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Valeriia V. Salo [1]

Principles of architectural and planning organization of underground research complexes [1]

Abstract: The issue of the architectural and planning organization of underground research complexes is a significant criterion of modern urban planning, considering the limited surface areas, the rapid development of scientific fields, and growing urbanization. Designing underground facilities requires a specific safety, functionality, and comfort approach. The article focuses on the principles of architectural and planning organization of underground research facilities. The author has analyzed works of foreign and Ukrainian scientists and considered world analogues of underground laboratory design in Europe and the United States. Based on the analysis, the basic principles of scientific relevance, autonomy, ergonomic compliance, and spatial development are identified. The author discusses the critical characteristics of each principle that affect the optimal conditions for conducting experimental research in physics, astrophysics, geology, biology, and chemistry. The author pays special attention to the issues of isolation from external influences, the organization of an ergonomic environment, and the possibility of adaptation to the complex. The importance of using alternative energy sources to ensure the autonomy of the complex and the use of modular solutions is substantiated. Recommendations for further research are proposed: improvement of automated life support control systems; introduction of innovative materials for insulation; study of ergonomics and psychological comfort of personnel; development of modular solutions for spatial development.

Keywords: underground research complexes, underground urbanism, principles of architectural organization.

Introduction

In recent decades, global megacities have been characterized by rapid urban infrastructure development. The advantages of developing underground space are the ability to solve several problems inherent in modern cities: territorial, transport, energy, demographic, and environmental. Underground space can provide citizens free movement, access to the city's remote or densely built-up areas, and access to water and energy resources. In modern realities, one of the key advantages of the integrated use of Ukraine's underground space is the ability to accommodate various facilities. They include research facilities and military and defense industry facilities, which contribute to public safety and the development of these industries (*Pankratova et al., 2020*).

The relevance of building underground research facilities lies in the need for their operation in physics, astrophysics, geology, geophysics, and biology. Underground research complexes can provide the necessary conditions for experimental research in physics and astrophysics, which require ultra-clean and ultra-quiet environments, and for research of geological processes in the deep layers of the Earth.

Research by foreign and Ukrainian scholars: E. Reynolds (*Reynolds & Reynolds, 2015*; *Reynolds, 2019*). H. Admiraal and A. Cornaro (*Admiraal, 2015*; *Admiraal & Cornaro, 2016*; *Admiraal & Cornaro, 2018*; *Admiraal & Cornaro, 2020*), R. Sterling (*Carmody & Sterling, 1987*; *Sterling & Nelson, 2013*), G. I. Gayko (*Gayko, 2014*; *Gayko, 2018*; *Gayko, 2019*), S. Ryndiuk (*Ryndiuk & Maksymenko, 2021*), focus on the theoretical basis of underground urbanism, the

peculiarities of the volumetric-spatial organization of underground buildings and structures, the complexity of underground space in the context of sustainable development. In the works of foreign physicists: A. Bettini (*Bettini, 2003*; *Bettini, 2008*; *Bettini, 2012*; *Bettini, 2014*), E. Coccia (*Coccia, 2006*), L. Votano (*Votano, 2010*), Jose Manuel Carmona (*Carmona, 2021*), A. Ianni (*Ianni, 2020*) provide an overview of the technical characteristics and schematic view of the world's underground laboratories. The architectural and planning organization of underground research complexes is relevant and requires further and in-depth study.

The article aims to determine the basic principles of architectural and planning organization of underground research complexes that are important for design theory and practice. The object of research is underground research complexes. The subject of the study is the architectural and planning organization of underground complexes.

Materials and methods

The methods the author uses in the study are based on the systematization of the architectural and planning organization of the world's underground research complexes. The general methodology of the study includes comparative analysis, graphoanalytical method for determining the characteristic features of the functional, planning, and urban planning organization of existing underground research complexes; conceptual analysis, during which the features of the volumetric and spatial organization of underground complexes were investigated; typological method for determining the leading types of underground complexes and significant principles of architectural and planning organization of their environment.

The study considered the works "Underground Urbanism" (*Reynolds, 2019*), "Underground Spaces Unveiled" (*Admiraal & Cornaro, 2018*), "Think Deep: Planning, development and use of underground space in cities" (*Admiraal, 2015*). The articles "Underground space development key planning factors" (*Stones & Tan, 2016*), "Underground Laboratories" (*Votano, 2010*), "Considerations on Underground Laboratories" (*Ianni, 2020*), "New Underground Laboratories: Europe, Asia and the Americas" (*Bettini, 2014*). The study covered world analogs of designing underground research complexes, such as Gran Sasso in Italy (*Bettini, 2003*), SNOLab in Canada (*Smith, 2012*), Sandford Underground Center in the United States, and Canfranc Laboratory in Spain.

Studying the principles of architectural and planning organization of underground research complexes is uncommon among world scientists, so this topic requires further study.

Results

The study revealed the key principles of underground research complexes' architectural and planning organization.

The principle of scientific conformity. The peculiarities of the scientific field and the course of experimental research require certain conditions to be met at all stages of design: minimizing external noise and vibrations for the accuracy of experiments, ensuring stable temperature and chemical characteristics of the air, and optimizing the organization of above ground and underground space. The scientific specificity of the complex has an impact on:

- urban planning organization: selection of the design site, which should consider geological conditions, groundwater levels, and seismic risks; functional zoning of the ground territory,

which is determined by the quantitative and qualitative composition of premises, buildings, and personnel; interaction with the surrounding infrastructure: population intensity, transport accessibility, availability of underground utilities, transport structures, industrial tunnels, and the possibility of expanding the ground part;

- volumetric and spatial structure: the arrangement of experimental halls, research laboratories, auxiliary and service premises, and functional connections between them is determined by the physical and technical characteristics of the experimental facilities. The different sizes and layouts of research, analytical, administrative, sanitary and hygienic, and technical premises;
- architectural and planning organization: a clear functional division of the underground and above-ground parts of the complex, logical functional connections between groups of premises;
- subject-spatial organization: the use of modern technologies and materials; safety in planning to minimize risks; compliance with ergonomic requirements; use of generally accepted means of visual communication to designate different functional areas.

The following principle identified by the author is *the principle of autonomy*. This principle implies the use of renewable energy sources:

- solar panels, wind turbines, and geothermal systems;
- availability of independent life support systems: water supply and sewage system, heating system, ventilation, air conditioning, and filtration of incoming air with the possibility of its purification;
- waste disposal system; ensuring information autonomy: availability of monitoring systems, control systems, and local servers and databases;
- use of alternative sources of electricity: equipment.

In this context, it is advisable to consider *the factor of environmental friendliness* in terms of sustainable development. Given their scientific specificity, speaking of these facilities' one hundred percent environmental friendliness is impossible. However, it is possible to apply specific environmental approaches to their design: the use of modern materials and energy-efficient technologies to minimize energy consumption, multipurpose functional purpose, reduction of energy and greenhouse gas emissions; organization of a sanitary zone on the territory of the complex; organization of measures to adapt to climate and natural changes.

Applying *the principle of ergonomic compliance* creates comfortable conditions for the work of scientific, technical, and service personnel. Among the critical aspects of this principle, the author identifies the following:

- creating an easy and understandable environment, providing quick and unhindered access to the functional areas of the complex;
- meeting ergonomic requirements: designing light as it is on the surface; giving preference to natural sunlight, which is possible only by placing the upper levels of the complex directly under the surface; and designing artificial white lighting to simulate the spectrum of sunlight; designing rooms with noise insulation and noise absorption requirements; ensuring disinfection of personnel and the object-spatial environment;

- satisfaction of psychological, physiological, and social needs: organization of communication zones, areas of privacy, relaxation, separation of work processes and flows; creation of an optimal color and texture solution; optimal distribution of functional zones, variety of individual spaces, optimal layout of work and individual spaces, use of optimal materials and textures;
- arrangement of shelters and emergency tunnels; consideration of evacuation routes with the possibility of evacuation outside the complex; location of firefighting equipment; arrangement of a medical and paramedic station with the possibility of providing first aid; prevention and minimization of occupational risks;
- organizing a system of perimeter paramilitary security with access to their permanent base on the complex's ground territory and to the weapons depot.

The spatial development principle is the possibility of transforming, adapting, and modernizing underground research facilities in a limited space. The key aspect of this principle is modularity: the use of standardized block modules of four types. These modules can be used to construct underground buildings and structures for various functional purposes. Experimental block modules can be used in the design of underground industrial facilities and oil and gas storage facilities. Research modules can be used for the construction of underground parts of hospitals, laboratory facilities of institutes, and computer laboratories. These modules can also construct administrative, educational, cultural, and entertainment facilities. Since the auxiliary modules are designed for personnel to stay in them, they should be used to construct shelters and underground premises that perform administrative, communication, and recreational functions. D-shaped transport modules of reinforced concrete tubes should be used to construct transport and pedestrian routes, roads, and railroad tunnels.

Thus, using this principle in the design of underground research complexes will allow the possibility of adapting the plan to new scientific tasks thanks to mobile partition structures. Using these structures will allow you to quickly change the configuration of certain rooms and provide flexibility in the planning structure. It is necessary to consider the possibility of expanding the complex horizontally by creating new horizontal tunnels and cells and vertically by creating new levels, provided that geological conditions are favorable. It is crucial to maintain the primary functional connections between different areas. During the design stage, it is necessary to provide reserve areas that can be used to expand the complex if necessary. Further research and study of the principles of architectural and planning organization of underground research complexes is an urgent issue and one of the critical stages in designing this type of complex.

Discussion

The author highlights the fundamental principles of architectural and planning organization of underground research complexes based on analyzing the complexes' scientific specifics, ergonomic requirements, autonomy, and spatial development. These principles are important to consider not only for research complexes but also for underground complexes in general. The author pays special attention to the practical aspects of the principles and prospects for future underground complex development.

1. The study results are consistent with the author's hypothesis that the scientific specificity of the complex impacts the architectural and planning solutions of the complex. The functional zoning of the space depends on the type of research: experimental halls, research and analytical laboratories, storage facilities, staff quarters, and auxiliary and service areas, which should be designed to meet the requirements for noise, vibration, and sterility. It is essential to create conditions to ensure uninterrupted experimental research and comfortable working conditions for staff. One of the most influential factors is the accessibility of the premises, ventilation, and filtration of the incoming air, like ergonomic requirements. One of the critical aspects of designing this type of complex is modularity, which allows you to adapt the space to experimental needs by expanding the functional and planning structure of the complex and modernizing individual elements. Ergonomic conditions also play a significant role. They are especially relevant for the design of underground spaces, as there are requirements for lighting design, noise insulation, and meeting the psychological and physiological needs of staff. The determining factor is also the autonomy of life support systems, which must ensure the smooth operation of the underground complex. In general, applying the principle of scientific conformity in the design of underground research facilities can increase their efficiency and functioning.

2. It is critical to compare the principles of architectural and planning organization of underground research facilities with underground complexes of transport and engineering infrastructures and shelters and to study their standard features. Safety, ventilation, and autonomy aspects can be adapted for underground research facilities, including maintaining optimal working conditions for personnel and experimental facilities. Much attention is paid to the optimal planning and use of spaces in parking garages and underground warehouses. However, some design techniques differ between underground research and development complexes and underground complexes of other functional areas. The design of underground complexes focuses on functional and logistical aspects. The specifics of underground R&D facilities require taking into account such factors as special requirements for sterility, noise insulation, environmental stability, and the volumetric and spatial characteristics of the premises. In addition, underground R&D facilities require the installation of more complex life support systems, such as ventilation, air conditioning, air filtration, heating, and electricity.

3. The principle of spatial development is crucial to underground research facilities' architectural and planning organization. It allows the designer to adapt architectural and planning solutions to new conditions. These conditions may be due to scientific specifics, such as using new experimental facilities, integrating modernized equipment, and expanding the complex territory. Modular planning systems involve standardized structural elements, which are especially important in limited underground space use conditions. The advantage of using different functional modules is to minimize the impact on the current structures in expanding the complex's territory. This ensures the continuity of research work even during changes. The process of adaptation and transformation is accompanied by some challenges: ensuring optimal air chemistry, ergonomic requirements, access, and integration of the modules' life support systems into the existing general life support system.

Conclusion

The study's results show that the architectural and planning organization of underground research complexes is a complicated process considering several fundamental principles, including scientific relevance, ergonomic relevance, the principle of autonomy, and spatial development. These principles are based on ensuring functionality, safety, and sustainability. They are essential for creating an environment that will meet the requirements for experimental research in physics, astrophysics, biology, geology, and chemistry.

A significant factor influencing the urban planning, volumetric-spatial, architectural, and planning organization of underground research facilities is creating an environment isolated from negative external influences, such as noise, vibration, and temperature. Adherence to the principle of ergonomic compliance contributes to the development of comfortable working conditions in the underground space. This is achieved by minimizing transport routes, separating transport and passenger flows, efficiently using space, and providing evacuation routes and shelters from potentially dangerous areas. The author believes it is significant to use energy-efficient technologies, ensure uninterrupted power supply to the complex, and manage life support systems, which will contribute to the efficient operation of all structures and allow for compliance with the basic principles of sustainable development. The introduction of modern technologies, automation of life support systems, and the use of energy-efficient materials can improve the safety characteristics of the complex and provide the necessary degree of isolation of experimental and research facilities. The author's use of modular approaches to the design of underground research complexes, which is the basis of the principle of spatial development, can increase the adaptability of underground complexes to changes that may be caused by the use of new experimental facilities within the complex.

The process of architectural and planning organization of the underground environment is complex and time-consuming. It involves an integrated approach combining functionality, sustainability, innovative materials and methods, and aesthetic expression. The author argues that the key principles considered in the study aim to create an environment capable of meeting not only the scientific community's current requirements but also the potential for further development.

Conflict of interest

The author declares that there is no conflict of interest.

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Serhii S. Poliushkin [2]

Visual communications in park environments [2]

Abstract: Analysing the current state and historical development of visual communications necessitates thorough research to enhance the organisation and interaction of visual information in urban environments. With cities' increasing complexity and reliance on effective communication systems, optimising the placement and integration of visual elements is crucial for functionality and aesthetics. This study contributes to a deeper understanding of how visual communications shape the experience and usability of urban spaces. The study subject is the principles and methods of organising and integrating visual information within urban spaces. The study object is the system of visual communications in urban environments. The analysis of the current state and historical development of visual communications necessitates thorough research and careful analysis to improve the placement and interaction of visual information within urban environments. The study aims to analyse and propose strategies for enhancing the functionality, accessibility, and aesthetic quality of visual communications in urban environments. The author combined academic literature, case studies, and urban design guidelines, which provided a foundation for the theoretical framework and practical recommendations. The author concludes that visual communications in park environments are essential for the larger urban space, contributing to its functionality and aesthetic appeal. They guide movement, convey information, and create a cohesive identity for the area. Improving visual communications in urban parks enhances the overall structural harmony of the city and strengthens its cultural and social fabric.

Keywords: visual communications, visual systems, environment, integration of visual elements.

Introduction

Analysing the current state and historical development of visual communications necessitates thorough research to enhance the organisation and interaction of visual information in urban environments. With cities' increasing complexity and reliance on effective communication systems, optimising the placement and integration of visual elements is crucial for functionality and aesthetics. This study contributes to a deeper understanding of how visual communications shape the experience and usability of urban spaces.

The study subject is the principles and methods of organising and integrating visual information within urban spaces.

The study object is the system of visual communications in urban environments.

The analysis of the current state and historical development of visual communications necessitates thorough research and careful analysis to improve the placement and interaction of visual information within urban environments.

The study aims to analyse and propose strategies for improving the functionality, accessibility, and aesthetic quality of visual communications in urban environments.

Based on this goal, the following tasks were developed:

- study the history of visual communication development;
- understand the significance of visual systems;
- examine the types and forms of external visual communication elements and signage.

The study employed specialised methods, such as comparative analysis, modelling, and field observations, to evaluate the organisation and integration of visual communications. These methods allowed for identifying patterns and practical solutions to optimise urban visual systems.

The author combined academic literature, case studies, and urban design guidelines, which provided a foundation for the theoretical framework and practical recommendations.

Results

The quality of modern life is directly influenced by the quantity and quality of visual information surrounding individuals and by the speed at which people can understand and perceive it. Effective external visual communications can simplify and accelerate the process of receiving and interpreting information in urban spaces.

Visual communications in urban design have become crucial to sustainable modern consumption. The informational and communicative processes within the spatial environment form a constantly evolving system that harmonises over time with the surrounding environment.

The study and improvement of visual communications require a multidisciplinary approach, considering various aspects from different academic fields. Therefore, it is essential to draw from cultural history, art, psychology, sociology, and urban planning knowledge, including insights from domestic and international authors. This research uses literary sources and practical design examples to investigate the origins and historical development of visual communication systems, signs, symbols, emblems, heraldry, and writing. It also seeks to understand the significance of visual systems and to explore the types and forms of external visual communication elements and signage.

A comprehensive and comparative analysis of the interaction between elements of the overall urban environment and spatial visual communication systems is essential. This holistic approach to studying literature and practical project examples is fundamental for creating an independent project of external visual communication, as it will be based not only on the analysis of the existing situation but also on principles and methodologies for designing visual imagery in society's communicative sphere.

Park space is the primary object for creating external visual communication and is viewed as an element of the broader urban area. A user-friendly navigation system should effortlessly guide pedestrians to service areas or points of interest without confusion.

Urban landscapes and recreational areas are classified by their functional structure based on usage, size, location within the city layout, and user demographics. They are divided into three groups:

(1) Public green spaces;
(2) Restricted-access green spaces;
(3) Green spaces for special purposes (*Petryshyn, 2022*).

The area of public green spaces (parks, gardens, squares, boulevards) located within urban and rural settlements is determined according to DBN B.2.2-12:2019 (*2019*).

Structurally, consumers of external visual communications within urban areas include:

- City residents in districts or neighbourhoods, both those living close to the area and those who are visiting from farther locations;
- Internally Displaced Persons (IDPs) who require rapid and comfortable orientation in the city, including locating administrative buildings, infrastructure facilities, and recreational areas;
- Organized local tourist groups or individual visitors;
- Foreign organised tourist groups or individual foreign visitors.
- Signs and informational indicators should be easy to visually perceive and understand, accommodating both local citizens and foreign visitors (achieved through universal design and multilingual information). Placement systems must be standardised and mutually coordinated to suit the urban space. Sign locations should be logical and intuitively accessible, providing easy and convenient navigation across the cityscape. When positioning signs, they should harmoniously blend with the existing historical or surrounding environment, considering stylistic elements, transportation infrastructure, and engineering networks. The structural design, textual content, and imagery should comply with DBN B.2.2-40:2019, particularly regarding inclusivity and universality (*2019*).

