieth century, continues in the present day. According to the publicly available dataset analysed by Cosby et al. (2024), more than 2 billion people, or approximately 29% of the global population, lived within 50 kilometres of the shoreline in 2018, while more than 1 billion people, or around 15% of the global population, lived within 10 kilometres of the water. Thus, a considerable part of the world's

population is already located in zones where urban development is directly influenced by the dynamics of natural water bodies.

The concentration of population, infrastructure, transport systems, recreational facilities, and economic activity in coastal areas creates a complex planning situation. On the one hand, coasts remain highly attractive for settlement, tourism, public space development, and economic activity. On the other hand, these territories are increasingly exposed to environmental risks associated with flooding, storm surges, erosion, hydrological instability, and ecological degradation. Consequently, the traditional planning model based primarily on the separation of land and water is no longer sufficient. Contemporary urban planning requires a more integrated approach in which coastal areas and adjacent water spaces are considered as interconnected components of a single spatial and ecological system.

The problem addressed in this article lies in the fact that the terminological apparatus currently used in legislation, hydrology, geography, environmental protection, and urban planning does not provide a sufficiently clear definition of water spaces as objects of architectural, landscape, and urban planning activity. Existing concepts such as “territorial waters”, “internal waters”, “water fund lands”, “coastal waters”, “water protection zones”, “coastal protection strips”, and “aquatic landscapes” are important within their respective disciplinary contexts. However, they do not fully describe the planning nature of water spaces that may be designed, functionally organised, protected, regulated, and developed either independently or together with adjacent coastal areas.

The research problem is therefore not only environmental or technical, but also conceptual. In order to develop contemporary methods for the architectural and landscape organisation of water spaces, it is necessary first to clarify the terminology that defines these spaces as planning objects. Without such clarification, urban planning practice remains dependent on fragmented terms borrowed from legal, hydrological, geographical, and environmental discourse, while the water surface, water column, submerged shore, and related spatial elements remain insufficiently articulated in planning theory.

The scientific novelty of this study consists in substantiating the concept of “water territories” as a new urban planning and architectural-landscape term. Unlike legal or hydrological terms, the proposed concept is intended to describe natural water spaces not only as physical or ecological phenomena, but also as spatial objects that may be included in planning documentation, design strategies, landscape organisation, functional zoning, environmental protection, and future urban development scenarios. The article defines the main components of water territories, identifies their boundaries, and proposes their classification according to the type of natural water body.

The object of the study is the system of natural water bodies and adjacent coastal spaces considered in the context of urban planning, architectural design, and landscape organisation. The subject of the research is the conceptual and terminological framework used to define water spaces as potential objects of urban planning and architectural-landscape design.

The study aims to substantiate the concept of “water territories” as an urban planning term and to define its meaning, components, boundaries, and typological characteristics within the contemporary theory and practice of coastal and water-area planning.

To achieve this aim, the study addresses the following research objectives:

- to analyse existing terms related to the aquatic environment in national legislation, international maritime law, geographical and hydrological sciences, urban planning regulations, and scientific literature;
- to compare the meanings and disciplinary functions of these terms in order to identify their conceptual limitations for urban planning;
- to systematise the selected terms according to their legal, geographical, hydrological, environmental, and planning contexts;
- to identify the conceptual gap between existing terminology and the practical need to plan and design water spaces;
- to formulate the definition of “water territories” as a new object of urban planning and architectural-landscape design;
- to define the components, boundaries, and main types of water territories;
- to demonstrate the theoretical and practical significance of this concept for contemporary planning practice.

The theoretical significance of the study lies in the development of the conceptual apparatus of urban planning and landscape architecture in relation to water spaces. The proposed term “water territories” enables a more precise description of aquatic spaces as spatial-planning objects and contributes to the interdisciplinary integration of urban planning, hydrology, geography, environmental law, maritime regulation, and architectural-landscape design.

The practical significance of the research lies in the possibility of applying the proposed concept in planning documentation, coastal development strategies, landscape design projects, water-based recreational planning, climate adaptation measures, floating architecture, artificial island projects, ecological infrastructure, and the regulation of future forms of settlement and construction in water environments. The concept may also be useful for developing planning principles for areas where coastal territories and water bodies form a single functional and ecological system.

Methods

This study is based on a qualitative conceptual and terminological research design. The methodological approach was selected because the central objective of the article is not to measure a physical phenomenon or test an engineering solution, but to clarify, compare, and theoretically substantiate a planning concept that is currently insufficiently defined in urban planning discourse. The research therefore combines documentary analysis, comparative terminology, conceptual analysis, systematisation, and inductive-deductive generalisation.

The empirical and documentary basis of the study includes several groups of sources. The first group comprises national legislative acts regulating water bodies, water fund lands, coastal protection zones, and state territory, including the Water Code of Ukraine, the Land Code of Ukraine, and the Law of Ukraine On the State Border of Ukraine. The second group consists of international legal documents and conventions, particularly the United Nations Convention on the Law of the Sea and the Convention on the Territorial Sea and the Contiguous Zone. The third group includes European regulatory documents, including Directive 2000/60/EC, which

provides important definitions concerning coastal waters and water policy. The fourth group comprises geographical, hydrological, and encyclopaedic sources that define aquatic landscapes, water surfaces, water columns, water areas, and related hydrological concepts. The fifth group consists of urban planning regulations and scientific works in architecture, landscape architecture, urban planning, geography, and legal studies that address coastal zones, coastal strips, water protection areas, aquatic zones, and the planning organisation of coastal and water-related spaces.