The system of general spatial orientation within the external urban environment – visual communications – consists of navigation elements such as:

- Orientation signs: provide information on the current location or nearby points of interest;
- Directional indicators;
- Identification markers and signs.

According to the typology of visual communication elements, the following types can be distinguished:

- Entrance informational pylons;
- Informational structures (e.g., city lights);
- Pedestrian signs;
- Address indicators;
- Tourist direction signs.
- Since city parks serve as functional elements within the urban spatial framework, their visual communications should align with citywide standards, adapting to the park's functional zoning.
- Contact points where park areas intersect with urban spaces – entrances, exits, access roads, parking zones, and landscaping – should feature visual elements like entrance informational light pylons or portals. These elements should prominently display the park's name and logo (if available). Additionally, they may include a park map that provides graphical information about the general functional layout and primary structural components (*Figure 1*).

Park alleys should, in addition to essential park amenities – such as benches, waste bins, and lighting systems – include pedestrian signs that provide directional information and distances to key park infrastructure, including civil defence shelters. These paths should also be

equipped with public address systems and wireless internet access to enhance accessibility and connectivity for visitors (*Figure 2*; *Figure 3*).

The park area can be equipped with information structures that provide general content, such as announcements for upcoming events, interesting historical facts about the park's creation, information on citywide events, and QR codes for more detailed information. Each location within the park should also display specific information on the rules for using services and the guidelines for that particular area.

For visitor safety, the parking area should feature surveillance systems and emergency call devices for contacting security or park staff, with signage indicating the location and use of these systems.

Establishing this kind of informational visual communication in park spaces will make the area more accessible, logical, and safe, ultimately creating an open and comfortable environment.

Discussion

The study of visual communications in urban environments faces several challenges. First, there is a lack of standardised methodologies for analysing and optimising visual elements in diverse urban settings, as each city has unique cultural, historical, and spatial characteristics. Second, the rapid evolution of digital technologies complicates the integration of traditional and digital visual systems, requiring adaptive approaches. Third, insufficient collaboration between urban planners, graphic designers, and sociologists hinders the creation of cohesive visual systems that meet functional and aesthetic demands. Additionally, limited data on public perception of urban visual communications makes it difficult to assess their effectiveness and adjust them to societal needs. Finally, financial and regulatory constraints often prevent the implementation of innovative visual solutions in public spaces.

(1) How can digital and interactive visual technologies be effectively integrated into traditional urban visual systems?
(2) What methodologies can be developed to evaluate the effectiveness of visual communications in urban environments?
(3) How do cultural and historical factors influence the design and perception of visual communications in different cities?
(4) What role do environmental sustainability and energy efficiency play in the future of urban visual systems?
(5) How can urban visual systems be adapted to enhance accessibility for people with disabilities?
(6) What are the most effective strategies for engaging the public in designing and implementing urban visual elements?
(7) How can interdisciplinary collaboration between designers, planners, and policymakers be improved to create more cohesive urban visual systems?

Conclusion

Visual communications in park environments are essential for the larger urban space, contributing to its functionality and aesthetic appeal. They guide movement, convey

information, and create a cohesive identity for the area. Improving visual communications in urban parks enhances the overall structural harmony of the city and strengthens its cultural and social fabric. Additionally, well-designed visual elements in parks improve accessibility and the quality of life for residents and visitors alike.

Conflict of interest

The author declares that there is no conflict of interest.

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Appendix

Figure 1. Graphical information about the general functional layout and main structural components

Figure 2. Public address systems and wireless internet access to enhance accessibility and connectivity for visitors

Figure 3. Public address systems and wireless internet access to enhance accessibility and connectivity for visitors

Liudmyla Tsymbal [3], *Iryna Uninets* [4]

The digitalisation era as a framework for the development of the global education market [3]

Abstract: The global educational market is being transformed under the influence of the above factors and the factors of generalised development. Digital technologies radically change the educational services market, opening up new opportunities for students and educational institutions, like posing new challenges. Digital technologies have significantly impacted the education market, changing both the ways of learning and the structure of the education market itself. By this, the study aims to identify the key features of the global market development for educational services in the era of digitalisation of economic activity. The study object is the global market for educational services; following the purpose and object of the study, the key tasks are to identify the features of the development of the global market for educational services, analyse them, and characterise them in detail. Modern scholars studying the global market of educational services represent various fields of knowledge, including economics, sociology, pedagogy, and information technology. Iryna Kaleniuk, Larysa Antoniuk, Denys Ilnytskyi, Nataliia Ushenko, Simon Marginson, Hans de Wit, Philip Altbach, Robert Fisher, Anne-Marie Nohlén study the structure, dynamics, and peculiarities of the development of national and global markets for educational services. However, the constant transformation of both the global and educational services markets and the development of technologies actualise this issue at the present stage of developing the world economic system.

Keywords: digitalisation, online education, global education services market, digital technologies.

Introduction

The global market of educational services is undergoing profound transformational changes at the current stage of world order formation. The COVID-19 pandemic has brought changes to key teaching methods and technologies, the war in Ukraine has redrawn the flow of students and academic staff, and technological developments have led to the need to change the technological basis of the learning process. In the global context, educational services are becoming increasingly significant, driven primarily by the transformation of the labour market. In turn, it is being transformed under the influence of both the above factors and the factors of generalised development. Digital technologies radically change the educational services market, opening up new opportunities for students and educational institutions, like posing new challenges. Digital technologies have significantly impacted the education market, changing both the ways of learning and the structure of the education market itself.

By this, the study aims to identify the key features of the global market development for educational services in the era of digitalisation of economic activity.

The study object is the global market for educational services.

Following the purpose and object of the study, the key tasks are to identify the features of the development of the global market for educational services, analyse them, and characterise them in detail.

Modern scholars studying the global market of educational services represent various fields of knowledge, including economics, sociology, pedagogy, and information technology. Iryna Kaleniuk (*Tsymbal & Kalenyuk, 2023*), Larysa Antoniuk, Denys Ilnytskyi, Nataliia Ushenko

(*2023*), Simon Marginson (*Cantwell et al., 2018*), Hans de Wit (*2013*), Philip Altbach (*Global perspectives…, 2011*), Robert Fisher, Anne-Marie Nohlén study the structure, dynamics, and peculiarities of the development of national and global markets for educational services. However, the constant transformation of both the global market and the educational services market and the development of technologies actualise this issue at the present stage of the development of the world economic system.

The results of the study

The transformation of the labour market is quite active. At the present stage, under the influence of the paradigm shift in general civilisation development, it has acquired a new characteristic – turbulence. In this context, knowledge is becoming one of the most significant assets. The key trends in the development of the educational services market are manifested through increasing demand for online education, increasing demand for technical and information education, increasing competition, increasing international mobility, the growing popularity of short-term courses and certificates, increasing requirements for the quality of education; social transformation; universities as a driving force for local development; public activity of universities; long-life education; ed-tech partnership; data age; digital skills; internationalisation policy (*Figure 1*).

As a result of the COVID-19 pandemic, most educational institutions were forced to switch to distance learning, which led to a significant increase in demand for online education. This trend will likely continue in the future, as most people are interested in the opportunity to study at a convenient time and place. In 2021, the number of requests to digital platforms increased by 98%. Thus, according to experts, Ukrainians began to attend online courses three times more often in 2021 and became one of the top three European countries where they buy online education. The most significant demand is in the capital. Kharkiv, Odesa, Lviv, and Dnipro are also among the leaders. The most popular courses are English, modern business, IT programming, and training courses for schoolchildren (*There is a growing…, 2022*).

However, it is worth noting that Ukraine has only just entered global trends, as the online services market is growing significantly (*Figure 2*).

In 2023, online education revenue is expected to reach USD 166.60 billion, with a compound annual growth rate (CAGR) of 9.37%, leading to a projected market size of USD 238.40 billion by 2027. The largest market segment is online university education, with a projected market size of USD 103.80 billion in 2023. In a global comparison, the United States will generate the most significant revenue (USD 74,800.00 million in 2023), with an average revenue per user (ARPU) in online education of USD 0.21 thousand in 2023. Additionally, there is a growing trend towards personalised and adaptive learning, with online education platforms incorporating artificial intelligence and machine learning technologies to offer personalised learning experiences. The implications of these trends can be seen in the numbers: the global online education market is expected to reach USD 325 billion by 2025, growing at a CAGR of approximately 7%. In addition, the COVID-19 pandemic has accelerated the adoption of online education, as the number of students enrolled in online courses has increased significantly over the past year. The online education segment is expected to continue its growth trajectory, driven by increasing demand for distance and flexible learning options, like technological advances,

allowing for personalised learning. Nevertheless, the industry may also face challenges such as ensuring the quality and accreditation of online courses, like addressing the digital divide and unequal access to technology and internet connectivity. However, the overall outlook for the online education segment remains positive, with strong growth potential in the coming years. Between 2011 and 2021, the number of students enrolled in massive open online courses (MOOCs) increased from 300,000 to 220 million (*Shah, 2021*). Between 2012 and 2019, the number of students enrolled in blended and distance learning at traditional universities grew by 36 per cent, while the circumstances of the COVID-19 pandemic in 2020 rapidly accelerated this growth by another 92 per cent (*Diaz-Infante et al., 2022*).

A recent analysis of total student enrolment data from the Integrated Postsecondary Education Data System (IPEDS) found that while the overall market for degree programs decreased by about 3 per cent from 2019 to 2020, four of the largest providers of open-access online education – Southern New Hampshire University (SNHU), Liberty University, Western Governors University (WGU), and Grand Canyon University (GCU) – increased their total enrolment by an average of 11 per cent.

At the present stage, a significant area of the educational services market development is the development of EdTech, which is all digital tools that help development and learning (*What is EdTech…, 2022*). Numerous start-ups in digital education are disrupting the space, driven by the growth of venture capital funding. Between 2017 and 2021, venture capital funding for US educational technology (EdTech) increased from $1 billion to $8 billion. In 2021, the demand for these investments was evident in the successful IPOs of several EdTech companies, including Coursera (valued at over $4 billion). Investments in EdTech can be much higher, as the current stage of global market development, the possibility of a pandemic, and wars contribute to the demand for digital tools, increasing competition in the EdTech market (*Table 1*).

In 2021, venture capitalists (VCs) invested $20.8 billion in the electronics sector, more than 40 times the amount they invested in 2010.

In June 2021, 2U announced the acquisition of edX, a Harvard and MIT non-profit organisation, for $800 million. This acquisition gives 2U access to a strong customer brand, approximately 40 million registered users, and hundreds of university partners. These assets provide 2U with a significant presence in growing markets outside the United States and can help reduce CAC as it develops a free degree model (*Sanghvi & Westhoff, 2022*).

Online learning companies are expanding and focusing on their corporate offerings to meet the demand for upskilling and retraining. Of the 15 adult learning companies that received the most funding in 2021, only one offered corporate programs (*Figure 3*). Companies such as Coursera initially focused on consumers, but have recently significantly increased their revenue from corporate clients (*Sanghvi & Westhoff, 2022*).

Such an active development of the financial sector requires the attraction of additional financial resources, which contributes to the development of venture capital financing as an element of the educational services market, which has grown significantly due to the pandemic (*Figure 4*).

It is worth noting that the Indian market has become much more active as regulatory restrictions have been significantly tightened in China. Thus, in 2020, the Chinese market

covered 63% of the financing of educational technologies; in 2021, this figure dropped to 13%, while India increased from $0.2 billion in 2017 to $3.8 billion in 2021, which was 18% of global investment. There has also been an increase in the activity of Indian companies in the global market, as Indian Emeritus has reached a billion-dollar capitalisation and is actively entering the US market through the purchase of American companies. Accordingly, the quality standards of online education are increasing, and the distinction between classical and non-formal education is blurring, forming a new structure for educational competitors. For example, in partnership with Coursera, Google's Grow with Google program offers courses in user experience design and data analytics that can provide potential applicants with cost-effective educational options. At the same time, traditional digital education providers focus on obtaining diplomas. However, even so, there is an opportunity to supplement their programmes with non-formal options and strengthen their competitiveness. At the current stage, applicants are becoming more demanding of classical education, creating demand for individual programs and considering the possibility of obtaining additional knowledge in the informal sector to gain specific knowledge and skills that may be more significant than the program or brand of the institution.

The next trend is the increasing demand for technical education, as a growing number of jobs require technical and information literacy, leading to an increase in demand for training in these areas. The nature of work and the technologies that support it are changing. Ongoing and comprehensive digitalisation has changed the work of even teachers, who now need programming knowledge, among other things. A growing number of educational institutions and online platforms provide students with more learning options, creating a new competitive environment. This forces educational institutions to compete for students by offering more innovative and effective teaching methods. As a result, the number of online education lovers and users is growing rapidly (*Figure 5*).

The increase in the number of higher education institutions and online platforms offering courses leads to more competition in the market. This can lead to lower tuition prices and improved quality of education. Short-term courses and certificates are becoming increasingly popular among people who want to improve their skills or gain new knowledge. This may lead to a decrease in demand for full-fledged degree programs and an increase in the popularity of alternative forms of education. Short-term courses are more mobile and flexible and respond more quickly to the needs of the labour market, employers' requirements, and consumer demands. In the context of global turbulence, they lead to the demand for a workforce with specific skills. New competitors in the education market are affecting traditional educational institutions and changing how they deliver educational programs (*Figure 6*).

New competitors offer flexible learning models that allow students to study at their own time and pace. Short-term courses are often cheaper than traditional university programs, making them more attractive to a broader audience. Many new programs focus on specific professional skills in demand in the labour market, ensuring that graduates are quickly employed. New competitors are changing the landscape of educational services, forcing traditional institutions to adapt to new realities and innovate their strategies and programmes.

The liberalisation of migration policy and the war have increased international mobility, with students increasingly travelling abroad to study and gain additional experience. This trend leads to increased demand for international education and opportunities for educational

institutions to attract students from other countries. Economies, markets, and technologies are developing rapidly, and skilled workers need training to keep up with new developments, discoveries, and trends. The learning and development sector is growing significantly as people, like companies, constantly strive to improve themselves and their employees. In particular, in recent years, learning and development have become increasingly digital, with a significant increase in the use of technology-based learning. Increasing requirements for the quality of education from employers and graduates, changing the structure of education and its dynamisation. Old learning technologies are ineffective in the modern world, and comprehensive digitalisation leads to a decrease in concentration, with knowledge becoming both more superficial and more concentrated. However, it is worth noting that there is a separate segment of consumers who, realising the value of high-quality education for the modern labour market, create demand for high-quality educational services, creating demand for concentrated knowledge that meets these high standards (*Figure 7*).

The second group of trends in the development of the global education market reflects the qualitative plane of transformation, which becomes the basis for universities' transformational leadership. These trends include social transformation, internationalisation policy, public engagement of universities, and expanding their role as a driving force for local development.

Universities have always played a driving force for change, but this is only realised if universities are closely involved in the work of local governments, self-governance, or processes. The internationalisation policy in modern conditions finds a dual manifestation, as universities are looking for a balance between the needs of the local level and the role of driving transformational changes at the local level and the challenges of globalisation, the need to attract students from other countries (*A new global…, 2022*).

Discussions on the internationalisation of higher education are moving in two opposite directions. The first is associated with the rise of nationalist and protectionist sentiments and denies the myth of unlimited growth. The second points to the continuous growth of student and programme mobility as evidence of the unstoppable momentum of internationalisation (*A new global…, 2022*).

Technology and the digital age provide new opportunities, including for the service sector, and digital content development has changed the educational services market development (*Wit, 2013*). Higher education is not immune to these trends, and the pandemic has forced the market to adapt to digital technologies quickly. In contrast, the trends only indicate an increase in the technologicalisation and digitalisation of the global education market development.

Conclusion

Universities play a significant role in the digital age, where technology is becoming increasingly significant. The key trends in the global education market in the digitalisation era include the education and training of students to work in the digital economy, as students are preparing to work in the digital economy, where competencies in technology and information systems are becoming increasingly significant, including through the education system, development, and implementation of new technologies used in various spheres of life. They help to introduce new technologies in various fields, including education, medicine, science, and business. A relatively new trend is open learning and online courses, which are helping to

increase the accessibility of learning and learning resources and allowing students to study from anywhere and at any time. At the present stage, digital libraries and research centres are being created, allowing students and researchers to collect and analyse information from anywhere in the world. Partnerships are being formed with businesses and other institutions to develop digital content. Digitalisation remains a significant aspect of the development of the global education market.

Conflict of interest

The author declares that there is no conflict of interest.

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Appendix

Quantitative

- Increasing demand for online education
- Increased demand for technical and information education
- Increased competition
- Increased international mobility
- Growing popularity of short-term courses and certificates
- Increasing requirements for the quality of education
- Ed-tech partnerships

Quality.

- Social transformation
- Universities as a driving force for local development
- Public activity of universities
- Long-life education
- The age of data
- Digital skills
- Internationalization policy

Figure 1. Key trends in the development of the educational services market

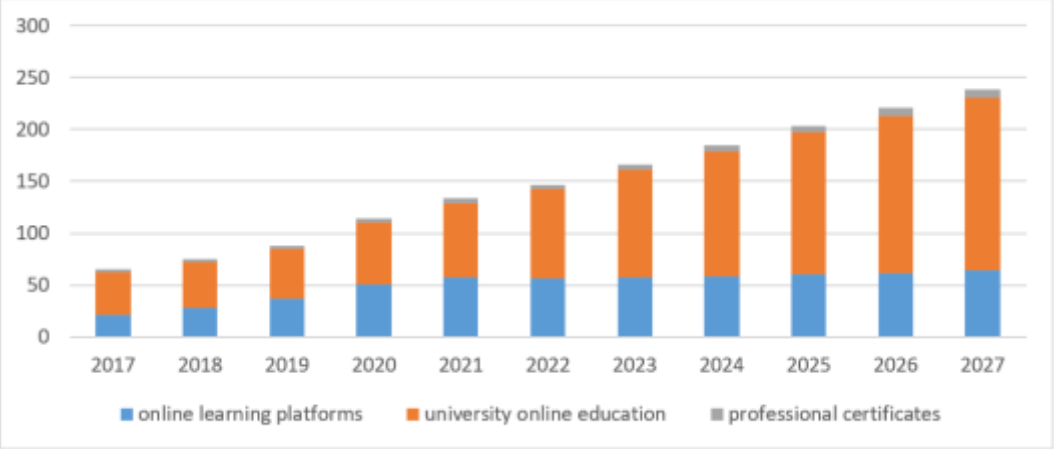

Figure 2. Expected profitability of the online education market, USD million (*Online Education – Worldwide, 2022*)

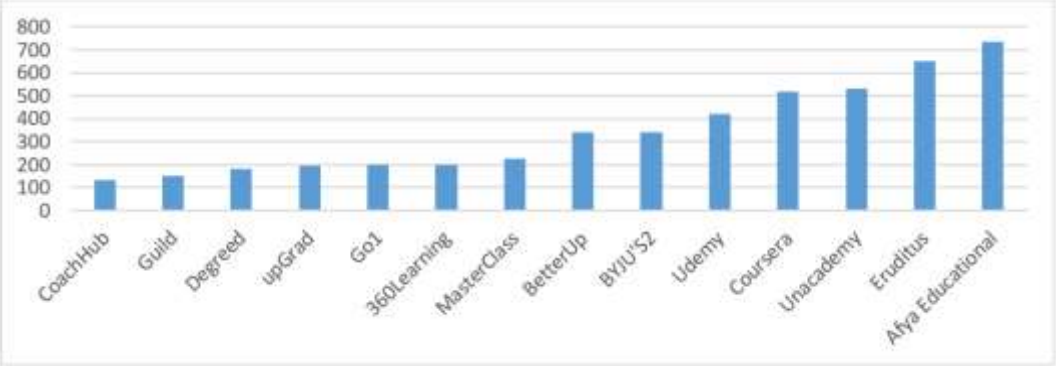

Figure 3. Largest global edtech deals in 2021, USD million (adult sector) (*Sanghvi & Westhoff, 2022*)

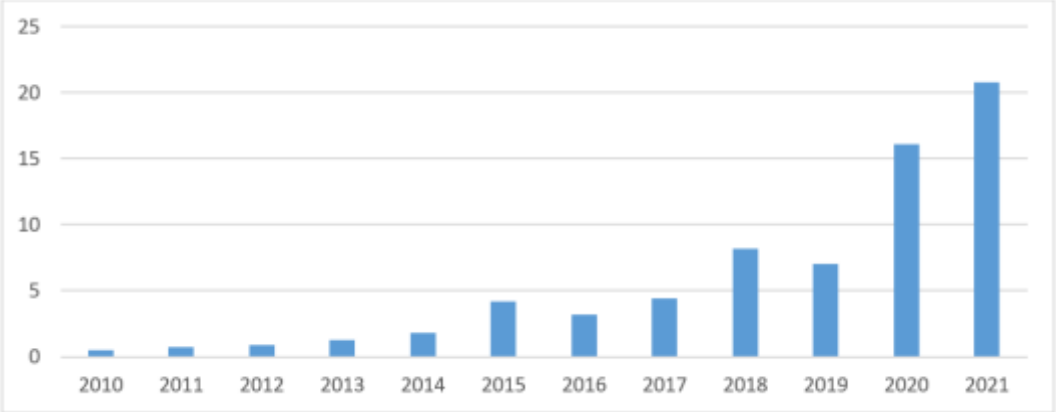

Figure 4. Global venture capital funding for educational projects (*Sanghvi & Westhoff, 2022*)

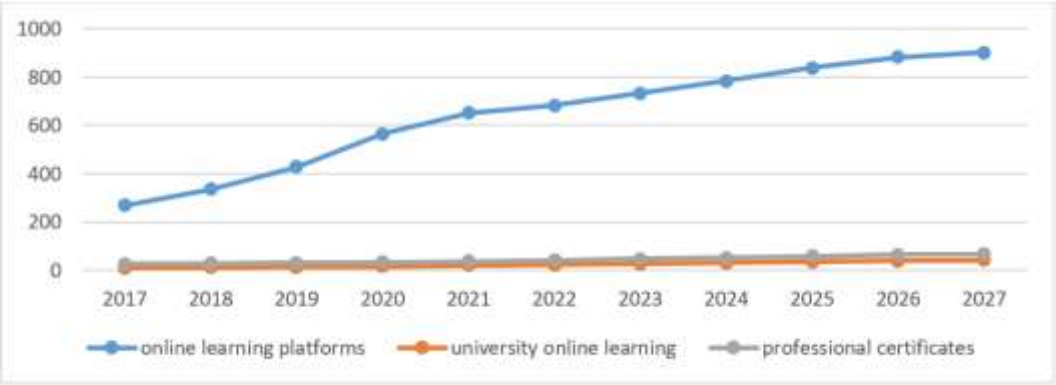

Figure 5. Number of users, million people (*Online Education – Worldwide, 2022*)

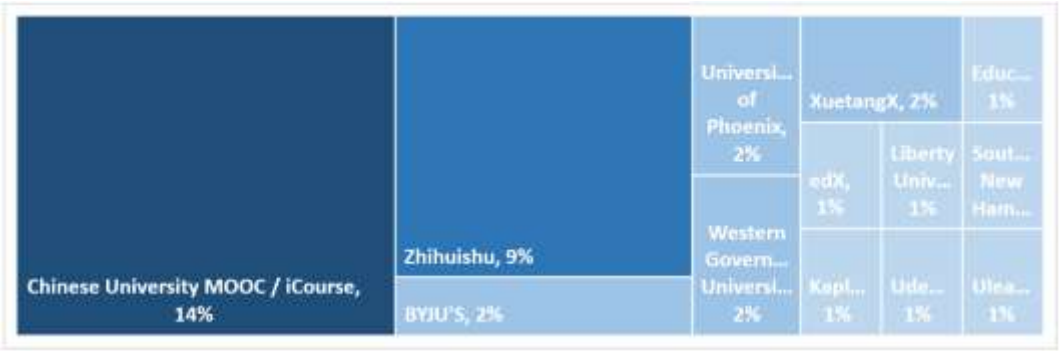

Figure 6. Market share of educational services, % (*Online Education – Worldwide, 2022*)

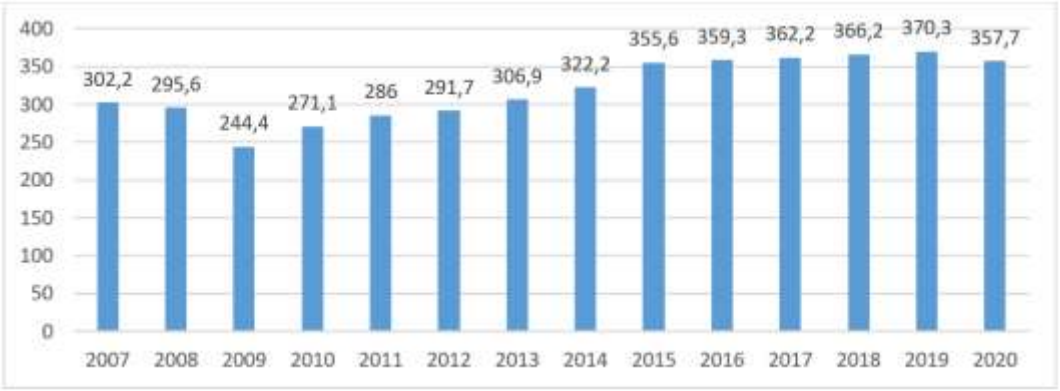

Figure 7. Market size of the global workplace learning industry from 2007 to 2020 (in billions of US dollars) (*There is a growing…, 2022*)

Table 1. Key players in the online education market, revenue, USD billion, 2017-2021 (*Online Education – Worldwide, 2022*)

Company	2017	2018	2019	2020	2021
2U, Inc.	0,29	0,41	0,57	0,77	0,95
Coursera, Inc.			0,18	0,29	0,42
New Oriental Education & Technology Group, Inc.	2,45	3,10	3,61	4,28	
Tal Education Group	1,72	2,57	3,28	4,51	
Udemy, Inc.			0,28	0,34	

Tetiana V. Gorokhova [5]

Corporate social responsibility in the era of digital transformation: Bridging technology and sustainability [4]

Abstract: The article explores the critical intersection of corporate social responsibility and technological innovation within the context of digital transformation. In an era where rapid technological advancements are reshaping industries, the integration of corporate social responsibility principles has emerged as both a strategic necessity and a moral obligation for businesses. The study examines the relevance of corporate social responsibility in fostering sustainable development, emphasizing its role in addressing key societal and environmental challenges, including data privacy, digital inclusion, and environmental sustainability. The study object is the evolving relationship between corporate social responsibility and digital transformation, focusing on how organizations navigate their ethical responsibilities while embracing innovation. The study aims to analyze the strategic role of corporate social responsibility in technological advancements, identify challenges in its implementation, and propose actionable solutions for enhancing its integration into corporate practices. The study draws on a comprehensive review of seminal works by scholars such as Al-Shammari, Kim, Barauskaite, etc., who have explored the interplay between corporate social responsibility, corporate performance, and financial outcomes. Using qualitative analysis, the research synthesizes findings from existing literature, case studies, and international frameworks such as the European Green Deal to outline the best practices and emerging trends in CSR-driven digital transformation. The results highlight the dual benefits of aligning corporate social responsibility with technological innovation: enhanced competitiveness and long-term societal value creation. Key findings include the importance of robust frameworks for data security, the necessity of promoting digital skills and inclusion, and the potential of leveraging technology to address global challenges like climate change and resource management. The article concludes that integrating corporate social responsibility into technological innovation supports sustainable development and enhances organizations' trust, collaboration, and innovation. These insights offer valuable guidance for academics, policymakers, and business leaders striving to balance technological progress with social responsibility.

Keywords: corporate social responsibility, digital transformation, technological innovation, sustainable development, data privacy, digital inclusion, environmental sustainability.

Abbreviation:

CSR is corporate social responsibility,
EGD is European Green Deal,
ESG is environmental, social, and governance,
ERP is enterprise resource planning,
GDPR is General Data Protection Regulation,
IIoT is the Industrial Internet of Things,
NGO is non-governmental organization,
SDG is Sustainable Development Goal,
SIAs are social impact assessments,
SMEs are small and medium-sized enterprises.

Introduction

Rapid technological advancements and digital transformation reshape industries, economies, and societies in the contemporary era. These shifts offer unparalleled economic growth and social development opportunities, but they also pose significant challenges. Against this backdrop, CSR has emerged as a crucial framework that bridges business objectives with ethical imperatives, addressing the growing need for sustainable and inclusive progress (*Velte, 2022*).

CSR encompasses the economic, environmental, and social commitments that businesses must fulfill. It ensures that technological innovation while driving progress, aligns with broader societal and environmental goals. As organizations adopt new technologies to remain competitive, CSR provides a guiding framework to balance profit motives with responsibilities toward stakeholders, communities, and the environment.

The relevance of this study lies in the increasing interplay between CSR and digital transformation. Scholars emphasize the transformative potential of CSR in shaping ethical, sustainable, and inclusive technological advancements. For instance, Al-Shammari et al. (*2022*) highlight CSR's role in guiding technological innovation, focusing on responsibilities businesses should uphold during innovation processes. Kim S. et al. (*2021*) introduce the concept of "dual responsibility", examining how companies balance social responsibilities with economic goals and the resultant impact on corporate performance. Meanwhile, Barauskaite G. et al. (*2021*) explore the relationship between CSR and financial performance, addressing how socially responsible practices influence business outcomes while identifying gaps in conceptual clarity and evaluation methods.

This study aims to delve deeper into the strategic role of CSR in digital transformation. The study object is the interaction between CSR and technological innovation, focusing on their combined impact on sustainable development. The primary purpose is to analyze how CSR can guide digital transformation to address societal challenges, enhance corporate accountability, and promote long-term sustainability. The objectives include examining how CSR influences technological innovation, identifying challenges in CSR implementation during digital transformation, and proposing actionable strategies for integrating CSR into business practices.

The research employs a qualitative methodology, synthesizing insights from a comprehensive review of existing literature, case studies, and global frameworks such as the EGD and the United Nations SDGs. Theoretical contributions from Al-Shammari, Kim, Barauskaite, and others form the foundation for this analysis, providing diverse perspectives on the interconnection between CSR and technological progress.

The findings target multiple audiences, including business leaders, policymakers, academics, and sustainability advocates. By offering actionable recommendations, this article aims to guide enterprises in leveraging CSR as a strategic tool to navigate the complexities of digital transformation. Ultimately, this study contributes to the broader discourse on how CSR can drive ethical innovation, strengthen stakeholder trust, and ensure that technological progress benefits businesses and society.

The results of the study

1. Understanding the foundations of corporate social responsibility

Conceptual framework and core principles of corporate social responsibility

CSR encompasses businesses' social and environmental obligations as part of their operations. It represents a company's commitment to addressing the needs of society and its stakeholders, aiming to enhance societal well-being and ensure environmental sustainability through active participation in social initiatives and adopting sustainable practices (*Tibiletti et. al, 2021*). CSR is typically divided into three main dimensions: economic, environmental, and social responsibilities.

Economic responsibility focuses on the need for businesses to operate lawfully and ethically while delivering stable returns to investors. Companies are expected to comply with legal standards, honor contracts with integrity, and ensure fair treatment and equitable rewards for shareholders and employees.

Environmental responsibility highlights the proactive steps businesses must take to mitigate their impact on the planet (*Kemp, 1994*). These include reducing energy consumption, minimizing waste and emissions, and adopting renewable energy sources. These measures aim to conserve natural resources, protect ecosystems, and foster sustainable development for future generations.

Finally, social responsibility emphasizes the importance of addressing social welfare and justice within business operations. Companies are expected to actively participate in community initiatives, support educational and cultural programs, care for vulnerable groups, and contribute positively to societal development. Fulfilling these responsibilities helps businesses gain trust and support from consumers, employees, and investors, enabling them to achieve sustainable economic success while promoting shared social values.

The principles of corporate social responsibility provide a framework to guide businesses in integrating social and environmental considerations into their operations. Transparency and accountability require companies to openly disclose their social and environmental performance, accept public oversight, and take responsibility for their actions (*Padilla-Lozano et al., 2021*). Respect for stakeholders' rights and interests obliges businesses to balance the needs and concerns of all stakeholders, including shareholders, employees, consumers, communities, and the environment, ensuring their rights are protected, and their voices are heard.

Sustainable development is another key principle, encouraging businesses to align economic, social, and environmental goals by making environmentally responsible decisions, optimizing resource use, and minimizing harmful emissions (*Lombardi et al., 2021*). Additionally, companies are urged to engage in social welfare and philanthropic activities, such as supporting education, healthcare, cultural projects, and community development, to give back to society. Respect for human and labor rights is equally vital, requiring companies to uphold fair working conditions, provide adequate remuneration, and eliminate unethical practices such as forced labor, child labor, and discrimination.

By adhering to these principles, businesses fulfill their ethical obligations and contribute to advancing sustainable and equitable development in society.

The significance of corporate social responsibility

CSR holds immense significance for contemporary businesses. By embracing their social responsibilities, companies can cultivate a strong reputation and positive brand image, fostering trust among consumers and investors. This trust forms a stable foundation for sustainable growth and long-term success. Moreover, CSR initiatives attract and retain top talent, boost employee satisfaction and loyalty, and enhance overall competitiveness.

CSR is also vital for the sustainable development of society and the environment. In the face of escalating environmental challenges and complex social issues, businesses have a crucial role (*Ehrnström-Fuentes et al., 2023*; *Toussaint et al., 2021*). Companies can mitigate their ecological impact, optimize resource use, and elevate societal welfare through environmental protection measures and promoting sustainable practices. Furthermore, CSR efforts focused on employee well-being, education, healthcare, and cultural development contribute significantly to societal advancement.

In addition to its societal benefits, CSR opens avenues for business innovation and new opportunities. Businesses can uncover untapped markets and create innovative products and services by addressing social challenges and aligning with customer needs. Engaging in CSR also enables companies to build strong relationships with governments, NGOs, and other stakeholders, fostering collaboration and mutual success.

Ultimately, adopting CSR allows businesses to achieve a dual objective: driving economic success while creating social value. By doing so, they contribute to developing a more prosperous, equitable, and sustainable society.

2. Advancing through technological innovation and digital transformation.

Understanding technological innovation and digital transformation

Technological innovation and digital transformation are pivotal forces shaping contemporary enterprises and society. They drive profound changes in traditional industries and create new paradigms of operation and interaction. As science and technology evolve, these advancements enhance productivity and efficiency, fuel innovation, elevate living standards, and unlock fresh business opportunities.

Technological innovation and digital transformation significantly boost productivity and operational efficiency. By integrating advanced technologies such as automation, artificial intelligence, and machine learning, enterprises can optimize production processes, reduce costs, and improve the quality of products and services (*Managi et al., 2021*). For instance, robotics can take over physically demanding, hazardous, or monotonous tasks, allowing human employees to focus on higher-value, strategic activities. Simultaneously, digital transformation enhances organizational agility through streamlined workflows, improved data sharing, and faster decision-making processes. Tools like cloud computing and ERP systems enable real-time collaboration and allow enterprises to adapt swiftly to changing market dynamics (*Hansson, 2010*).

Technological innovation and digital transformation catalyze continuous innovation, empowering businesses to meet evolving market demands and create breakthrough products and services. Digital platforms enable companies to gather and analyze vast amounts of data, uncovering insights that drive customer-centric innovation. This agility allows organizations to

remain competitive in an increasingly dynamic business environment. Moreover, these advancements extend beyond enterprises to enhance societal living standards. Innovations such as smart home technologies, digital payment systems, and online education platforms have revolutionized daily life, offering greater convenience and accessibility. In healthcare, digital technologies, including telemedicine, wearable health devices, and AI-driven diagnostics, have transformed patient care, improving outcomes and expanding access to medical services (*Potocan, 2020*).

Despite their advantages, technological innovation and digital transformation present challenges and risks that businesses must navigate strategically. Data security and privacy protection are among the most pressing concerns, as the digital economy relies heavily on collecting, storing, and processing sensitive information. Enterprises must implement robust cybersecurity measures and establish transparent policies to safeguard customer data and build trust. Additionally, the rapid pace of technological advancement can lead to job displacement as traditional roles are automated. To address this, organizations should prioritize employee upskilling and reskilling, providing training programs that equip workers with the competencies needed to thrive in the digital age.

Thus, technological innovation and digital transformation are transformative drivers of economic growth and societal progress. By embracing these changes while addressing associated challenges responsibly, businesses can achieve greater resilience, innovation, and societal impact, paving the way for a more sustainable and inclusive future.

In conclusion, actively advancing technological innovation and digital transformation enables enterprises to sustain their competitiveness, achieve long-term sustainable development, and contribute significantly to societal progress. Simultaneously, the critical role of CSR must not be overlooked. CSR serves as a cornerstone for the enduring success of businesses, fosters the sustainable development of society and the environment, and opens avenues for new business opportunities and innovative solutions.