The selection of sources was guided by three criteria: relevance to water-related terminology; authority within the respective disciplinary or regulatory field; and relevance to urban planning, architectural, landscape, legal, geographical, or hydrological interpretation of water spaces. Particular attention was given to sources in which water bodies or adjacent areas are treated as objects of regulation, classification, protection, planning, design, or functional organisation.

The research procedure consisted of several consecutive stages. At the first stage, terms related to natural water bodies, coastal zones, aquatic landscapes, water areas, territorial waters, water fund lands, and water protection zones were collected from the selected sources. At the second stage, these terms were grouped according to their disciplinary origin: national legislation, international maritime law, geographical and hydrological sciences, urban planning legislation, and scientific works in urban planning and landscape architecture. At the third stage, the semantic content of the terms was analysed in order to determine whether they describe water spaces as legal, geographical, hydrological, ecological, recreational, or planning objects. At the fourth stage, the identified terms were compared with the practical needs of contemporary urban planning and architectural-landscape design, especially in relation to coastal development, floating architecture, artificial islands, recreational water zones, and climate adaptation. At the fifth stage, the conceptual gap was identified: existing terminology describes water spaces from several disciplinary perspectives, but does not sufficiently define them as independent or integrated objects of urban planning. At the final stage, the concept of “water territories” was formulated and theoretically substantiated.

The study applies the method of analysis and synthesis to examine individual terms and then integrate the findings into a coherent conceptual framework. The comparative method is used to identify similarities and differences between legal, hydrological, geographical, and urban planning interpretations of water-related spaces. The method of systematisation is applied to organise the selected terms into meaningful groups and to establish their relation to the proposed concept. The method of abstraction is used to move from specific definitions and regulatory formulations to a more general urban planning concept. The method of concretisation is then applied to define the components, boundaries, and types of water territories. Inductive reasoning allows the study to derive the need for a new concept from the analysis of existing terms and practices, while deductive reasoning is used to test the applicability of the proposed concept to different types of natural water bodies, including lakes, rivers, seas, and oceans.

The validity of the proposed conceptual framework is supported by interdisciplinary triangulation. The article compares terms and definitions from legal, geographical, hydrological, environmental, and urban planning sources rather than relying on a single disciplinary tradition.

This approach makes it possible to distinguish between terms that define water spaces as objects of sovereignty, environmental protection, geographical classification, or recreational use, and the proposed term “water territories”, which is intended to define them as objects of planning and architectural-landscape organisation.

The study has several limitations. It does not include field measurements, hydrodynamic modelling, GIS-based spatial analysis, or empirical case-study evaluation of specific coastal projects. Its purpose is conceptual and terminological rather than technical or quantitative. However, the proposed framework may serve as a methodological basis for subsequent applied research, including spatial modelling, comparative case studies, design guidelines, environmental assessment, and the development of planning regulations for coastal and water territories.

Literature Review

The terminology associated with water bodies and aquatic environments has been developed within several disciplinary fields, including hydrology, geography, environmental law, maritime law, urban planning, and landscape architecture. However, these fields use different conceptual frameworks and often assign different meanings to similar terms. This creates difficulties for urban planning theory and practice, particularly when water spaces are considered not only as natural or legal objects, but also as potential spaces for design, functional organisation, development, and adaptation to climate change.

In hydrological and geographical literature, basic terms relating to land hydrology and water resources are presented in encyclopaedias, conceptual and terminological dictionaries, textbooks, standards, and scientific publications. Such sources include the Encyclopedia of Hydrology and Water Resources (1998), the Geographical Encyclopedia of Ukraine (1993), the conceptual and terminological dictionary by Alaev (1983), the hydrological works of Chebotarev (1960; 1978), the State Standards of Ukraine DSTU 3517-97 Land Hydrology (1997), and scientific studies by Kononov (2011), Studennikov et al. (2005), and other authors. These publications provide an important basis for understanding watercourses, water bodies, river systems, hydrological regimes, coastal zones, and related natural phenomena. Their primary focus, however, is the scientific classification and description of hydrological and geographical objects rather than their interpretation as objects of urban planning and architectural-landscape design.

Geographical scholarship also uses terms such as “aquatic landscape”, “surface-water landscape”, “underwater landscape”, “littoral landscape”, and “aquatic-anthropogenic landscape”. Petrov (1989), for example, defines aquatic landscapes as aquatic complexes within the Earth’s landscape envelope that differ according to origin, hydrological regime, geological foundation, bottom relief, and biocenoses. Such definitions are valuable because they emphasise the internal structure and ecological specificity of aquatic environments. Nevertheless, they remain primarily geographical and ecological in orientation. They explain the nature and classification of aquatic environments, but do not provide an urban planning concept that would define water spaces as territories for design, spatial organisation, regulation, and development.