3. The strategic role of corporate social responsibility in driving technological innovation

CSR is integral to fostering technological innovation that balances commercial success with societal and environmental sustainability goals. As enterprises navigate innovation challenges, CSR serves as both a guiding framework and a regulatory force, ensuring that technological advancements align with ethical standards and contribute to the greater good. The role of CSR in technological innovation is multi-faceted and can be explored through the list of dimensions.

One of the primary responsibilities of enterprises engaged in technological innovation is guaranteeing the quality and safety of their products and services. This requires a commitment to rigorous testing, robust quality control mechanisms, and proactive risk management to ensure that innovations do not harm users or society (*Cera, 2017*). CSR principles encourage businesses to allocate resources toward developing reliable and safe solutions, thus fostering consumer trust and mitigating potential legal or reputational risks.

Technological innovation, such as increased energy consumption or waste generation, often significantly impacts the environment. CSR demands that businesses prioritize sustainable practices in their innovation processes. This includes promoting renewable energy adoption,

reducing emissions, minimizing resource waste, and implementing eco-friendly production methods (*Dao, 2011*). By integrating sustainability into technological advancements, companies can address environmental challenges while creating long-term value for stakeholders and society.

Employees are a critical driving force behind technological innovation, and CSR emphasizes the importance of safeguarding their well-being and rights. Enterprises should provide a safe and inclusive working environment, fair compensation, and opportunities for professional growth (*Shiroishi et al., 2018*). Offering training programs and career development initiatives boosts employee morale and satisfaction and ensures the workforce is equipped with the skills required to thrive in an evolving technological landscape. Companies that prioritize employee welfare are better positioned to attract and retain top talent, fostering innovation and productivity.

CSR extends beyond a business's internal operations to include active participation in community development. Enterprises can contribute by supporting local education, cultural initiatives, and infrastructure projects and creating job opportunities within the community. Sponsoring community events and collaborating with local stakeholders can enhance the company's reputation and establish stronger ties with the community, ultimately fostering a more supportive environment for innovation.

CSR guides enterprises toward responsible innovation and constrains activities that may have adverse societal or environmental consequences. By aligning their innovation strategies with CSR principles, companies can ensure that their technological advancements contribute positively to the broader ecosystem, earning societal recognition and stakeholder trust.

In summary, CSR is pivotal in shaping technological innovation that benefits businesses and society. By integrating CSR principles into their innovation strategies, enterprises can achieve a harmonious balance between economic objectives and sustainable development, driving progress while upholding ethical and social responsibilities.

4. Technology and corporate social responsibility. Ukrainian case

Developing CSR in Ukraine has gained significant traction over the last decade, spurred by internal transformations and external geopolitical influences. As Ukraine continues its path toward European integration, CSR has become an increasingly vital tool for aligning business practices with international standards, promoting social equity, and addressing environmental challenges. However, the interplay between technological innovation and CSR in Ukraine is particularly notable, as it illustrates the potential for technology-driven solutions to accelerate sustainability and societal progress.

CSR in Ukraine emerged as a formal concept in the early 2000s, largely driven by multinational corporations introducing global standards into the Ukrainian market. Over time, local businesses began to adopt CSR practices, encouraged by growing consumer awareness and pressure from civil society. The 2014 Association Agreement with the European Union marked a pivotal moment in establishing CSR in Ukraine. This agreement emphasized compliance with EU ESG standards, pushing Ukrainian businesses to adopt more robust CSR policies.

Since then, the CSR landscape in Ukraine has evolved across various dimensions. Companies in export-driven industries such as agriculture, metallurgy, and IT have integrated

CSR into their operations to enhance global competitiveness. This progress is also reflected in the rise of public-private partnerships and civil society initiatives to foster sustainable development (*Sytch et al., 2024*). For instance, many Ukrainian companies now support social programs in education, healthcare, and cultural heritage preservation as part of their CSR strategies.

Technological innovation has become a cornerstone for CSR advancement in Ukraine. The country's burgeoning IT sector, recognized globally for its skilled workforce, has led the charge in integrating technology with CSR initiatives. For example, numerous tech companies have launched digital education programs targeting underserved communities, addressing the digital divide, and fostering greater social inclusion. These programs contribute to societal development and align with broader SDGs.

Ukrainian companies have begun implementing green technologies in the manufacturing and energy sectors to reduce their environmental footprints. Initiatives such as adopting energy-efficient production systems, transitioning to renewable energy sources, and investing in waste management technologies demonstrate the integration of CSR principles with technological advancement. These efforts align with Ukraine's commitments under the Paris Agreement and its aspirations to meet the EGD's ambitious climate goals (*Honcharenko et al., 2022*).

Despite these advances, significant challenges hinder the seamless integration of CSR and technology in Ukraine. A primary challenge is the uneven distribution of CSR adoption across industries. While sectors like IT and large export-oriented businesses have made considerable progress, SMEs face resource constraints and limited awareness, which impede the implementation of CSR initiatives.

Moreover, data security and privacy have emerged as critical issues in the digital transformation era. Ukrainian companies must navigate complex regulations, including compliance with the European Union's GDPR, while simultaneously fostering public trust. The lack of robust cybersecurity frameworks and the growing threat of cyberattacks pose additional risks that companies must address to maintain the integrity of their CSR initiatives.

Another significant barrier is the absence of standardized metrics for evaluating the impact of CSR-driven technological innovations. Without comprehensive frameworks to assess environmental, social, and economic outcomes, businesses struggle to quantify their contributions to sustainability goals. This lack of clarity can lead to inconsistent implementation and hinder broader societal benefits.

Ukraine's ongoing digital transformation presents immense opportunities for deepening the integration of CSR and technology. The government's "Digital Ukraine" strategy, which aims to create a more inclusive and innovative digital economy, provides a platform for businesses to align their technological advancements with CSR objectives. For example, digital tools can be leveraged to improve access to healthcare and education in rural areas, enhance transparency in supply chains, and optimize resource utilization in manufacturing processes.

Additionally, Ukraine's alignment with the EGD offers an opportunity to accelerate the adoption of green technologies. Ukrainian enterprises can advance their environmental performance by leveraging EU funding and expertise while meeting global sustainability standards. Investments in renewable energy, circular economy practices, and sustainable agriculture are particularly promising areas for aligning CSR and technological innovation.

Furthermore, fostering collaboration between academia, industry, and government could amplify the impact of CSR-driven technological solutions. Research institutions and universities in Ukraine can play a critical role in developing innovative technologies that address societal challenges, while businesses can act as enablers by scaling these solutions. Government policies, meanwhile, can provide the regulatory frameworks and incentives necessary to support such initiatives.

The integration of CSR and technology in Ukraine is a dynamic and evolving process, shaped by the country's unique socio-economic context and aspirations for European integration. While significant progress has been made, particularly in the IT and export-oriented sectors, addressing challenges such as uneven adoption, data security, and the lack of standardized impact metrics is essential for achieving holistic progress.

By leveraging its technological potential and aligning with international CSR standards, Ukraine can position itself as a leader in sustainable development. However, this will require a concerted effort from all stakeholders – businesses, government, civil society, and academia – to ensure that CSR and technology work hand in hand to create a more equitable, innovative, and sustainable society. Through such collaboration, Ukraine can enhance its global competitiveness and contribute meaningfully to advancing societal and environmental well-being.

5. Technological innovation and the path to sustainable development

Emerging technological paradigms, such as Industry 4.0, IIoT, and Society 5.0, are fundamentally reshaping the discourse on sustainable development (*Hanson, 2010*; *BMBF, 2010*). These frameworks emphasize the sustainability of technological innovations, their alignment with societal needs, and long-term environmental stewardship. At the heart of these visions lies the critical challenge of transitioning from the current state of technological development to a future that integrates sustainability into every facet of human progress. This transition necessitates a more transdisciplinary, multifunctional, and inclusive understanding of technological advancement, considering its implications for the future of humankind.

Several objective and subjective factors impede the achievement of sustainability in technological development. A significant limitation is the difficulty in assessing basic and applied research sustainability in fields such as optics, laser technology, or artificial intelligence. These fields are often evaluated based on their scientific merit or economic potential rather than their alignment with sustainability goals (*Bottcher et al., 2023*). While specific technological solutions emerging from these fields may contribute to sustainable outcomes, the underlying research is rarely designed with sustainability in mind.

Furthermore, the unpredictable nature of technological innovation complicates the alignment of new developments with sustainability objectives. The trajectory of fundamental research often does not lend itself to forecasting or directing outcomes toward sustainable goals. For instance, breakthroughs in materials science or quantum computing may yield applications that enhance sustainability, but such outcomes are rarely the explicit focus of the foundational research.

Despite these challenges, a growing body of research and development focuses on creating technologies with high sustainability potential. These include innovations that address pressing

environmental and societal issues, such as renewable energy systems, waste management technologies, and circular economy solutions (*Cardinali et al., 2022*). To ensure the effectiveness of such technologies, society must establish the conditions for their adoption and integration. This involves defining the societal, infrastructural, and regulatory frameworks necessary for their implementation and scaling.

An illustrative example is the development of autonomous vehicles, such as Honda's Level 3 self-driving cars, which aim to enhance transportation sustainability. These vehicles necessitate advancements in automotive technologies, the creation of supporting infrastructure (e.g., smart traffic systems), and the establishment of cultural, legal, and social norms to regulate their use. The success of such innovations depends not only on technological progress but also on the readiness of society to embrace these changes. This highlights the interplay between technological innovation, policy development, and societal adaptation.

Currently, the adoption and development of sustainable technologies are largely governed by market dynamics, particularly the interplay of supply and demand. Government policies and incentives sometimes accelerate the transition to sustainable technologies, as seen with subsidies for renewable energy or electric vehicles. However, reliance on market mechanisms alone cannot drive the systemic changes required for sustainable development.

To address this gap, new mechanisms that actively guide technological innovation toward sustainability goals are needed (*Chen et al., 2023*). Businesses, governments, and research institutions must collaborate to create targeted strategies that prioritize sustainability in the development and deployment of new technologies. This could involve designing incentive structures, fostering public-private partnerships, and integrating sustainability criteria into research funding frameworks.

Transitioning to a sustainable technological future requires a holistic approach that integrates environmental, societal, and economic dimensions. It is not enough to develop environmentally friendly technologies; their adoption must be supported by robust infrastructure, progressive policies, and societal readiness (*Padilla-Lozano et. al., 2021*). For instance, implementing renewable energy technologies depends on the availability of smart grids, storage solutions, and regulatory frameworks that incentivize their use. Similarly, the success of circular economy initiatives hinges on societal behavior, corporate commitment, and governmental support.

The challenge of ensuring the sustainability of emerging technologies also extends to evaluating their broader impact. Comprehensive sustainability assessment frameworks must be developed to measure the immediate benefits of new technologies and their long-term implications for society and the environment. These frameworks should account for factors such as resource use, emissions, social equity, and economic viability, enabling a more nuanced understanding of sustainability.

The transition from the current technological state to a future characterized by sustainable technological operations is a critical area of focus for organizations and society. This transition involves numerous interconnected factors, including societal awareness of sustainability, organizational willingness to invest in sustainable technologies, and the development of supportive environments for their adoption and integration (*Kim et al., 2021*). Research

emphasizes that society's policies and priorities significantly influence this transition, shaping the context in which organizations operate and adopt sustainable technologies.

One of the most significant drivers of the transition is the development of societal awareness regarding the importance of sustainable development. As awareness grows, so does the demand for sustainable technologies, pushing organizations to align their operations with these expectations. However, the financial commitment of companies to adopt and utilize sustainable technologies is equally crucial (*Potocan et al., 2020*; *Toussaint et al., 2021*). Organizations must invest not only in the technologies but also in the infrastructure, training, and systems necessary for effective implementation.

Institutional requirements also play a pivotal role. Most countries enforce regulations to ensure the sustainable use of technologies within organizations. In more developed economies, there is an additional emphasis on adopting inherently sustainable technologies, creating a more robust framework for advancing sustainability (*Dao et al., 2011*). However, research suggests that these regulatory measures are not uniform across regions, resulting in varied levels of sustainable technology adoption and implementation. A deeper understanding of the interaction between diverse technological combinations and their sustainability outcomes in different contexts remains underexplored.

The integration of technology within CSR has been an evolving discourse. Over the past decade, researchers have emphasized expanding CSR models to include a technological dimension. This includes understanding the relationship between technology and the core dimensions of CSR – economic, social, and environmental responsibilities. While there is broad consensus on the relevance of technology within CSR, researchers differ on the depth and scope required for its integration.

Technological CSR encompasses several aspects: the sustainability of the technology itself, the sustainability of its implementation, and the sustainability of its outcomes. Each of these facets requires nuanced consideration, influenced by factors such as the technology's specific characteristics, the organization's market position, and technological infrastructure. For example, the sustainability of a technology like renewable energy systems extends beyond its intrinsic characteristics to include its deployment within a specific organization, its impact on operations, and its long-term benefits for society.

One of the key challenges in incorporating technology into CSR is the lack of standardized frameworks for evaluating sustainability. Researchers highlight the need for methodologies that differentiate between new and traditional technologies and assess technologies across a spectrum from completely unsustainable to entirely sustainable (*Chen et al., 2023*; *Ehrnström-Fuentes et al., 2023*). However, these assessments often occur outside the organization's purview, relying instead on societal criteria and contextual factors. Consequently, organizations may adopt sustainable technologies within their operational context, even if they do not fully meet broader sustainability standards.

Another unresolved issue pertains to the scope of sustainability assessments. Should organizations focus on the sustainability of the technology itself, its implementation process, or its results? Alternatively, should they adopt a holistic approach that integrates all three? Current research suggests that the decision largely depends on the organization's priorities, technological capabilities, and market conditions. For instance, a company operating in a resource-intensive

industry might prioritize technologies that reduce emissions and optimize resource use. At the same time, a technology-focused organization might emphasize innovations that enable broader societal benefits.

Given these complexities, the technological dimension of CSR is often treated as an independent but integral part of CSR frameworks. By developing contextual and methodological solutions, researchers advocate for a more comprehensive inclusion of technology in CSR models. This involves addressing the sustainability of individual technologies, their implementation, and their outcomes while also considering their broader societal and environmental impacts.

For example, an interdisciplinary and multifunctional approach to technology within CSR could examine how new technologies contribute to reducing carbon footprints, improving labor conditions, or enhancing community well-being. At the same time, it would address the systemic changes required to support these outcomes, such as regulatory reforms, public-private partnerships, and capacity-building initiatives.

Discussion

CSR is a pivotal element in digital transformation, shaping how enterprises navigate the complexities of integrating technology into their operations while addressing societal and environmental concerns. CSR ensures that digital transformation is a means to achieve efficiency and innovation and a pathway to ethical and sustainable development. The intersection of CSR and digital transformation can be analyzed through several critical dimensions:

Digital transformation inherently involves extensive data collection, processing, and storage, making data privacy and security a central CSR responsibility. Companies must prioritize safeguarding user data by adhering to stringent privacy regulations and implementing robust cybersecurity measures. Compliance with frameworks like the GDPR is not merely a legal obligation but also an ethical imperative to build stakeholder trust. Beyond compliance, businesses should invest in advanced encryption technologies, secure data infrastructure, and proactive threat detection systems to prevent data breaches and misuse. Transparent communication about data usage policies further reinforces user confidence and demonstrates accountability.

One of the primary objectives of digital transformation should be fostering social inclusion. The digital divide remains a significant challenge globally, with marginalized communities often excluded from the benefits of technological advancements. CSR calls for businesses to design accessible and user-friendly digital solutions that cater to diverse populations, including those with limited digital literacy, disabilities, or restricted access to technology. Initiatives such as providing affordable internet services, developing inclusive interfaces, and collaborating with governments or NGOs to expand digital access can help bridge this divide. Digital inclusion ensures that the advantages of technology are equitably distributed, contributing to broader social and economic development.

The success of digital transformation depends on the digital competence of employees and stakeholders. CSR-driven organizations have a responsibility to facilitate skill development and knowledge-sharing initiatives. Training programs, workshops, and certifications empower

employees to adapt to new technological demands, enhancing their professional growth and ensuring workforce readiness. Such efforts improve employee retention and satisfaction and contribute to the resilience and adaptability of businesses in an ever-evolving technological landscape. Moreover, extending these educational opportunities to local communities or underprivileged groups further demonstrates a commitment to societal progress.

Digital transformation can lead to profound societal changes, such as shifts in employment patterns, new social hierarchies, and the redefinition of community structures. Companies must conduct thorough SIAs to understand the potential consequences of digital initiatives on various stakeholders. These assessments enable businesses to anticipate and mitigate adverse effects, such as job displacement due to automation, and to implement proactive measures like reskilling programs or policy advocacy for equitable labor practices. By considering the broader societal implications of digital transformation, enterprises can align their strategies with sustainable development goals and foster a positive societal impact.

Digital transformation offers unparalleled opportunities for innovation that can address pressing social and environmental challenges. CSR encourages businesses to leverage technological advancements to develop solutions for issues such as climate change, urbanization, and resource scarcity. Examples include creating smart city infrastructure to optimize resource utilization, developing renewable energy technologies, and deploying digital health platforms to enhance healthcare accessibility. By aligning technological innovation with social problem-solving, companies can amplify their societal contributions, enhance their reputation, and differentiate themselves as leaders in sustainable innovation.

CSR is a guiding principle and a regulatory framework in the digital transformation journey. It ensures that technological advancements are pursued with an ethical lens, balancing corporate interests with societal welfare. CSR-driven digital transformation strategies help businesses address critical questions: How does this transformation affect society? Who benefits? Are there unintended negative consequences, and how can they be mitigated? Companies can navigate these challenges by embedding CSR into digital strategies while fostering trust and accountability.

Conclusion

Corporate Social Responsibility plays an indispensable role in ensuring that digital transformation contributes positively to society and the environment. By addressing key issues such as data privacy, digital inclusion, skills development, societal impact, and innovation, CSR provides a holistic framework for ethical and sustainable digital advancements. Enterprises that embrace CSR in their digital transformation initiatives gain societal recognition and stakeholder support and position themselves as leaders in sustainable development. Ultimately, by aligning technology with responsibility, businesses can drive progress that benefits society and the environment, ensuring a more equitable and sustainable future.

The technological dimension of CSR is as significant as its economic, social, and environmental counterparts. Organizations can address complex sustainability challenges by integrating technology into CSR frameworks while fostering innovation and competitiveness. However, achieving this integration requires overcoming several hurdles, including developing

standardized evaluation frameworks, aligning organizational priorities with societal goals, and creating supportive policy environments.