Legal and regulatory sources provide another important layer of terminology. In national legislation, terms such as “state territory”, “territorial waters”, “internal waters”, “water fund lands”, “coastal protection strips”, “water protection zones”, and “sanitary protection zones”

are used to regulate sovereignty, ownership, environmental protection, land use, and economic activity. The Water Code of Ukraine, the Land Code of Ukraine, and the Law of Ukraine On the State Border of Ukraine define the legal status and composition of water-related territories. These definitions are essential for governance and regulation, but they do not establish water spaces as architectural or urban planning objects. Their function is primarily legal and administrative.

International maritime law further develops the terminology of the aquatic environment through concepts such as “territorial sea”, “internal waters”, “contiguous zone”, “high seas”, and areas beyond national jurisdiction. The Convention on the Territorial Sea and the Contiguous Zone (1958) and the United Nations Convention on the Law of the Sea (1982) define the maritime zones over which coastal states exercise sovereignty or jurisdiction. These instruments are fundamental for international relations, navigation, maritime rights, and the delimitation of state authority. However, their terminology is not intended to describe the internal spatial, functional, ecological, and design characteristics of water spaces as objects of urban planning.

European regulatory documents also contribute to the definition of water-related concepts. Directive 2000/60/EC introduces the concept of “coastal waters” as surface waters extending towards the shore from a defined maritime line. This definition is important for environmental policy and water management. Nevertheless, as in other legal and regulatory frameworks, the emphasis is placed on water quality, protection, governance, and ecological management rather than on architectural-landscape design or the spatial organisation of water areas.

Urban planning regulations introduce terms that are more closely related to spatial organisation, but they usually focus on land adjacent to water bodies rather than on water spaces themselves. In Ukrainian urban planning legislation and standards, concepts such as “water protection zone”, “coastal protection strip”, “sanitary protection zone”, “recreational areas”, “water zones”, and “beach zones” are used in relation to the planning and regulation of areas near rivers, lakes, and seas. The State Building Standards B.2.2-12-2019, for example, regulate landscape and recreational areas, beach zones, and adjacent water zones. These documents acknowledge that water-related areas may have recreational and planning functions, but they generally treat the water body as an adjacent or supporting element rather than as an independent planning territory.

Scientific works in urban planning and landscape architecture have made a significant contribution to the study of coastal territories and water-related spaces. Vadimov (2003) investigated the ecological and urban development of riverside urbanised territories; Onyshchenko (2010) studied the integrated development of coastal cities in the Azov-Black Sea region; Lukomska (2014) examined the architectural and landscape organisation of river valley spaces in the Ukrainian Carpathians; Vyazovska (2019) analysed planning principles for water and green areas of the city. These studies demonstrate the increasing importance of water bodies in urban development. However, they mostly focus on coastal territories, river valleys, shorelines, water-green systems, or protection zones rather than on the water surface and water column as independent objects of planning.

Several studies move closer to the problem addressed in this article. Khomych (2000) considered the functional-territorial organisation of coastal zones; Sydorova (2014) analysed the

functional and planning organisation of the coastal strip of seaside resorts and identified aquatic zones within resort planning structures; Potapchuk (2005) proposed considering the coastal strip of the seas as an object of legal protection that includes both the coastal part and the marine environment. These works are important because they show that parts of the aquatic environment may be included in planning, functional organisation, or legal protection. Nevertheless, even in these studies, the aquatic component is usually interpreted as part of a broader coastal system rather than as a clearly defined urban planning object with its own structure, boundaries, and typology.

The literature therefore reveals a clear research gap. Existing terminology describes water spaces as legal zones, hydrological objects, geographical landscapes, ecological systems, recreational zones, or components of coastal protection. However, it does not provide a sufficiently integrated concept for defining natural water spaces as objects of urban planning and architectural-landscape design. This gap becomes particularly important in the context of contemporary design practice, where artificial islands, floating buildings, floating neighbourhoods, underwater structures, water-based recreational infrastructure, marine parks, and adaptive coastal projects increasingly transform water spaces into sites of human activity and spatial organisation.

In response to this gap, the present study develops the concept of “water territories”. The proposed term is intended to complement, rather than replace, existing legal, hydrological, geographical, and environmental terminology. Its specific contribution is to define water spaces as planning territories that include the water surface, water column, submerged shore, and related spatial components, and that may be designed independently or together with adjacent coastal areas. In this sense, the concept provides a bridge between scientific classification, legal regulation, environmental protection, and contemporary urban planning practice.

Results

In various sciences and spheres of state activity, there are terms describing phenomena and aspects of the existence of the natural waters of the World Ocean, which the author has selected, systematised, and analysed.

As a new concept in urban and landscape planning, the author has established the concept of ‘*water territories*’ in this work, following an in-depth analysis of selected concepts and terms drawn from the following sources: terminological dictionaries, encyclopaedias, world atlases, etc., as well as the international maritime and domestic law acts. The analysis also included legislative acts and scientific works in urban planning.

Domestic Legislation

The territory associated with a state’s natural water bodies is defined in various sources as ‘territorial waters’, ‘the territorial sea’, ‘internal waters’, ‘water fund lands’, etc.

‘State territory consists of land, water, airspace, and subsoil. The legal regime governing the components of state territory is determined by the constitution, the state’s current legislation, and the norms of international law. The state’s water territory includes rivers, lakes, reservoirs, straits, and canals located within its borders. The state’s water territory also includes internal sea

waters (bays, estuaries, gulfs, port waters, etc.) and territorial waters washing the state's coastline" (*On the State Border of Ukraine, 1992, part 13*).

According to the provisions of the Law of Ukraine On the State Border of Ukraine, the term 'territorial waters (territorial sea)' is defined as 'a maritime zone located along the coast or immediately beyond the internal waters of a coastal state and falling under its sovereignty.' The width of the territorial sea in the vast majority of states is 12 nautical miles.

There are three main methods of measuring territorial waters:

- 1) from the low-water line along the coast of the coastal state;
- 2) if the coastline is indented or jagged, or if there is a chain of islands near the coast, the method of straight baselines connecting the points on the coast and islands that project furthest into the sea may be applied;
- 3) from the internal waters.

Thus, the outer boundary of the territorial sea is a line, every point of which is situated at a distance from the nearest point of the straight baseline equal to the width of the territorial sea (12 miles) (*On the State Border of Ukraine, 1992*).

Internal waters and the territorial sea are defined in the Water Code of Ukraine as 'water bodies of national importance' (*Water Code of Ukraine, 1995, art. 5*).

In Water Code of Ukraine, 1995 water fund lands are defined as 'lands occupied by seas, rivers, lakes, coastal protection strips, hydraulic structures, and the coastal strips of waterways' (*Water Code of Ukraine, 1995 art. 4*); internal sea waters, territorial seas, and the water areas of seaports are defined as water bodies of national importance (*Water Code of Ukraine, 1995 art. 5*).

According to Part 1 of Article 58 of the Land Code of Ukraine, 2002, the concept of water fund lands is defined by their composition (*Land Code of Ukraine, 2002, art. 58*). 'Water fund lands include lands occupied by: seas, rivers, lakes, reservoirs, other water bodies, marshes, as well as islands not covered by forests; coastal protection strips along seas, rivers and around water bodies, except for lands covered by forests; hydraulic engineering and other water management structures and canals, as well as land allocated for their right-of-way; the shore zones of waterways; and artificially created land plots within the water areas of seaports.' (*Water Code of Ukraine, 1995, art. 4; Land Code of Ukraine, 2002, art. 58*).

'The country's water fund of Ukraine covers 2 million hectares, or 3% of the country's territory, including natural watercourses (rivers and streams)—2,000 hectares, lakes and estuaries—4,000 hectares, ponds—3,000 hectares, artificial reservoirs—5,000 hectares, and marshes—5,000 hectares.' (*The concept and composition of water fund lands, 2012*).

International Maritime Law

International relations are governed by two legal instruments: the Convention on the Territorial Sea and the Contiguous Zone of 29 April 1958, Geneva (ratified by the USSR on 20 October 1960) (*Convention on the Territorial Sea and the Contiguous Zone, 1958*) and the United Nations Convention on the Law of the Sea, 1982 (*United Nations Convention on the Law of the Sea, 1982*), as well as the state's domestic legislation. It was the 1982 Convention on the Law of the Sea that established a unified approach to the understanding of the territorial sea (territorial waters) and set out the method for measuring their width.

‘The sovereignty of the coastal State extends to the waters of the territorial sea, the airspace above it, and the seabed and subsoil in that zone’ (*Convention on the Territorial Sea and the Contiguous Zone, 1958, art. 1, 2; United Nations Convention on the Law of the Sea, 1982, art. 2*). The territorial sea forms part of the territory of the State concerned. The regime of these zones must, however, take into account the right of all states to enjoy, within such a zone, the universally recognised freedoms of the high seas, including freedom of navigation.

‘Areas beyond the national jurisdiction of States constitute the international common heritage of mankind; these include: the high seas (including the seabed) and the airspace above them, Antarctica, outer space and celestial bodies; no State’s sovereignty extends to these areas, and they are for the common use of mankind’ (*On the State Border of Ukraine, 1992*).

Thus, in international maritime law, the components of state territories are identified as the ‘the state’s water territory’, ‘land territory’, and ‘airspace’, but no definitions, interpretations or planning characteristics are provided for these (*On the State Border of Ukraine, 1992, part 13*); the term ‘territorial waters (territorial sea) of a state’, used in the legal sphere and in international law, also does not pertain to the planning of water territories (or areas), but defines the physical boundaries of a country’s sovereign water territories (areas) and regulates international relations.

Geographical and Other Sciences

In geographical sciences, the concept of ‘aquatic landscape’ is defined within the general classification of geographical landscapes.

The aquatic (water-surface) variant of the landscape sphere is formed within the upper layer of water with a thickness of up to 200 m (the lower limit of photosynthesis), but at depths exceeding 200 m, that is, outside the distribution of shallow-water landscapes. It is a zone of direct contact and active interaction of only two shells of the Earth - the hydrosphere and the atmosphere, and differs from all other water and land landscapes in the absence of a lithosphere. This class of aquatic landscapes is characterized by latitudinal zonation, which is to some extent similar to the latitudinal zonation of land landscapes (*Aquatic landscape science, 2025*). In terms of area (approximately 333 million square kilometres), this is one of the most widespread variants of the landscape sphere. It is found everywhere in the surface layer of ocean waters where depths exceed 200 m. At shallower depths, it transitions into the terrestrial-aquatic or shallow-water variant

‘An aquatic landscape is an aquatic complex within the Earth’s landscape envelope. It is distinguished from others by its origin, stable hydrological regime, geological foundation, uniform bottom relief, and biocenoses. Classification of aquatic landscapes: river landscapes; lake landscapes; littoral landscapes; shallow-water landscapes; surface-water landscapes; underwater landscapes’ (*Petrov, 1989*).