As organizations continue to navigate the transition to sustainable technological operations, the role of technology within CSR will become increasingly prominent. By adopting a holistic and interdisciplinary approach, businesses can leverage technological innovation to achieve their CSR objectives, contributing to a more sustainable and equitable societal future. This vision calls for a concerted effort among researchers, policymakers, and organizations to redefine the role of technology within CSR and unlock its full potential for sustainable development.

Conflict of interest

The author declares that there is no conflict of interest.

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Digital economy and information systems: Problems and challenges in globalisation [5]

Abstract: The article examines the problems and challenges of the digital economy in the international space. This article is devoted to analysing the key challenges facing the digital economy in the context of globalisation. At the global level, the emphasis is on the problems states and organisations face. The authors emphasise cyber security problems, the digital divide between countries, regulatory barriers in data, monopolisation of the technology market, and labour automation. Environmental challenges are considered, particularly energy consumption growth and geopolitical competition between major powers for technological leadership. It is also important to determine the changes and transformations of the world economy regarding the conditions of globalisation. Special attention is paid to ethical aspects such as transparency of artificial intelligence algorithms, data privacy and bias in technology. The article proposes ways to solve these problems through international coordination, standardisation of legislation, development of digital infrastructure in developing countries, and harmonisation of approaches to regulation. The study focuses on identifying the main problems and challenges that will improve the effectiveness of creating the digital economy in the context of globalisation, to improve the understanding of digitalising and the forming strategies in a globalised world, to determine the main ones for ensuring the sustainable development of the digital economy.

Keywords: digital economy, globalisation, information globalisation, information technologies, digitalisation, cyber security, digital technologies, digital transformations, data.

Abbreviations:

AI is artificial intelligence,

ICT is information and communication technologies,

IoT is the Internet of Things.

Introduction

The digital economy is one of the most significant components of the globalised world, rapidly transforming traditional business operation models, job creation, and interaction between states. Globalisation offers new opportunities for transnational cooperation, innovation, and improved efficiency of economic processes. At the same time, digitalisation presents many challenges, such as cybersecurity, the digital divide, regulatory restrictions, and ethical dilemmas. In modern conditions, these challenges substantially impact the stability and sustainable development of the global economy.

The study object is the digital economy as a system of economic relations based on the use of digital, information, and communication technologies within its functioning in conditions of globalisation.

The study aims to analyse the problems and challenges of the digital economy in the context of globalisation and to develop strategic approaches to overcome them, considering international experience.

To achieve this aim, the following tasks need to be completed:

– examine the main characteristics and aspects of developing the digital economy in the global space;
– identify the key problems and challenges associated with developing the digital economy, including issues of cybersecurity, the digital divide, and regulation;
– assess the extent of globalisation's impact on developing information technologies, their integration into the global economy, and the competitiveness of states;
– analyse international approaches to regulating the digital economy and the experience of addressing key challenges;
– develop recommendations for improving the conditions for growing the digital economy in a globalised world.

The study's methodological framework on "Problems and Challenges of the Digital Economy in the Context of Globalisation" includes a wide range of approaches, methods, and tools that enable a comprehensive analysis of the phenomenon. The main methods used are as follows:

- analysis and synthesis – used to examine the key aspects of developing the digital economy and the interconnections of its elements in the global environment;
- systemic approach – enables the digital economy to be considered as a complex of interconnected technological, social, and economic processes;
- comparative analysis – applied to study the digital transformation experience in various countries and regions.

The digital economy and its development in the context of globalisation attract the attention of both domestic and international researchers.

A significant number of domestic academic studies have been dedicated to examining the identification of problems and challenges of the digital economy in the context of globalisation. In particular, V.M. Geets has investigated the impact of digital technologies on Ukraine's economy (*Geets, 2022*). A.M. Kolot and O.O. Herasymenko, in their article "Social and Labour Development in the 21st Century", address the global challenges of the digital economy in the labour sphere (*Kolot & Herasymenko, 2019*). K.M. Kraus, N.M. Kraus and O.V. Manzhura explore the nature of technological progress, digital technologies, and innovations (*Kraus et al., 2022*). A.O. Sloboda and N.Ye. Skorobohatova studied the impact of the digital economy on a state's competitive advantages (*Sloboda & Skorobohatova, 2020*). O. Trokhymets and other scholars analysed the interconnections between the digital economy and classical economic sectors, focusing on the challenges arising from these relationships (*Trokhymets et al., 2024*). N.M. Kraus, O.P. Holoborodko, and K.M. Kraus explored and summarised key trends in the digital economy, defining its content (*Kraus et al., 2018*). O. Pankova, O. Kasperovych, and O. Ishchenko examined innovative platforms to advance conceptual and managerial support for digital transformation (*Pankova et al., 2020*).

Notable international scholars who have contributed to research on this topic include Manuel Castells, Klaus Schwab, Brian Arthur, and others.

This study aims to provide a comprehensive understanding of contemporary digitalisation challenges and facilitate the development of effective strategies to ensure economic growth.

The results of the study

Theoretical aspects of the digital economy in the context of globalisation

The theoretical foundation of the digital economy is a model based on the use of digital technologies, information resources, and infrastructure to create, store, process, and transmit data. It encompasses all spheres of societal life where digital technologies are actively employed to enhance economic processes' efficiency, foster the creation of new business models, and drive innovation.

The digital economy has emerged due to the development of ICT and globalisation processes. Its theoretical aspects encompass several key areas:

The digital economy relies on using digital technologies to create, distribute, and consume goods and services. The primary components of this system include:

- digital platforms (e.g., Amazon, Google, Facebook), which are reshaping global markets;
- data as a new economic resource, where data collection, processing, and analysis have become critical processes in a world where data is often referred to as "the new oil";
- e-commerce, which is transforming traditional business models.

Interdisciplinary approaches shape the digital economy's theoretical basis, including economic theory, computer science, sociology, etc. Digitalisation has redefined the traditional concept of globalisation. Its key features include:

- borderless market access, as digital technologies eliminate barriers between countries;
- integration of economies through technological solutions such as cloud computing, fintech, and blockchain;
- a new geography of labour, driven by the rise of remote work and outsourcing through platforms like Upwork and Fiverr.

A critical aspect of digital transformation is the integration of digital technologies, particularly the synergy between information and communication systems.

To understand the digital economy comprehensively, it is essential to identify its core theoretical aspects, which serve as a framework for analysing its dynamics. These include:

- network theories, such as the concept of a "network society," where digital technologies foster new economic relationships;
- innovation cycle theory, which views digitalisation as a technological revolution reshaping market structures and creating new opportunities;
- institutional theories highlighting the role of governments and regulators in shaping digitalisation policies.

Data has become a pivotal resource underpinning innovation, managerial decision-making, and business development in the digital economy. The application of big data enables market analysis, trend forecasting, and product and service improvement.

Digitalisation has given rise to new forms of business, such as e-commerce, sharing economy platforms (e.g., Uber, Airbnb), remote services (EdTech, FinTech), and the creation of digital products and services. A dynamic interplay exists between these services, ICT, and digital solutions, driven by unpredictable environmental changes. Thanks to the internet and digital platforms, goods and services have become accessible regardless of the consumer's location, expanding markets and facilitating integration into the global economy.

In conclusion, the theoretical essence of the digital economy lies in defining the core characteristics of an economic model that leverages innovative digital technologies and big data. This is achieved through the adoption and application of digital technologies within the context of globalisation, enhancing market adaptability to digital transformation processes.

Main aspects of the problems and challenges of the digital economy in the context of globalisation

The digital economy, in the context of globalisation, faces many problems and challenges, which can negatively affect digital transformation and the formation of a new economic model.

As an integration phenomenon of the modern world, the digital economy poses new problems and challenges to society. These aspects are analysed from the viewpoint of the interaction of economic, technological, social and legal processes in the global environment.

It is advisable to group the problems and challenges of the digital economy into some categories, which will help to clearly identify certain aspects and highlight the main points of their impact on the development of the digital economy in the languages of globalisation.

Conceptual problems of the digital economy reveal the essence of forming the methodology for implementing programme measures of digitalisation (digital transformation). It is necessary to define the following conceptual problems:

1. The digital divide:

- Its essence lies in the uneven access to digital technologies between developed and developing countries;
- The reasons for their concept are to determine that there are infrastructure restrictions, financial insolvency of individual regions, insufficient digital literacy;
- The bottom line challenge is to reduce the imbalance in access to the Internet and technology to ensure equal participation in the digital economy.

2. Automation and the labour market:

- Bottom line: Process automation replaces manual labour, creating the threat of unemployment;
- Challenge: Developing strategies for retraining personnel and creating new professions in digital industries.

3. Data protection and cybersecurity:

- Bottom line: The growing amount of personal data and transactions requires the creation of reliable systems for their protection;
- Challenge: Ensuring legal and technological regulation of cybercrime at the international level.

Along with conceptual ones, the digital economy faces economic challenges in the context of globalisation. These challenges relate to economic aspects that characterise the state's economy and reveal deviations from specific economic indicators that hinder the digital transformation of the economy.

These include the following economic challenges of digitalisation:

1. Monopolisation of markets

- Bottom line: Concentration of market power in large technology companies such as Google, Amazon, and Facebook;
- The challenge, in its essence, is to develop an antitrust policy in the global digital economy.

2. Financial risks

- The bottom line is that the use of digital currencies, such as cryptocurrencies, poses threats to the stability of traditional financial systems;
- Challenge: Regulating digital assets and integrating them into traditional financial systems.

3. Tax transparency

- Bottom line: Global digital companies use low-tax jurisdictions;
- Challenge: Harmonisation of international taxation rules for digital businesses.

Technological challenges are also highlighted when analysing the digital economy in the context of globalisation.

1. Infrastructure Development:

- Bottom line: Insufficient development of digital networks in underdeveloped countries;
- Challenge: Investing in global digital infrastructure, including satellite internet.

2. integration of innovations

- Bottom line: Integration of AI, blockchain and the IoT into traditional sectors of the economy;
- Challenge: Ensuring the ethics, security, and accessibility of technology.

When analysing the digital economy in the context of globalisation, social aspects and ethical challenges are also highlighted:

1. Digital inequality

- Bottom line: inequality in access to digital resources between social groups and regions;
- Challenge: Creating an inclusive digital economy for all population categories.

2. Ethics of using AI

- Bottom line: Using algorithms to make decisions may violate ethical principles;
- Challenge: Developing ethical standards for digital technologies.

3. Education and digital skills

- The bottom line: the lack of digital competencies among the population;
- Challenge: Implementing educational programmes for developing digital literacy.

Based on these challenges, it is necessary to create a mechanism for overcoming them since forming a digital economy requires coherence and the proper development strategy. It is necessary to highlight the main effective theoretical ways to overcome challenges: an institutional approach; its essence is to ensure effective regulation of digital processes at the global level; an innovative economy, meaning development that emphasises the role of digital networks as the basis of the global economy.

Thus, the theoretical aspects of the problems and challenges of the digital economy in the context of globalisation emphasise the need for an integrated approach to overcome inequality, regulate technology and ensure sustainable development in the digital environment.

Strategic directions for addressing the problems and challenges of the digital economy in the context of globalisation

Developing the digital economy in the context of globalisation is a key priority for most countries because it provides economic growth, increases competitiveness and promotes integration into global markets. However, this process faces many challenges that require strategic approaches to overcome them. In particular, the digital divide between countries and regions remains a serious problem that hinders full access to digital technologies for all population segments. Solving this problem requires significant investment in developing digital infrastructure, including the introduction of high-speed internet, particularly in remote and rural regions, which will provide more equal opportunities for participation in the digital economy.

Another important component is strengthening cybersecurity, as the spread of digital technologies is accompanied by an increase in the risks associated with data leaks, cyber-attacks, and crime in the virtual space. To do this, it is necessary to implement national and international cyber defence strategies, develop innovative technologies to ensure information security, and create specialised centres for monitoring and responding to cyber threats.

In addition, improving the regulatory framework in the digital economy is crucial. Globalisation requires harmonisation of legal norms at the international level to ensure the protection of personal data, regulation of cryptocurrencies, artificial intelligence, and co-consumption platforms. Harmonisation of legislation will create transparent and fair conditions for developing digital services and technologies.

Special attention should be paid to the education and training of specialists because the digital economy requires highly qualified personnel. To do this, it is necessary to integrate digital competencies into the education system, introduce professional development and retraining programs, and promote digital literacy among the population. Training human capital will contribute to developing the national economy and strengthening its position in the global market.

Another strategic direction is to encourage innovation in digital technologies. Investments in developing AI, the IoT, blockchain, and other latest solutions will strengthen countries' technological potential and create new opportunities for business and society. In this context, supporting start-ups, research, and innovation projects through grant programs, tax breaks, and venture funding is important.

Strengthening international cooperation is also an important element in overcoming the challenges of the digital economy. Coordinating efforts between countries will contribute to the fight against cybercrime, the development of joint innovative solutions, and the assurance of fair access to digital technologies for all.

Thus, strategic directions for developing the digital economy should aim to overcome existing problems and challenges, ensure the integration of countries into the global digital space, increase the level of digital literacy of the population, develop innovation, and strengthen security. A systematic approach will maximise the digital economy's potential and ensure sustainable development in a globalised world.

Discussion

The digital economy is one of the main driving forces of modern economic development, significantly changing the structure of the world economy, ways of doing business, and interactions between countries. However, its development is accompanied by many problems and challenges that are becoming more acute in globalisation. One of the key problems is uneven access to digital technologies. The digital divide observed between developed and developing countries, such as urban and rural regions, creates significant barriers to full integration into the global digital economy.

The issue of cybersecurity is also becoming critical. The growing volume of digital data and its strategic importance makes information resources vulnerable to cybercriminals. Infrastructure attacks, personal data hacks, and financial fraud cause significant economic damage, undermine trust in digital platforms and hinder their spread. In this context, there is an acute problem of insufficient regulatory regulation, particularly at the international level, making it difficult to coordinate efforts to counter cyber threats effectively.

Promising areas for solving these problems require a systematic approach. Investing in developing digital infrastructure and providing access to high-speed internet in remote regions is necessary, such as creating programmes to improve the population's digital literacy. Harmonising legislation at the international level to regulate cybersecurity, personal data protection, and the use of artificial intelligence is important. Developing cooperation between the two countries, attracting investment in digital innovation, and supporting small and medium-sized businesses will increase integration into the global digital economy.

The digital economy is a powerful tool for transforming global society, but its development must be based on addressing existing challenges that will ensure fair and sustainable development in a globalised world.

Conclusion

In the context of globalisation, the digital economy is one of the main drivers of economic growth, innovative development, and society's transformation. At the same time, its development is accompanied by many problems and challenges that need to be resolved quickly. One of the most important is the digital divide, which restricts access to modern technologies for many regions and countries. This requires the active implementation of programs to expand the digital infrastructure, which will contribute to a more even distribution of opportunities in the digital space.

Ensuring cybersecurity is an important challenge, as risks of leakage, fraud, and attacks on key infrastructure facilities accompany the growth of digital data. Adequate protection requires international coordination, developing a legal framework and introducing innovative security technologies.

Another key aspect is the lack of qualified personnel. The development of the digital economy is impossible without human capital that can adapt to new technological challenges. This requires modernising the education system, supporting training programmes, and promoting digital literacy among the population.

The conditions of globalisation also place high demands on harmonising legislation regulating the digital economy. Insufficient legal frameworks make it challenging to regulate

new areas such as cryptocurrencies, artificial intelligence, and data sharing, creating risks of using unregulated technology.

To address the relevant problems, strategic approaches that include investment in infrastructure, innovation development, promotion of international cooperation, and adaptation of legal mechanisms to the requirements of the digital economy are necessary.

Thus, for the sustainable development of the digital economy in the context of globalisation, overcoming existing challenges, ensuring equal access to digital technologies, strengthening security, promoting innovation and creating conditions for effective integration into the global digital space is important. This will allow us to fully realise the potential of the digital economy to grow well-being, increase competitiveness and form a modern global society.

Conflict of interest

The author declares that there is no conflict of interest.

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Consumer behavior management influenced by laundry detergent quality [6]

Abstract: The study aims to assess the quality of laundry detergents sold on the Ukrainian market and to determine their competitive advantages for consumers. The study is based on official materials from the State Customs Service of Ukraine and the scientific works of domestic and foreign scientists in this field. The article examines the state of the synthetic detergents market in Ukraine, including laundry detergents, during 2020-2024. The results of a study of the market saturation with domestic and foreign products are presented. The dynamics of export-import operations of the studied product are characterized. The current requirements for the quality of laundry detergents are analyzed, and a comparative characteristic of different classifications is given. A sociological survey of consumers was conducted, which determined the main brands in the highest demand among the latter. A study of the organoleptic and physicochemical quality indicators of selected samples (based on the consumer survey results) of laundry detergents was conducted. General scientific methods – a collection of information, its analytical processing, and theoretical generalization; statistical methods – for quantitative assessment of the volumes of export-import operations of the studied product; graphical – for illustrating the dynamics of the studied indicators were used. It was established that consumers prefer relatively inexpensive goods among the variety of laundry detergents. An assessment of the quality of the studied samples showed that they all meet the requirements of the current regulatory documents.

Keywords: laundry detergent, import, export, quality, classification.

Abbreviations:

EACH is registration, evaluation, authorization, and restriction of chemicals;

UCGFEA is Ukrainian Classification of Goods for Foreign Economic Activity.

Introduction

The rapid development of scientific and technological progress in the chemical industry leads to a constant expansion of the capacity and assortment of the laundry detergent market. This allows consumers to use various products to facilitate washing and achieve cleanliness and freshness of things at home. For modern people around the world, laundry detergents have become an integral part of a high quality of life, including environmental quality, living conditions, safety, physical comfort, sleep quality, and rest (*Voloshyna, 2017*). Consumers use laundry detergents almost daily. Each homemaker chooses different washing products depending on the manufacturer, volume, composition, and price category. Both domestic and imported goods are present in household use. Consumers prefer products that can provide the expected result, but it is important not to forget about the quality of these detergents, as it has a direct impact on health and the environment. According to the Resolution of the Cabinet of Ministers of Ukraine No. 717 of August 20, 2008, "On Approval of the Technical Regulation of Detergents" (*2008*), a detergent is any substance or preparation containing soap and/or other surfactants intended for washing or cleaning and used in households and industry, in the form of a liquid, powder, paste, bar, tile, tablet, etc. Laundry detergent is a synthetic detergent (SD) as a powder or granules that provides a washing effect (*Synthetic Detergents…, 1995*).