The Earth’s water surface accounts for over 70% (according to other sources—71%) (*World Atlas, 2005; Collins World Factfile, Atlas, 2010*); it is studied by geographers, oceanographers, and other scientists who investigate the structure of the Earth (e.g., the scientific works of geographer E.A. Dolginov, oceanologist H. Wright, academician V.I. Vernadsky, etc.). ‘Ocean water is the most important and widespread natural environment. More than half of all the water in the Earth’s crust is found here,’ according to V.I. Vernadsky (*Vernadskyi, 2004*).

‘Coastal waters are surface waters extending towards the shore from a line, every point of which is situated at a distance of one nautical mile seaward from the nearest point of the baseline from which the breadth of the territorial waters is measured, extending, where appropriate, to the outer limit of the transitional (intermediate) waters.’ (*Directive 2000/60/EC, 2000, p. 179*).

Another term similar in meaning to ‘water territories’ is ‘water area (aquatorium)’, which in official publications and legislative acts is defined as ‘a section of the water surface of a specific body of water or part thereof (port, bay, sea) within defined boundaries’ (*Small Mining Encyclopaedia, 2004, Vol. 1*). For example, a port’s water area encompasses the roadstead, inner harbour, approaches to the port, and quays. The Water Code of Ukraine uses the term ‘seaport water area (port water area)’ to mean ‘a part of a water body (or bodies) defined by boundaries, excluding the shipping channel, intended for the safe approach, manoeuvring, mooring and departure of vessels’. The water areas of seaports are defined in the Water Code of Ukraine as ‘water bodies of national importance’ (*Water Code of Ukraine, 1995, art. 5*).

As for the definitions of the terms ‘aquatic landscapes’, ‘aquatic-anthropogenic landscapes’, ‘water surface’ and ‘water column’, these refer to coastal (marine), surface, oceanic and natural waters; there are also corresponding concepts for river, lake, surface water and other landscapes. For example, aquatic or water landscapes are those with a depth of over 200 m; water-anthropogenic landscapes include reservoirs and ponds, etc.

Urban Planning Legislation and Scientific Works

According to domestic legislation (*Water and Land Codes of Ukraine, 1995*), in relation to natural water bodies, a distinction is made between a “water protection zone”, a “coastal protection strip”, and a “sanitary protection zone” (for the protection of certain water bodies to meet the medical and health needs of the population). “A water protection zone is a nature-protected area of regulated economic activity” (*Water Code of Ukraine, 1995, Art. 87*). “A coastal protection strip is a part of a water protection zone of the appropriate width along a river, sea, around water bodies, on which a stricter regime of economic activity is established than on the rest of the territory of the water protection zone” (*Water Code of Ukraine, 1995, Art. 1*). These zones become objects of urban planning design, for example, in 2015, the design documentation “Scheme for determining the boundaries of the coastal protection strip of the Dnipro River in the city of Vyshgorod, Kyiv region” (*SE “DNIIP Urban Planning”*).

In the State Building Standards B.2.2-12-2019 ‘Planning and development of territories: concepts and definitions’, a general description of landscape and recreational areas and nature reserve sites is provided, which uses the phrase ‘water protection areas’ and other types of sites’, which are established by Ukrainian legislation and form part of the structural territorial elements of the ecological network (*State Building Standards, 2019, subpara. 8.1.1, p. 43*).

The organization of a “water protection zone”, a “coastal protection strip”, and a “sanitary protection zone” concerning the banks of natural water bodies, their coastal territories.

‘Recreational areas (water areas) are sections of land (or water space) designated for recreational activities and the leisure of holidaymakers’ (State Building Standards, 2019, para. 3.54).

In Chapter 8 ‘Landscape and Recreational Areas’, the dimensions of beaches in the riparian zones of rivers, lakes, and seas are regulated (*State Building Standards, 2019, subpara. 8.4.4., 8.5.6*).

In the areas and water bodies adjacent to the beach zone, beachfront and water zones should be established, for which indicative calculated areas are provided (*State Building Standards, 2019, subpara. 8.4.5*). The water zone is divided into sectors: swimming (the sector covers 70–90% of the water zone), children's, sports, and fishing (*State Building Standards, 2019, tabl. 8.4*). For its calculation, a figure of 5 square metres per swimmer is recommended (*State Building Standards, 2019, para. 8.4.5*); the beach zone is allocated for administrative and utility, rescue and medical sectors, service sectors, and pedestrian routes, etc. (*State Building Standards, 2019, tabl. 8.4*).

According to the nomenclature of structural elements of the network of natural landscape, recreational and other green areas, the following are classified as landscape-recreational areas outside built-up areas within settlements: forest parks, meadow parks, water parks, etc.; recreational areas (short-term rest zones, forest parks; areas of summer cottage and gardening societies and associations) are listed without considering natural water bodies and watercourses. Water bodies (rivers, lakes, ponds, reservoirs, canals, except those included in green infrastructure) are classified as non-green areas within and outside built-up areas (*State Building Standards, 2019, annex D1, p. 136*).

Scientific works mainly investigated native shores and coastal water protection zones, etc., but some scientific researchers developed proposals for the organization of water spaces.

For example, Sydorova V.V. in her study “Principles of functional and planning organization of the coastal strip of seaside resorts (e.g., Bolshoi Alushta)” exploring the terms related to the coastal zone (“coastal territory”, “coastal strip”, etc.) interprets term “coastal water area” as the part of the sea surface adjacent to the shore, which is part of the coastal territory of the resort with dimensions from 500 m (minimum) to 1 nautical mile (*Sydorova, 2014, p. 4*). By Sydorova V.V., the coastal strip of seaside resorts includes zones: beach and near-beach; embankment, aquatic, cultural and household services, resort and recreational facilities, green spaces and economic and industrial; in the aquatic zone, sectors are allocated according to functional purpose: swimming, children's, sports, fishing, etc. (*Sydorova, 2014, p. 158*).

In a scientific work on the legal direction “The coastal strip of the seas as an element of the legal protection of the seas”, I.M. Potapchuk proposes the creation of a new object of legal protection of the “coastal strip of the seas”, which will extend its influence to both the marine environment and the coastal part simultaneously within the specified limits, for a more progressive approach to more effective protection of the sea (*Potapchuk, 2005*).

So, an analysis of scientific and theoretical research by geographers, urban planners, and lawyers indicates that part of the water surface can be classified as a planning object. For example, the following are identified as planning objects: the ‘coastal zone’ (comprising the ‘coastal (aquatic) zone’) (by L.V. Khomych) (*Khomych, 2000*), and the ‘coastal strip of seaside resorts’ within which the ‘aquatic zone’ is distinguished (according to Sydorova V.V.) (*Sydorova, 2014*); a new object of legal protection—the ‘coastal strip of the seas’, including the coastal part and the marine environment (after I.M. Potapchuk) (*Potapchuk, 2005*); a new strategy for settlement and the perception of ‘maritime spaces as new territory’ (after P. Velev) (*Velev, 1985*), etc.

Water Territories (or Areas) with an Urban Planning Context

In the context of architectural and landscape practice, a comprehensive approach to planning coastal areas and water bodies is essential. Based on the provisions of the Water Code of Ukraine and other sources, the author defines the concept of ‘water territories’ in an urban planning context as territories covered by the waters of natural water bodies, comprising the water surface, the water column and the submerged part of the shore, which are the subject of architectural and landscape design and development; the boundaries of these territories with the coastal part are defined from the water’s edge (during the low-water period or from the line of the greatest ebb along the shore) towards the water body (*Ruban, 2017; Ruban, 2020; Ruban, 2025*) (*Figure 1*).

As evidenced by international experience (in the UK, the Netherlands, Denmark, Japan, the UAE, Singapore, the USA, Canada, etc.), coastal and aquatic territories can be standalone or integrated objects of architectural and landscape design. For example, in the Dubai Bay (UAE), the artificial ‘Palm’ islands have been constructed, whilst in Abu Dhabi, the Louvre cultural museum centre has been built on the water’s surface; in the Netherlands and Denmark, floating neighbourhoods have been created on the water’s surface, along with floating livestock and plant farms; in Italy – underwater plant farms; in Singapore—numerous public buildings on pontoons are situated in the Marina Bay lagoon and in the coastal areas—the Gardens by the Bay; in the USA, there is rapid development of the hotel industry, which is expanding not only into above-water but also underwater spaces (hotels, such as the ‘Jules Undersea Lodge’, and restaurants); in Canada, designated marine nature reserves such as ‘Bruce Peninsula National Park’ and others (*Ruban, 2020; Ruban, 2025; Ruban, 2026*).

All this indicates that in our time humanity has already begun a wide, intensive expansion into the water spaces of the World Ocean, including for architectural and construction purposes. Therefore, in the author’s opinion, it is timely and appropriate to consider water areas from the point of view of a qualitatively new development - as an area of probable human habitation.

Thus, summarising the above and clarifying the concept of ‘water territories (or areas)’, it should be emphasised that their constituent elements in architectural and landscape planning are: (a) the water space, be it territorial waters, a river or a lake, in which the water surface and the water column (water) can be distinguished; (b) the bottom surface, where the general shoreline slope and the riverbed are distinguished (in accordance with the natural water body); (c) the airspace above it (*Ruban, 2018; Ruban, 2020; Ruban, 2025*) (*Figure 1*).

Depending on the types of natural water bodies, a distinction is made between lake, river, and marine water areas. It should be noted that every natural water body (sea, river, lake) is a unique natural complex (with its own hydrological, geomorphological, microclimatic, and biotic characteristics), characterised by the natural processes of the corresponding aquatic ecosystems (marine or freshwater bodies). The water column (for the sea—the water column; for a lake—the pelagic zone; for a river—the river channel) is divided into layers that differ in depth and conditions of sunlight penetration; in some cases, by distance from the shore, etc. Thus, the main ecological zones (layers) of the marine water column are the littoral (in shallow waters), the pelagic zone (epipelagic up to 200 m deep, mesopelagic up to 1,000 m, batipelagic (from 1,000 to 4,000 m), and benthal (deep water—over 4,000 m); in the pelagic zone of a lake, the following main ecological zones are distinguished: littoral (or coastal); transitional (or sublittoral); deep-water (or profundal); these zones on the underwater slope of the lake are also

referred to as: lower, underwater portion of the coast (littoral), coastal shoal (sublittoral), deep-water bottom of the lake basin (profundal) (*Ruban, 2020; Ruban, 2025*).