Before the full-scale invasion, the Ukrainian laundry detergent market could be considered entirely developed. Several factors confirmed this. Firstly, almost all international brands were represented in Ukraine. Secondly, there was a variety of price and functional offers: consumers could choose products in any price range and purchase detergent designed for different types of laundry or clothing of a specific color. Thirdly, the share of contraband goods, which could reach 20-25% of all supplies ten years ago, had significantly decreased to acceptable levels due to regulatory changes, increased border control, and a larger share of legal trade in total sales. Fourthly, more and more Ukrainians were showing interest in the environmental safety of detergents, which is a progressive indicator even for the European market.

The supply of the Ukrainian market with high-quality laundry detergents is influenced by several factors: consumer needs, market demands, technological advancements, and environmental safety standards. As Ukraine integrates into the European Union, the domestic laundry detergent market is increasingly filled with foreign-made products. Therefore, improving the assortment of the latter by enhancing their quality is extremely important. The relevance of the research topic is determined by the fact that in modern conditions, new substances, groups, and classes of compounds are being actively developed and introduced into production. These substances find wide application in many sectors of the economy as both intermediate and final products and require hygienic regulation. Thus, the quality of laundry detergents is critical for further developing this market segment and meeting consumer needs.

The issue of assessing the quality of synthetic detergents (including laundry detergents) has been addressed in the works of many domestic and foreign scientists. T. Kolomiets and L. Chernyak (*2017*) evaluated the quality of phosphate-free laundry detergents. I.S. Ilchuk (*2015*) determined the impact of synthetic detergents on human health by studying the components of these products. A.Yu. Chernyavska (*2023*) conducted a study on the impact of chemical compounds in synthetic detergents on the environment using bioindication. T.M. Cherevata (*2014*) studied laundry detergents' assortment and consumer properties.

In addition, the problems of the quality of synthetic detergents were also highlighted in the works of foreign scientists. A. Ferri (*2016*) studied the impact of detergents and additives on consumer satisfaction. Irshad N. Shaikh and M. Mansoor Ahammed (*2024*) researched the impact of the washing method and the type of detergent on the characteristics of the water after washing. Abdal-Rhman Magdy Abdullah Youssef (*2019*) researches and improves the main components of laundry detergents that increase their washing ability. However, the publications of these scientists containing an assessment of the quality of synthetic detergents (including laundry detergents) are pretty limited in number and highly specialized. Thus, there is a need for current research on other aspects of the quality assessment of laundry detergents in the Ukrainian market.

Under war conditions, companies producing laundry detergents require constant improvements and the ability to respond quickly to risks associated with large-scale missile strikes on Ukraine's infrastructure. However, manufacturers must understand that precisely the quality of laundry detergents is the key determinant of consumer choice.

The study aims to assess the quality of laundry detergents sold on the Ukrainian market and to determine their competitive advantages for consumers.

The study is based on official materials from the State Customs Service of Ukraine and the

scientific works of domestic and foreign scientists in this field.

A survey was conducted using a questionnaire among respondents. Since laundry detergents are mass-consumption goods, consumers of various categories and social groups participated in the survey. The main criteria for dividing consumers were age, gender, and monthly income. The survey involved 136 respondents living in different regions of Ukraine.

Labeling research was conducted according to the requirements of the Technical Regulations for Detergents (*2008*).

The quality of the laundry detergent samples was assessed based on organoleptic and physicochemical indicators. The appearance of the powders was determined visually at an ambient temperature of (20±2)°C and under natural daylight. The washing ability was determined by the ratio of the degree of soil removal by the test detergent solution to the ideal degree of soil removal on one type of fabric according to DSTU 2665:2012 "Synthetic detergents. Method for determining washing ability" (*2012*). pH, foaming, and foam stability were determined according to DSTU 2972:2010, "Powder Synthetic Detergents. General Technical Requirements and Test Methods" (*2010*).

The results of the study

Trends in the laundry detergent market

Ukraine is an attractive market for household chemicals, primarily due to its large population and favorable geographic location. However, the percentage of domestic industrial production of surfactants such as sodium alkylbenzenesulfonate, higher alcohol sulfates, alkyl ether sulfates, nonionic, and other types of surfactants, which form the basis of synthetic detergents, including laundry detergents, is relatively low (*Ternova, 2021*).

The assortment of laundry detergents on the Ukrainian market is diverse, but their chemical composition is quite similar. Most are laundry detergents based on synthetic anionic surfactants, while laundry detergents based on other surfactants, particularly natural surfactants, are represented in small volumes.

The leading producers of laundry detergents are transnational companies: "Procter & Gamble" (brands "Ariel," "Tide," "Tix Bonux"); "Henkel" (brands "Persil," "Rex," "Perwoll," "Pur," "Bref," "Silan," "Losk"); "Cussons" (TME); "Unilever" (TM OMO), "Reckitt Benckiser" ("Dosia," "Lanza") (*Figure 1*) (*Economic Truth, 2024*).

Ukrainian-produced laundry detergents include brands such as "Vukhastik," "Alles GUT!," "WASCHKONIG," and those manufactured by "Procter & Gamble Ukraine" (*Nakonechna, 2024*). Next, we examine the overall characteristics of imports and exports of laundry detergents (*Figure 2*). An analysis of the data presented below shows that Ukraine has had a negative trade balance for this type of product over the past few years, indicating that it imports significantly more synthetic detergents than it produces and sells on the foreign market. Over the past 5 years, imports have exceeded exports by a factor of 15-30, which significantly impacts the economy. Despite a decline in 2022 due to the full-scale Russian invasion, imports of this product have been rapidly growing. The peak of imports for this period was reached in 2021 at $303,105 thousand. Export volumes fluctuate, with the lowest figure in 2022 at $8,675 thousand and the highest in 2023 at $14,758 thousand. This allows for hope in developing domestic production, increased volumes on the Ukrainian and foreign markets, and a gradual trade

balance improvement (*Statistics and Registers…, 2024*).

An analysis of data from the State Customs Service of Ukraine (*2024*) indicates that in 2019, the largest share of imports originated from Poland (22,97%), Germany (13,37%), and the Czech Republic (7,86%), with other countries accounting for 55,80%. Exports were primarily directed to Moldova (20,41%), Italy (15,49%), and Bulgaria (14,98%), with the remaining 49,12% going to other countries.

In 2020, the largest share of imported laundry detergents came from Poland (24,97%), Germany (11,23%), and Hungary (7,9%), with the remaining 55,90% from other countries. Exports were primarily directed to Moldova (25,57%), Bulgaria (18,91%), and the Czech Republic (6,93%).

In 2021, Moldova (26,89%), Bulgaria (21,33%), and Georgia (7,39%) were the top export destinations for laundry detergents, while Poland (24,20%), Germany (11,58%), and France (7,13%) were the primary import sources.

In 2022, Poland (29,70%), the Czech Republic (11,23%), and Germany (10,04%) were the primary exporters of laundry detergents to Ukraine, and Moldova (22,67%), Poland (11,91%), and Latvia (10,40%) were the main import destinations.

In 2023, significant volumes of laundry detergents were imported from Poland (22,52%), the Czech Republic (14,21%), and Germany (8,84%), with the remaining 54,42% from other countries. The largest export markets were Moldova (20,98%), Poland (19,03%), and Romania (12,27%).

An analysis of Figure 3 indicates that a similar trend persisted in 2024. Most laundry detergents were imported from Poland, the Czech Republic, and Germany, while exports were primarily directed to Romania, Moldova, and Poland.

Consequently, the most significant quantities of laundry detergents were imported from Poland, Germany, and the Czech Republic, with Hungary and France also emerging as leading sources in other years. Exports were primarily directed to Moldova and Bulgaria, as well as to the Czech Republic, Georgia, Romania, Latvia, and Italy.

The analysis of the laundry detergent market revealed that foreign-produced products dominate it. However, the emergence of new domestic brands that have gained significant consumer demand is worth noting. The study found that imports significantly exceeded exports of laundry detergents. The product range includes international brands such as "Procter & Gamble," "Henkel," "Cussons," "Unilever," and "Reckitt Benckiser." However, domestic brands like "Vukhastik," "Alles GUT!," "WASCHKONIG," and "Procter & Gamble Ukraine" have recently gained considerable market share. Most of the products studied were imported, primarily from Poland, Germany, and the Czech Republic. In contrast, Ukrainian products were mainly exported to neighboring countries, with Moldova and Bulgaria being the leading destinations.

Classification and quality requirements for laundry detergents

At this stage of the research, it would be beneficial to consider the classification of laundry detergents based on various criteria and compare the classification of the studied product according to the Harmonized System (HS) and scientific classification.

According to the scientific classification (*Merezko et al., 2019*), laundry detergents, including

powders, are divided into the following groups based on their intended use for:

- washing wool and silk fabrics (pH 7-8,5);
- washing cotton and linen fabrics (pH 10-11,5);
- washing various fabrics, including synthetic fibers (pH 9-9,5);
- washing children's clothes;
- washing coarse and heavily soiled fabrics, including workwear.
- based on consistency, laundry detergents are divided into:
- powdered;
- liquid;
- washing capsules (*Merezko et al., 2019*).

Powdered detergents have a higher pH level, making them more effective at tackling tough stains like clay. However, they can be challenging to dose: too little may not clean effectively, while too much can be hard to rinse. They dissolve less well in cold water and can leave stains on clothes, making pre-treatment with a stain remover beneficial. The undissolved powder can form clumps that clog washing machines. On the positive side, powdered detergents can help prevent mold growth in washing machines if used at least once a week (*Merezko et al., 2019*).

Liquid detergents are more manageable to dose, with measuring cups for precise amounts. They do not clog washing machines because they dissolve well, even in cold water. Liquids can also be used for pre-treating stains, especially greasy ones (*Merezko et al., 2019*).

Laundry capsules offer both advantages and disadvantages. They are compact, easy to store, and highly concentrated, making them efficient for machine washing. However, their concentrated formula can irritate the skin, so they should not be used for hand washing.

According to the scientific classification, the main characteristics for classifying laundry detergents are their intended use and consistency (*Merezko et al., 2019*).

According to the Ukrainian Classification of Goods for Foreign Economic Activity (UCGFEA), as approved by the Law of Ukraine "Customs Tariff," laundry detergents are classified under Section VI, "Products of the chemical and related industries" (*2022*).

This section is divided into 10 groups, with laundry detergents falling under group 34: "Soap, organic surface-active agents, washing preparations, lubricating preparations, artificial waxes, and prepared waxes, polishing or scouring preparations, candles, and similar articles, modeling pastes, "dental wax" and dental preparations with a basis of gypsum" (*UCGFEA, 2020*).

Commodity code 3402 "Organic Surface-Active Agents (Other Than Soap); Preparations for Washing, Cleaning (Including Auxiliary Washing Preparations) and Scouring, with or without Soap, but not Including Preparations of Heading 3401" covers laundry detergents (*UCGFEA, 2020*).

A complete classification of laundry detergents, depending on their composition and characteristics, is presented in the appendix (*Table 1*).

The main component of laundry detergents is organic surfactants, characterized by wetting, emulsifying, peptizing, and foaming abilities. The combination of these properties determines their cleaning action. Synthetic detergents are supplemented with alkaline and neutral electrolytes, alkylolamides, carboxymethylcellulose, and other substances to enhance this action.

For example, bleaching agents are functional additives (*Merezko et al., 2019*).

Anionic surfactants are paramount for laundry detergents. They dissociate in aqueous solutions into anions, negatively charged hydrophobic parts of the molecule (long hydrocarbon chains), and cations, small, positively charged ions, usually sodium and sometimes potassium. The larger anion, similar in size and properties to the hydrophobic part of a fat soap molecule, is responsible for the surfactant properties (*Merezko et al., 2019*).

According to the UCGFEA, the main classification features of laundry detergents, including laundry powders, are chemical composition, the presence of certain types of acids, intended use, and the type of surfactants.

It is necessary to note that the scientific classification of laundry detergents differs from the UCGFEA classification. The UCGFEA classification is primarily used for customs purposes. However, a common feature of both classifications is the intended use of laundry detergent (including laundry powders).

An integral part of the research is analyzing Ukraine's quality requirements for laundry detergents and comparing them with EU requirements.

The requirements for the quality and safety of laundry detergents are specified in the normative documents established for this product in Ukraine, such as technical regulations and state standards. Laboratory indicators of the quality of laundry detergents include the pH of an aqueous (1%) solution, the content of surface-active substances (alcohol-soluble) and unsulfonated compounds, the content of alkaline salts, moisture, carboxymethylcellulose, optical brighteners, etc.

According to the "Technical Regulations for Detergents", approved by the Cabinet of Ministers of Ukraine on August 20, 2008, No. 717, a detergent is any substance or preparation containing soap and/or other surfactants intended for washing or cleaning and used in households and industry, in the form of a liquid, powder, paste, bar, tablet, etc. A surfactant is any organic substance and/or preparation used in detergents, having surface-active properties and consisting of one or more hydrophilic groups and one or more hydrophobic groups of such a nature and size that they can reduce the surface tension of water, form monomolecular layers that spread or are adsorbed at the interface between water and air, emulsions and/or microemulsions, and/or micelles, and can also be adsorbed at the interface between water and a solid surface.

The introduction of detergents and surfactants into circulation is possible only if they do not pose a threat to the safety of the environment and meet the requirements for:

- the level of biodegradability of surfactants;
- the labeling of detergents;
- information provided upon request by the executive authorities specified by law;
- restrictions on the content of phosphates and other phosphorus compounds in detergents.

The complete biodegradability of surfactants included in the detergent must be at least 60% (in terms of carbon dioxide) or 70% (in terms of total organic carbon) within 28 days.

In cases where the level of complete biodegradability of surfactants contained in a detergent is less than 60% (based on carbon dioxide) or 70% (based on total organic carbon), the requirement for primary biodegradability of surfactants contained in the detergent shall apply

to industrial detergents.

The primary biodegradability of surfactants in detergents shall be at least 80% (*On the Approval…, 2008*).

Detergents, including laundry powders, are subject to restrictions on the content of phosphates and other phosphorus compounds (*Table 2*) (*On the Approval…, 2008*).

According to DSTU 2972:2010, "Synthetic Powdered Detergents. General Technical Requirements and Test Methods" (*2010*), laundry powders must meet the following requirements (*Table 3*).

According to DSTU 2972-2010 and the "Technical Regulations for Detergents" (*2008*), the labeling must include:

- name and trademark of the detergent;
- name, trademark, complete address, and telephone number of the manufacturer;
- information on the composition of the detergent;
- address, e-mail address (if available) and telephone number;
- rules and conditions of use and special precautions, if necessary;
- purpose of the powder;
- information on confirmation of conformity;
- net weight:
- date of manufacture and expiry date;
- designation of the regulatory document according to which the detergent is manufactured;
- EAN barcode.

In the EU, the safety and quality of detergents are regulated by Directive 648/2004 of the European Parliament and of the Council of 31 March 2004 on detergents. The hygienic safety of detergents in the EU is governed by the new chemicals' legislation REACH – a regulation of the European Union No 1907/2006, which defines the production and marketing of all chemical substances, including their mandatory registration. Since 2012, the EU has banned the sale of detergents for washing with a total phosphorus content of 0,5 g or more per wash in a standard washing machine (*Regulation…, 2006*).

Therefore, the requirements for the quality and safety of laundry detergents are established in the "Technical Regulations for Detergents," approved by the Cabinet of Ministers of Ukraine on August 20, 2008, No. 717, and DSTU 2972:2010 "Synthetic Powdered Detergents. General Technical Requirements and Test Methods" and are carefully monitored by the state. Requirements for the labeling and quality of laundry detergents are also outlined in the aforementioned regulatory documents. Laundry detergents must meet the latest organoleptic (appearance, color, odor) and physicochemical parameters: detergency, foam stability, foaming, and pH level.

A sociological survey of consumer preferences regarding laundry detergents

Laundry detergents are an integral part of household chemistry. While they simplify the washing process, they also raise concerns about their environmental and human health impact. Growing consumer awareness of environmental issues drives demand for safer and more effective laundry detergents. The purpose of this study is to examine consumer preferences

regarding laundry detergents. Specifically, we aim to determine the key criteria for choosing laundry detergent, how consumers assess the environmental characteristics of products, and their willingness to pay more for environmentally friendly products. A survey was conducted among 136 respondents using Google Forms to achieve the research goal.

The sociological survey involved consumers of laundry detergents, of which 67% were women (92) and 33% were men (44). By age, they were divided into three categories: 18-30 years – 68% of the total, 31-60 years – 23%; 61 years and older – 9%. Regarding average monthly income, 16% of respondents earn up to 10,000 UAH/month, 58% – up to 25,000 UAH/month, and 26% – more than 25,000 UAH/month.

The sociological survey revealed that laundry detergents from brands such as "Ariel," "Persil," "Gala," "Sila," "Sarma," and "Grunwald" received the highest rating on a 5-point scale (*Figure 3*). Consumer survey results also showed that laundry detergents from brands like "Losk" and Savex were in high demand, receiving a rating of 4,3 from consumers. Additionally, the survey found that 62% of consumers pay attention to the composition of laundry detergents, indicating consumer awareness when choosing a laundry detergent.

One key factor when choosing a laundry detergent is the type of fabric. Different fabrics have different structures and require different care. Therefore, laundry detergent manufacturers conduct numerous studies to determine which components and technologies are best suited for each type of fabric. In this regard, the questionnaire included questions regarding the importance of choosing the fabrics most frequently soiled. The survey results are presented in the appendix (*Figure 5*).

The survey found that consumers most frequently encounter stains on silk, flannel, cotton, and calico. Therefore, at this research stage, it is appropriate to present the results of a sociological survey regarding the most common types of stains on the aforementioned fabrics among consumers. The survey results are presented in the appendix (*Figure 6*).

Analysis of the survey results allowed us to identify the most common types of stains for different types of fabrics. Cotton fabrics most often have food stains (coffee, tea, juices, grease), grass, blood, and wine stains. This is due to the widespread use of cotton products in everyday life, particularly for cooking and outdoor activities. For synthetic fabrics, characteristic stains include cosmetics (mascara, lipstick), deodorants, as well as ink and marker stains. Such fabrics are often used for sportswear and everyday wear, which explains the specific nature of the stains. For woolen fabrics, the main problems are greasy stains, sweat stains, and moth damage. These stains require delicate removal to preserve the structure and appearance of woolen products. In addition to the main types of stains, color fading and graying after washing are a common problem for colored fabrics.