The boundaries of water territories are established in accordance with the requirements of international law at a distance of 12 miles (over 22 km 224 m) from the coastline; they must be differentiated in relation to natural water bodies: the boundaries of maritime territories are established in accordance with international law and the country's domestic legislation; the boundaries of river and lake water areas correspond to the shoreline and coincide with the boundaries (contours) of the water surface of natural water bodies (*Ruban, 2020; Ruban, 2025*) (*Figure 1*).

Discussion

The results of the study demonstrate that the traditional system of relations between a coastal area and a natural water body is being transformed into a more complex system of interaction between coastal territories and water territories. This transformation reflects not only changes in planning theory, but also changes in real design and construction practice. Contemporary cities and coastal settlements increasingly use water spaces for recreation, transport, public functions, ecological infrastructure, artificial islands, floating architecture, marine parks, and experimental forms of habitation. Consequently, water spaces can no longer be treated exclusively as external natural surroundings or as legal zones adjacent to land. They require their own planning interpretation.

The main theoretical contribution of this article is the formulation of “water territories” as an urban planning concept. The proposed term makes it possible to describe natural water spaces as territories covered by the waters of natural water bodies and including the water surface, the water column, and the submerged part of the shore. This definition is important because it shifts the focus from the shoreline alone to the entire spatial structure of the aquatic environment. In this sense, the concept expands the object field of urban planning and landscape architecture.

The analysis of existing terminology shows that each disciplinary field captures only part of the phenomenon. International maritime law defines the boundaries of sovereignty and jurisdiction, but does not define water spaces as design objects. Hydrology and geography describe natural water bodies, aquatic landscapes, and ecological zones, but do not formulate their planning status. Environmental and water legislation regulates protection, use, and management, but does not provide a full architectural-landscape concept. Urban planning regulations address coastal protection strips, beach zones, recreational areas, and water zones, but usually treat the water body as an adjacent or supporting element. The proposed concept of “water territories” responds precisely to this fragmentation.

The practical significance of the concept lies in its potential application to planning documentation and design methodology. If water territories are recognised as planning objects, it becomes possible to define their functional zoning, ecological constraints, design regimes, permissible forms of development, spatial boundaries, and relation to adjacent coastal areas. This is especially relevant for territories exposed to flooding, storm surges, erosion, and other climate-related risks. In such contexts, water territories may become part of adaptive planning strategies rather than remaining passive natural elements beyond the scope of design.

The concept also has implications for the development of coastal resilience. In many contemporary planning situations, adaptation cannot be achieved solely through the reinforcement of shorelines or the restriction of construction in coastal protection zones. It requires a more flexible understanding of the interface between land and water. Water territories may include floating structures, amphibious architecture, floodable public spaces, ecological buffers, wetland restoration zones, recreational water sectors, and landscape systems designed to absorb or redirect hydrological pressure. Thus, the proposed concept may contribute to the integration of climate adaptation and architectural-landscape planning.

Another important implication concerns the functional diversification of water spaces. International experience demonstrates that water territories are already used for different purposes: artificial islands, floating neighbourhoods, public buildings on water, floating farms, underwater agricultural experiments, marine reserves, recreational facilities, hotel infrastructure, and cultural objects. These examples indicate that water spaces are becoming not only environmental resources, but also spatial resources. However, such development requires careful regulation. Without a clear conceptual and planning framework, the expansion of architectural and construction activity into water spaces may create ecological, legal, infrastructural, and social risks.

The proposed concept should therefore be understood not as a call for uncontrolled expansion into aquatic environments, but as a methodological instrument for more responsible planning. Recognising water territories as planning objects makes it possible to establish stricter environmental criteria, hydrological limitations, safety requirements, navigation restrictions, biodiversity protection measures, and public-access principles. In this respect, the concept may support both development and protection, provided that it is integrated with environmental assessment, water management, ecosystem-based planning, and climate adaptation strategies.

The study also confirms the need to revise the methodological foundations of architectural and landscape organisation in coastal and aquatic contexts. Planning should move from a linear model based on the boundary between land and water towards a three-dimensional model that includes the water surface, water column, submerged shore, bottom relief, airspace above water, ecological zones, hydrological dynamics, and functional use. Such a model is especially important for marine, river, and lake territories, each of which has distinct hydrological, geomorphological, ecological, and planning characteristics.

From a theoretical perspective, the concept of water territories contributes to the development of interdisciplinary urban planning knowledge. It connects legal categories of water jurisdiction, geographical categories of aquatic landscapes, hydrological categories of water bodies, and architectural categories of spatial design. This interdisciplinary character is particularly important for contemporary urban studies, where the most urgent planning challenges often occur at the intersection of environmental risk, infrastructure, legal regulation, social demand, and spatial design.

At the same time, the proposed concept requires further elaboration. The present article offers a terminological and conceptual foundation, but it does not yet provide a complete regulatory model, design code, GIS-based classification system, or quantitative assessment methodology. Future research should therefore focus on the development of criteria for identifying water territories in planning documentation; methods for mapping their boundaries;

principles of functional zoning; environmental and hydrological assessment procedures; typologies of permissible architectural and landscape interventions; and comparative case studies of existing projects in different countries.

Further research is also needed to distinguish between different types of water territories. Lake, river, marine, and oceanic water territories differ significantly in terms of depth, hydrological dynamics, ecological sensitivity, ownership regimes, navigation, seasonality, and potential forms of use. For this reason, a universal planning model is unlikely to be sufficient. Instead, differentiated methodological approaches should be developed for each type of natural water body.

In summary, the discussion confirms that the introduction of the term “water territories” is both timely and theoretically justified. It responds to the growing importance of water spaces in contemporary urban development, the increasing risks faced by coastal populations, and the insufficiency of existing terminology for architectural and landscape planning. The proposed concept provides a basis for treating water spaces as integrated, multidimensional, and regulated planning objects that may support more adaptive, sustainable, and responsible interaction between human settlement and the aquatic environment.

Conclusion

The analysis of scientific and theoretical research on this issue makes it possible to conclude that numerous concepts and terms related to the aquatic environment are used in various fields of knowledge. However, their use remains inconsistent, particularly in urban planning. This inconsistency is especially evident in relation to the definition of “water areas”, since no unambiguous definition of this concept has been identified in official scientific sources, including geographical, hydrological, urban planning, and legislative domains.

The analysis covered several areas: domestic legislation, international maritime law, geographical and other sciences, urban planning legislation, and scientific works. Within each of these groups, terms and concepts related to aquatic ecosystems were identified and analysed.

For example, in the context of international and domestic legislation concerning Ukraine as an independent state, such terms as “state territory”, “territorial waters” or “territorial sea”, “internal waters”, “water fund lands”, and “the state’s water territory” are used. It should be noted that the term “territorial waters” or “territorial sea”, which is widely used in legal and international-law contexts, defines the physical boundaries of a country’s sovereign water territories and regulates international relations. However, this term does not refer to the planning or design of water territories or water areas in an urban planning context.

The geographical terms analysed in the article include “aquatic landscape”, “the aquatic” or “water-surface” variant of the landscape sphere, “coastal waters”, “water area” or “aquatorium”, “seaport water area”, as well as “aquatic landscapes”, “aquatic-anthropogenic landscapes”, “water surface”, “water column”, and other related concepts. These terms classify the aquatic environment and its components primarily as geographical phenomena.

In urban planning legislation and scientific works, such terms as “water protection zone”, “coastal protection strip”, “sanitary protection zone”, and “water protection areas” were identified. It is important to emphasise that, although these terms and concepts are relevant to

urban planning, they primarily refer to coastal areas adjacent to natural water bodies rather than to the water surface itself.

Additional evidence of the timeliness and necessity of introducing new urban planning terms in relation to aquatic ecosystems is provided by the fact that humanity has already begun extensive and intensive expansion into the water spaces of the World Ocean, including for architectural and construction purposes. Today, water spaces are used by humans for a variety of functional purposes, including the creation of artificial islands, housing, public buildings, industrial facilities, green modules, and recreational zones.

Scientific urban planning studies have primarily focused on natural shorelines, coastal water protection zones, and related areas. Some of these studies have also developed proposals for the organisation and use of water spaces. In this regard, the works of L. V. Khomych, V. V. Sydorova, and I. M. Potapchuk have made important contributions to the field.

In this context, the author introduces the concept of “water territories” within an urban planning framework. According to the author, water territories or water areas are territories covered by the waters of natural water bodies and include the water surface, the water column, and the submerged part of the shore. These territories are considered objects of architectural and landscape design and development. The article proposes approaches to determining the boundaries of water areas and classifying them into several types: lake, river, and marine water territories. Water areas may be designed either independently or in combination with adjacent coastal areas.

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Conflict of Interest

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Appendix

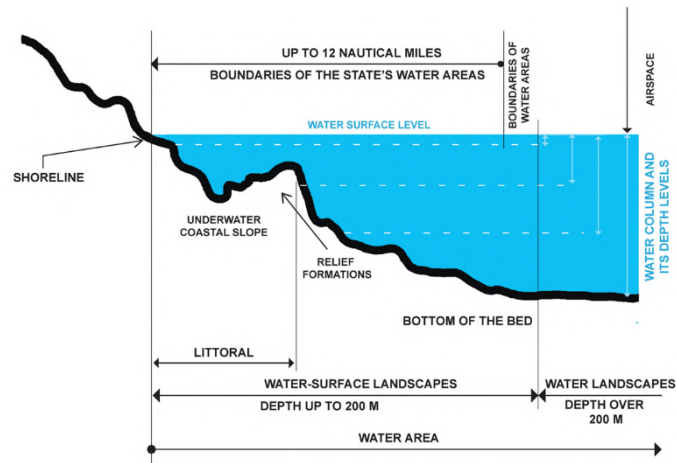


Figure 1. Schematic diagram of a water territory (or area) (by the author).

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