The survey results showed that Ukrainian consumers prefer laundry detergents in the middle price range. "Ariel," "Persil," "Gala," "Sila," "Sarma," and "Grunwald" were the most popular brands. Respondents appreciated the effectiveness of these detergents' stain removal and their hypoallergenic properties. Consumers face a wide range of stains, depending on the fabric type, lifestyle, and other factors. This indicates that modern laundry detergents should be universal and effectively cope with various types of stains. At the same time, about 30% of respondents noted that they would like to see more natural and environmentally friendly laundry detergents on the market. An analysis by age group showed that young people are more likely

to choose laundry detergents online, while older people prefer traditional formats. Social media and recommendations from friends were the primary sources of information about laundry detergents for most respondents.

A comparative study of the performance characteristics of different laundry detergents

According to the results of a sociological survey, it was established that consumers prefer the following brands, which were chosen among other samples for quality assessment (*Figure 7*):

- sample 1 – TM "Ariel" (Aqua powder. Bright colors);
- sample 2 – TM "Persil" (Expert color. Freshness);
- sample 3 – TM "Sila" (Spring Garden);
- sample 4 – TM "Sarma" (Active);
- sample 5 – TM "Gala" (Aqua powder. French aroma);
- sample 6 – TM "Grunwald" (Sapfir).

For the convenience of conducting research, samples of laundry detergents from brands "Ariel," "Persil," "Sila," "Sarma," and "Grunwald" were chosen as universal, meaning they can be used for both hand washing and machine washing. Laundry detergent from the brand "Gala" was selected in two different types (separately for machine washing and hand washing). This is due to the fact that the manufacturer does not produce a laundry detergent that can be used for both hand and machine washing simultaneously.

In the first stage of the research, the compliance of the laundry detergent labeling with the Technical Regulations for Detergents (*Table 4*) was determined.

Analyzing *Table 4*, it can be stated that all the studied laundry detergent samples meet the requirements of the Technical Regulations regarding labeling (*2008*). The packaging indicates the name and trademark, manufacturer and its address, composition, purpose, conditions of use, weight, date of manufacture, expiration date, and storage conditions.

The following research stage involved conducting an organoleptic evaluation of the laundry detergent samples according to DSTU 2972:2010 (*2010*). The evaluation was conducted at a room temperature of 20°C and under natural lighting. Thus, the obtained results can be considered reliable. The research results are presented in the appendix (*Table 5*).

The next step was to study the physicochemical indicators and compare them with the requirements of DSTU 2972:2010 (*Table 6*).

It was established that all the studied samples meet the requirements of DSTU 2972:2010. Samples 1 and 6 had the best solubility in hot water. The pH level was the same except for sample 6.

Samples 2 and 3 showed the best foam stability, and sample 5 had the best foaming ability.

Based on the results of a sociological survey, the following types of stains were selected for the study of laundry detergents' detergent properties: lipstick, grass, wine, blood, and deodorant (*Figure 8*).

An expert group of four individuals specializing in the evaluation of non-food products was formed to assess the cleaning performance of the selected laundry detergent samples. These experts were research associates from the Department of Commodity Science and Customs Affairs at the State University of Trade and Economics (SUTE). The removal of various types

of stains by the tested laundry detergent samples was evaluated using a developed 5-point scale:

5 – excellent stain removal without pre-soaking;

4 – leaves slight traces;

3 – requires pre-soaking;

2 – leaves visible stains;

1 – do not remove the stain.

When assessing the cleaning performance of the laundry detergent samples, the average score of all experts for each indicator was used.

The cleaning performance was evaluated after hand and machine washing at 30°C, a temperature selected according to each fabric type's recommendations.

The results of the cleaning performance assessment of laundry detergents on silk fabric are presented in the appendix (*Figure 9*).

The research results demonstrated that "Persil" was the most effective laundry detergent, regardless of the washing method or type of stain. However, it should be noted that for hand washing, "Persil" was most effective at removing deodorant from silk, while for machine washing, it excelled at removing blood and deodorant. Additionally, "Ariel" and "Gala" laundry detergents were quite effective for hand washing.

On the other hand, "Sarma" laundry detergent proved to be the least effective, performing poorly on all types of stains and fabrics. The results of the cleaning performance assessment of the tested samples on flannel are presented in the appendix (*Figure 10*).

It was established that Persil laundry detergent was the most effective at removing stains from flannel. All types of stains were completely removed when washing the tested samples in a washing machine. After washing (both by hand and in a washing machine) with "Ariel," "Sila," and "Gala" detergents, slight traces of stains remained on the fabric sample, which also indicates a fairly high cleaning performance. "Sarma" laundry detergent did not remove stains at all when hand washing, and visible stains remained after machine washing. This suggests that this laundry detergent is ineffective for washing flannel fabrics.

The results of the cleaning performance assessment of the tested samples on cotton are presented in the appendix (*Figure 11*).

The research results showed a trend similar to that observed for silk and flannel fabrics. For cotton, Persil proved to be the most effective detergent.

It completely removed grass, wine, blood, and deodorant stains from cotton fabric after machine washing. Lipstick stains were barely noticeable after washing. Additionally, Ariel detergent removed most of the aforementioned stains. "Sarma" detergent was the least effective, barely removing lipstick, grass, wine, and blood stains during hand washing.

However, when using this detergent in a washing machine, the stains were almost completely removed, although slight traces remained. "Sila," "Gala," and "Grunwald" laundry detergents also demonstrated fairly good cleaning performance. While they did not completely remove all stains, they were quite effective in both hand and machine washing.

The results of the cleaning performance assessment of the tested samples on linen are presented in the appendix (*Figure 12*).

It was established that "Persil" detergent was also the most effective for washing linen in a washing machine. When hand washing, it completely removed grass, wine, and deodorant stains.

In this case, "Ariel," "Sila," and "Gala" detergents were also effective. Similarly, "Sarma" was the least effective detergent. It barely removed any type of stain, except for deodorant.

As a result of the conducted research, the most significant factors enhancing the effectiveness of laundry detergents were identified in the appendix (*Figure 13*). It was established that foaming ability and foam stability are interrelated indicators. Foam creates a soft abrasive environment that helps to detach dirt from fabric fibers. Foam also contributes to the uniform distribution of detergent on the fabric surface, improving its interaction with contaminants. Additionally, foam creates a barrier between the metal parts of the washing machine and the fabric, reducing the risk of damage.

Another crucial factor directly influencing a laundry detergent's cleaning performance is solubility. Surfactants are primarily responsible for the detergent's cleaning action. The better they dissolve, the more effectively they wet the fabric, surround dirt particles, and detach them from the fibers. Dissolved surfactants form micelles – spherical structures that capture fat molecules and other contaminants, transforming them into an emulsion that can be easily rinsed off with water. Highly soluble detergent components ensure more efficient mixing with water, creating a homogeneous solution that promotes better stain removal. The dissolution rate of the detergent affects the speed at which the cleaning process begins. The faster the detergent dissolves, the faster stain removal starts.

Most surfactants in laundry detergents work best in an alkaline environment. Many stains (such as proteins and fats) dissolve better in alkaline conditions. This facilitates their removal from the fabric. An alkaline environment helps preserve bright colors and prevents yellowing of white fabrics. At low pH (acidic environment), the effectiveness of surfactants decreases, which can lead to insufficient stain removal. Additionally, an acidic environment can damage certain types of fabrics. An excessively high pH can damage fabrics, especially colored and delicate ones. Furthermore, excessive alkalinity can leave alkaline residues on the fabric, which can irritate the skin. The optimal pH for washing is usually in the range of 8-11. However, the specific optimal pH may vary depending on the type of fabric, the type of stain, and other factors.

One of the main factors directly influencing the enhanced effectiveness of laundry detergents is their composition. The optimal ratio of different components ensures effective removal of various types of stains. The choice of surfactants depends on the type of fabric, the type of stain, and the water temperature. Enzymes allow for the effective removal of complex organic contaminants but may be ineffective at low temperatures. Bleaches can damage colored fabrics, so their use is worth limiting. Water softeners improve the effectiveness of surfactants, while anti-scale agents prevent scale formation in the washing machine.

When choosing a laundry detergent, it is necessary to consider the type of fabric, the degree of soiling, the water temperature, and other factors. Some components of laundry detergents can cause allergic reactions, while others can negatively impact the environment. Based on the conducted research, the following recommendations have been formulated:

- Manufacturers are recommended to expand the range of laundry detergents, in particular, to develop products for the specific needs of consumers (e.g., for children's clothing, sportswear, delicate fabrics);
- The growing interest of consumers in environmentally friendly products requires

manufacturers to develop laundry detergents based on natural ingredients;

- The introduction of innovative technologies can allow for the creation of more effective and safe laundry detergents;
- An active marketing campaign that emphasizes the unique properties of the product and its advantages over competitors will help win over consumer loyalty.

Discussion

Promising directions for future research include a detailed study of the global laundry detergent market, specifically analyzing trends, innovations, and consumer preferences. Simultaneously, a comprehensive study of the quality and safety of phosphate-free detergents should be conducted, including an assessment of their cleaning ability, environmental impact, and human health effects, as well as a comparison with traditional detergents.

Particular attention will be paid to studying the composition of phosphate-free detergents, including the use of new, more environmentally friendly surfactants and enzymes. Additionally, the impact of various factors, such as water hardness, washing temperature, and fabric type, on the effectiveness of phosphate-free detergents will be evaluated. The research results will enable the development of recommendations for manufacturers and consumers aimed at improving the efficiency and safety of using laundry detergents.

A component of future research in this area will be the development of mathematical models for forecasting the development of the laundry detergent market, as well as studying consumer behavior and the factors influencing consumer choice.

Conclusions

The Ukrainian laundry detergent market is characterized by a significant presence of international corporations such as "Procter & Gamble," "Henkel," and "Unilever." While domestic producers are increasing their presence, they still occupy a smaller market share.

Most laundry detergents on the Ukrainian market have a similar chemical composition, based on synthetic anionic surfactants. This indicates general trends in the industry and a limited variety of offerings for consumers with specific needs (such as allergy sufferers or those who prefer environmentally friendly products).

A sociological survey revealed that the typical laundry detergent consumer in Ukraine is a woman aged 18-30 with a middle income. The most popular brands among respondents include "Ariel," "Persil," "Gala," "Sila," "Sarma," and "Grunwald."

Consumers primarily encounter food stains on cotton fabrics and cosmetic stains on synthetic materials. Laboratory tests have shown that Persil laundry detergent demonstrated the highest effectiveness in removing various types of stains from different fabrics.

Other popular brands also showed good results, especially "Ariel" and "Gala." "Sarma" laundry detergent proved to be the least effective.

Despite the dominance of international brands, there is potential for developing domestic manufacturers, who can meet the specific needs of consumers, such as offering more natural and hypoallergenic laundry products.

Conflict of interest

The author declares that there is no conflict of interest.

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Appendix

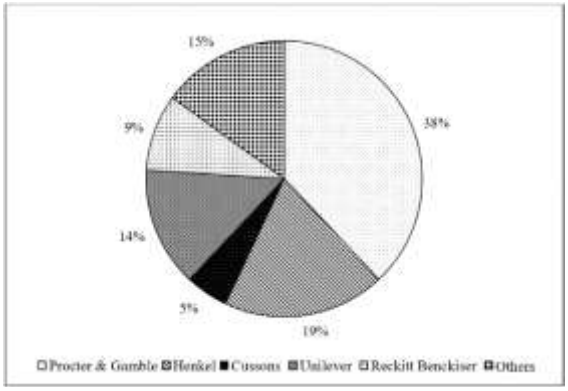

Figure 1. The share of the volume of imported manufacturers of washing powders in comparison with domestic ones on the Ukrainian market, 2024

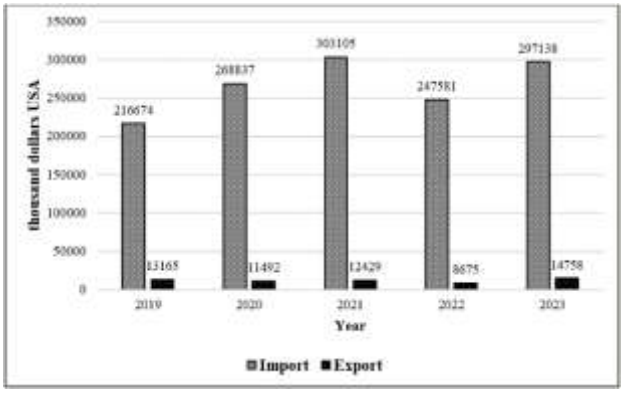

Figure 2. Dynamics of volumes of export-import transactions with laundry detergents in 2019-2023, thousand dollars USA

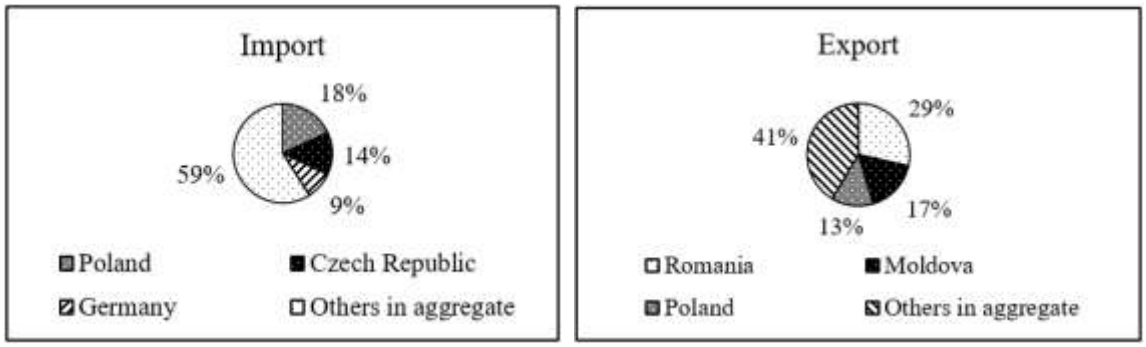

Figure 3. The share of the main importing and exporting countries of laundry detergents in Ukraine, 2024

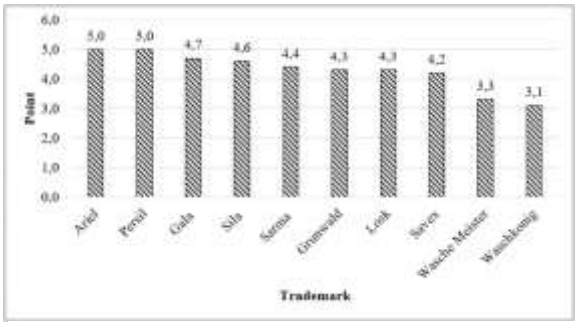

Figure 4. Rating of laundry detergent brands among surveyed consumers, 2024

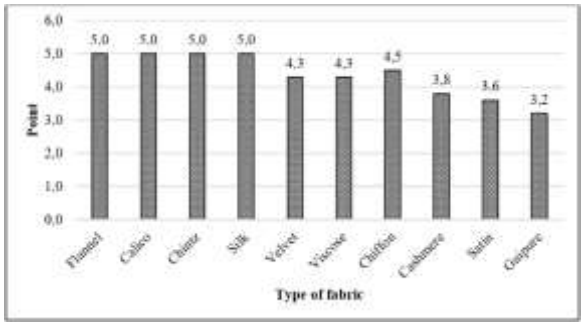

Figure 5. Rating of types of fabrics that are most often exposed to pollution, among surveyed consumers, 2024

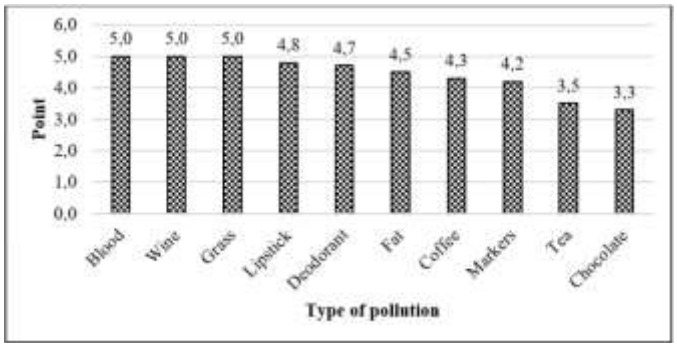

Figure 6. Rating of the most common types of pollution for different types of fabrics, among surveyed consumers, 2024

Figure 7. The appearance of selected investigated samples of washing powders

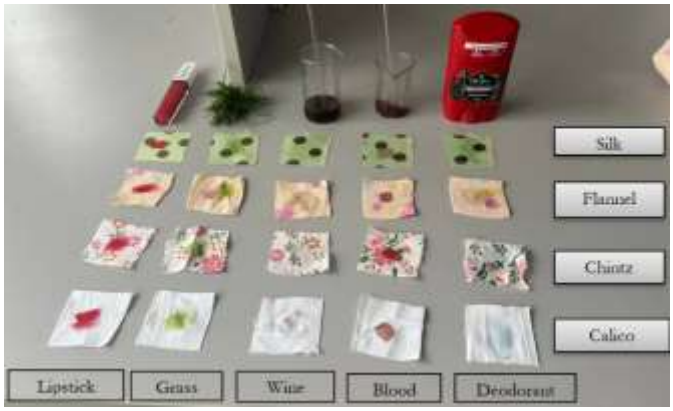

Figure 8. The appearance of selected types of stains for studying washing ability of laundry detergent

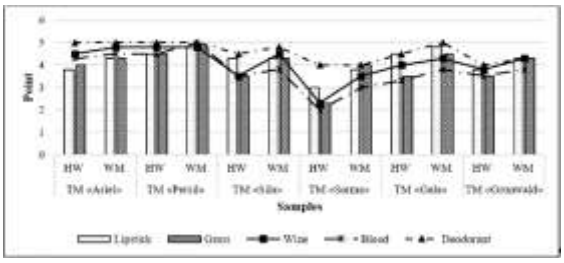

Figure 9. The results of the evaluation of the examined silk samples after HW and WM
* WM – washing in a washing machine
HW – hand washing

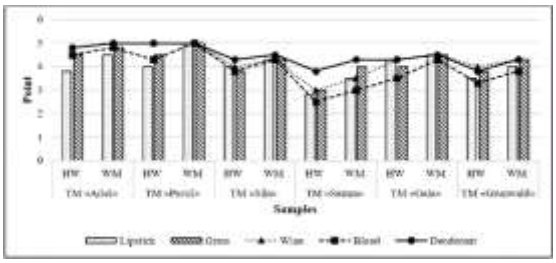

Figure 10. Results of evaluation of the tested flannel samples after HW and WM
* WM – washing in a washing machine
HW – hand washing

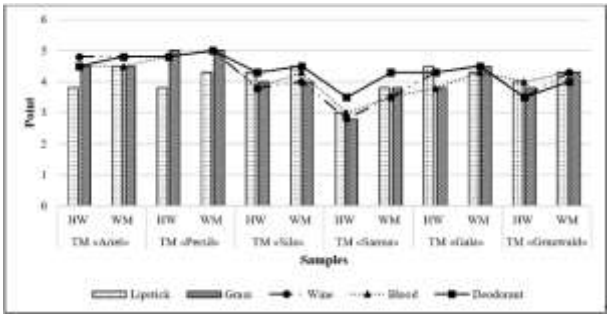

Figure 11. Evaluation results of the tested chintz samples after HW and WM
* WM – washing in a washing machine
HW – hand washing

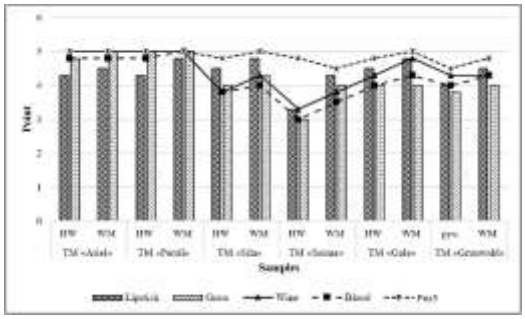

Figure 12. Evaluation results of the studied calico samples after HW and WM
* WM – washing in a washing machine
HW – hand washing

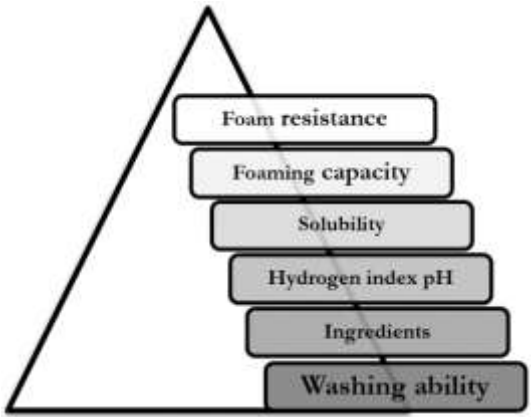

Figure 13. The significance of the main indicators of increasing the effectiveness of laundry detergent

Table 1. Classification of laundry detergents according to UCGFEA

Product code	Product description
3402	Surface-active organic substances (except soap); surface-active preparations, preparations for washing, washing (including auxiliary detergents) and cleaning preparations, whether or not containing soap (except preparations included in heading 3401):
[3402 3]	- anionic organic surfactants, whether or not put up for retail sale:
3402 31 00 00	- linear alkylbenzene sulfonic acids and their salts
3402 39	- others:
3402 39 10 00	- an aqueous solution of disodium alkyl [oxides (benzene sulfonate)] with a concentration of 30 wt.% or more, but not more than 50 wt.%
3402 39 90 00	- others
[3402 4]	- other surface-active substances, whether or not put up for retail sale:
3402 41 00	- cationic:
3402 41 00 10	- benzalkonium chloride (benzalkonium chloride INN)
3402 41 00 90	- others
3402 42 00 00	- non-ionic
3402 49 00 00	- others
3402 50	- means packaged for retail trade:
3402 50 10 00	- surfactants
3402 50 90 00	- detergents and cleaning products
3402 90	- others:
3402 90 10 00	- surfactants
3402 90 90 00	- detergents and cleaning products

Table 2. Restrictions on the content of phosphates and other phosphorus compounds in detergents

Name of the detergent	Restriction	Date of application of the restriction
1. Detergent for washing in household washing machines	- the total phosphorus content should not be equal to or exceed 0?2 grams in the recommended amount and/or dosage of the detergent for use in the main cycle of the washing process in hard water for the standard load of the washing machine for normally soiled fabrics in the case of using powerful detergents for lightly soiled fabrics in the case of using detergents for delicate fabrics	90 days after the termination or cancellation of martial law in Ukraine*
2. Detergent for washing in industrial washing machines	- the mass fraction of total phosphorus in the detergent should not amount to or exceed 0,1%	90 days after the termination or cancellation of martial law in Ukraine*
	- the mass fraction of total phosphorus in the detergent should not be equal to or exceed 0,05%	from December 31, 2026*
3. Detergent for hand washing, washing and cleaning	- the mass fraction of total phosphorus in the detergent should not be equal to or exceed 0,05%	90 days after the termination or cancellation of martial law in Ukraine*
4. Detergent for household dishwashers	- the total phosphorus content should not be equal to or exceed 0,1 grams in a standard dose of detergent for use in the main wash cycle for loading a dishwasher with a table set for 12 people	90 days after the termination or cancellation of martial law in Ukraine*
5. Detergent for industrial dishwashers	- the mass fraction of total phosphorus in the detergent should not be equal to or exceed 0,25%	90 days after the termination or cancellation of martial law in Ukraine*
	- the mass fraction of total phosphorus in the detergent should not amount to or exceed 0,1%	from December 31, 2026*
6. Another detergent	- the mass fraction of total phosphorus in the detergent should not be equal to or exceed 0,05%	90 days after the termination or

		cancellation of martial law in Ukraine*

* Voluntary application of established restrictions is possible before the date of their application.

Table 3. Indicators of the quality of laundry detergents

Name of the indicator	***Norm***	***Control method***
Appearance	Granules or powder	According to Clause 5.1 of DSTU 2972:2010
Washing ability, %, not less than	85	According to DSTU 2665
Indicator of the concentration of hydrogen ions, pH: - for washing products made of cotton and linen fabrics;	10,5-11,5	According to DSTU 2207.1
- for washing products made of mixed fabrics;	9,0-10,7	
- for washing products made of wool, silk, artificial and synthetic fabrics	7,5-9,0	
Foaming capacity: foam height, cm	20	According to DSTU 2207.1

Table 4. Conformity of labeling of washing powders to the Technical Regulation of detergents

Indicator	Sample					
	№1	№2	№3	№4	№5	№6
Trademark	Ariel	Persil	Sila	Sarma	Gala	Grunwald
Appointment	For washing products made of mixed fabrics	For all types of fabrics, except silk and wool	For all types of fabrics, except silk and wool	For all types of fabrics, except silk and wool	For all types of fabrics, except silk and wool	For all types of fabrics, except silk and wool
Ingredients	5-15% Anionic surfactants, <5% nonionic surfactants, bleaches, phosphonates, polycarboxylates, zeolites, enzymes, flavors	5-15% anionic surfactants, < 5% nonionic surfactants, phosphonates, polycarboxylates, zeolites, flavors, enzymes	>30%: sodium sulfate; 5-15%: anionic surfactants, sodium carbonate, sodium silicate, antiresorbents; <5%: fragrance, optical brightener	> 30%) sulfates; (5-15%) carbonates, anionic surfactants, silicates, oxygen-containing bleach; (< 5 %) polycarboxylates, defoamer	5-15% anionic surfactants, <5% nonionic surfactants, polycarboxylates, enzymes, optical brighteners, flavors, hexylcinnamic aldehyde	>30% sodium chloride; 15-30% sodium carbonate; 5-15% sodium silicate; <5% sodium percarbonate, anionic surfactants
Address	Procter & Gamble-Rakona, s.r.o.., Ottova 402, 269 32 Rakovnik, Czech Republic	Henkel Poland Operations, 02-672, m. Warsaw, str. Domanievska, 41, Poland	LLC "Slobozhansky Mylovar", 62371, Kharkiv Region with. Yards. St. Sumy Shlyach, 53, Ukraine	"ATHENA GROUP? LLC, 37 Zaporizhia Highway, m. Dnipro, 49000, Ukraine	Procter & Gamble Ukraine LLC, 08304, Kyiv region, m. Boryspil, str. Zavokzalna, 2, Ukraine	TPP "Velvet Bis" LLC, 85-825, m. Bydgoszcz, str. Voyska Polskigo, 65, Poland
Terms of use	Avoid contact with eyes, use personal protective equipment. In case of contact with eyes, rinse with water for 10-15 minutes. Protect from children					
Net mass, g	300	300	350	400	300	350
Date of	07.10.24	07.10.24	18.09.24	09.09.23	10.10.24	15.05.24

manufacture						
Expiry date, months.	24	36	60	36	24	60
Storage conditions	at a temperature no higher than 35ºC and a relative humidity of no more than 95%					

Table 5. Organoleptic evaluation of laundry detergent

Sample	Appearance	Color	Odor
Standard according to DSTU 2972:2010	The powder is coarse-grained or fine-grained, the presence of colored granules is allowed	Corresponds to the color indicated on the package, usually white	Corresponds to the smell indicated on the package, not sharp
№1	The powder is coarse-grained, multi-colored granules are present	White	Pleasant odor of freshness, not sharp
№2	The powder is coarse-grained, multi-colored granules are present		Pleasant odor of flowers, not sharp
№3	Powder with granules of different sizes, blue granules are available		A pleasant odor of a spring garden, not sharp
№4	The powder is fine-grained, lumps are present		A sharp unpleasant odor
№5	The powder is fine-grained, blue granules are present		Pleasant odor of perfume, not sharp
№6	The powder is fine-grained, green granules are present		Pleasant odor of flowers, not sharp

Table 6. Research of physico-chemical indicators of the quality of laundry detergent

Indicator	Sample					
	№1	№2	№3	№4	№5	№6
Solubility in hot/cold water, min	1,5 / 8	3 / 9	1,5 / 6	3 / 7	1,5/ 7	1 / 6
Hydrogen index pH	10	10	10	10	10	11
Foam resistance, %	72,7	76,9	76,6	61,5	72,7	72,7
Foaming capacity, см	2	3	5	4	7	5

Olena M. Yarmak [10], *Serhii F. Kostiv* [11]

Gender characteristics of the response of the cardiovascular system in military personnel to various types of physical exertion [7]

Abstract: The authors present a comparative analysis of the cardiovascular system response in 63 military personnel (32 men and 31 women) during orthostatic, isometric, and hypoxic functional tests. The study aimed to identify gender differences in response to various types of physical exertion. To achieve this goal, theoretical research methods, physiological measurement techniques, and mathematical statistics were employed. The findings underwent comparative analysis, revealing that men had an average systolic blood pressure of 156.6 ± 24.43 mm Hg during isometric loading, while women recorded an average of 143.6 ± 11.85 mm Hg ($p = 0.01$). The diastolic pressure in men reached 107.1 ± 13.95 mm Hg, whereas in women, it was 96.5 ± 6.11 mm Hg ($p = 0.001$). In the hypoxic test, men demonstrated an average systolic blood pressure of 148.0 ± 20.61 mm Hg; for women, it was 130.6 ± 10.84 mm Hg ($p = 0.001$). Similar results were obtained in the comparative analysis of indicators during the orthostatic test. These data indicate a higher cardiovascular reactivity in men, which may reflect differences in adaptive mechanisms between gender groups among military personnel. The results underscore the importance of considering gender-specific characteristics in designing physical training programs for military personnel to ensure optimal physical loads and minimise risks of cardiovascular strain, particularly for men.

Keywords: military staff, gender differences, isometric load, hypoxic test, orthostatic test, blood pressure.

Abbreviations:
AFU is Armed Forces of Ukraine
BP is blood pressure
HR is heart rate

Introduction

The relevance of the study of gender characteristics of the reactions of the cardiovascular system of military personnel to various types of physical activity is due to the need to optimise physical training in the AFU. Physical activity, which varies in intensity and nature, initiates specific adaptive responses of the cardiovascular system, which can differ significantly in men and women. Given the significant increase in the role of women in modern AFU, understanding the gender characteristics of the cardiovascular system's response to physical activity is important for developing effective and safe individual training programmes that will help increase the combat capability of military personnel and reduce the risk of injuries. Also, considering gender differences will not only optimise the level of physical fitness but also make it possible to develop the body's adaptive capabilities, ensuring a more stable functioning of the cardiovascular system in conditions of high physical and psychoemotional loads.

For a comprehensive approach to the study of this issue, we conducted a detailed analysis of the scientific and methodological literature; we paid particular attention to scientific research involving young men and women who performed various types of physical activity (*Linde et al., 2018*; *Hnatkova et al., 2019*; *Ferreira et al., 2022*; *Ferreira et al., 2024*). Scientific papers that indicate gender differences in functional tests are considered in more detail. Studies conducted (*Guenette*

et al., 2010; *Hunter et al., 2016*) suggest that women's diaphragms show higher resistance to respiratory muscle fatigue compared to men during endurance exercises. At the same time, according to the data (*Sheel et al., 2008*), women have smaller airway and lung volumes, such as lower rates of maximum exhalation at rest compared to men. As a result, women use up most of their respiratory reserve and have a higher metabolic cost of breathing. This fact has been confirmed in studies, which found that in women, during high-intensity physical activity, the respiratory muscles consume the greatest proportion of oxygen.

Based on the study's results (*O'Toole et al., 1989*), cardiac output increases proportionately to increased oxygen consumption during the acute phase of dynamic exercise. The mechanisms by which cardiac output increases during exercise may differ in men and women. However, despite some physiological differences that may affect the mechanism of changes, the overall response of the cardiovascular system to physical activity is similar in both sexes. However, studies conducted revealed gender differences in the cardiovascular system's response to different types of physical activity. Men had significantly higher absolute systolic blood pressure values at 50%, 75% to 100% peak heart rate in all modalities ($p < 0.05$). However, gender differences in systolic blood pressure responses varied when considering body weight, body surface area, and fat-free body weight.

Based on research results (*Barreto et al., 2015*), women had a more robust systolic blood pressure response under moderate intensity of physical activity, while men had less pronounced such reactions, regardless of the complexity of the exercise. The diastolic and mean blood pressure reactions were similar, but statistical significance for these indicators was not achieved. The results show that women usually show more pronounced cardiovascular responses to exercise.

When analysing the scientific literature, we found conflicting data, so according to the results of a pedagogical experiment (*Melrose, 2005*) involving 16 women and 15 men (mean age 22.6 ± 4.2 years), two isometric tests were performed at the level of 40% of the maximum. Participants performed the exercises in two different starting body positions. The results showed that men showed significantly higher values of mean blood pressure and diastolic blood pressure during exercise and recovery, regardless of body position. Gender differences in the cardiovascular response to relatively low levels of isometric exercise are a significant factor to consider when developing fitness programmes.

The study that was conducted (*Masatli et al., 2018*) implemented interval training protocols (+Gz; +2gz) under artificial gravity with blood pressure and heart rate detection; the study participants were 16 men and 12 women (mean age 28.4 ±5.3 years). The results showed that the +Gz and +2gz protocols were more effective in stimulating the cardiovascular system for women than men, especially during the exercise phases. Women experienced an increase in diastolic blood pressure at all stages, especially during the +2gz phases. At the same time, the authors of the study believe that in order to achieve the necessary cardiovascular responses that contribute to overcoming orthostatic instability when restoring the influence of normal gravity, it is advisable to use modified or individualised +Gz profiles, which is confirmed by the results of previous studies using artificial gravity (*Goswami et al., 2015*). Results obtained by a group of scientists (*Cheng et al., 2011*) indicate that during orthostatic exercise, women have more autonomic reactions than men. Women have a more active parasympathetic system, higher

estrogen levels, and a lower centre of gravity. Thus, women are less effective at compensating for changes in blood pressure in response to an orthostatic test.

Thus, despite significant progress in research on the physiological mechanisms of adaptation to physical exertion, gender differences in cardiovascular response remain poorly understood, especially in the context of military service.

The study aimed to conduct a comparative analysis of the cardiovascular system's response in men and women based on the results of orthostatic, hypoxic, and isometric tests to determine gender differences.

The study involved 63 military personnel, including 31 women and 32 men, with an average age of 32.8 ±2.4 years. The criteria for inclusion in the pedagogical experiment were an average level of physical fitness that meets the requirements of military service, the absence of acute or chronic diseases of the cardiovascular and respiratory systems, voluntary consent to participate in the study, and experience in performing physical activities similar to those provided for in the conditions of the pedagogical experiment.

Methods

To elucidate existing approaches and research results related to gender differences in cardiovascular responses to different types of physical activity, we conducted a systematic review of current scientific publications, which allowed us to identify theoretical concepts and methodological approaches in this area, as well as identify scientific gaps that require further research. We paid particular attention to gender differences in the mechanisms of adaptation of the cardiovascular system to isometric and orthostatic loads, which allowed us to formulate topical issues for further experimental studies. In addition, the analysis of modern literature allowed us to form the basis for functional tests that do not require additional diagnostic equipment and are pretty simple and convenient for practical use while providing high information content of the results.

To determine gender differences in cardiovascular function during different types of physical activity, we used three functional tests: orthostatic, hypoxic, and isometric. A detailed description of the diagnostic equipment, the sequence of conducting these samples and the gradation scale is presented in the authors' work (*Petrachkov & Yarmak, 2023*).

The results were analysed using Statistica 10.0 software. Descriptive and inference statistics methods were used to determine the reliability of differences between sample indicators. For independent samples, group mean values were compared using the student's t-test. The critical significance level (p) was assumed to be 0.05.

Results

The data we obtained, presented in the appendix (*Table 1*), show some sex differences in military personnel in the cardiovascular system response during the orthostatic test. However, there are also similar reactions of the body to changes in the initial position of the body. Thus, systolic and diastolic blood pressure indicators in the body's horizontal position indicate no significant differences between men and women. In particular, the average value of systolic blood pressure in the group of men was 125.4 ± 16.16 mm Hg, and the group in women – 121.3 ± 9.55 mm Hg (t=-1.33; p=0.19), which is not statistically significant. Similarly, the obtained

values of diastolic blood pressure in the horizontal position of the body were similar in both sex groups: 81.1 ± 12.57 mm Hg in men and 82.3 ± 7.95 mm Hg in women ($t = 0.48$; $p = 0.63$).

When moving to an upright body position, significant gender differences in systolic and diastolic blood pressure were found. In men, systolic blood pressure increased to 149.0 ± 22.27 mm Hg, while in women only up to 124.3 ± 11.78 mm Hg, which is a statistically significant difference ($t = -5.92$; $p < 0.001$). Similar results are observed in the reaction of diastolic blood pressure; the average group indicator in men in an upright body position was 99.9 ± 17.81 mm Hg compared to 86.1 ± 7.12 mm Hg in women ($t = -4.33$; $p < 0.001$). The results may indicate a more pronounced vascular response and adaptation of the cardiovascular system in men to orthostatic stress.

Regarding the heart rate, in the horizontal position, this indicator in men was 72.2 ± 8.90 beats·min-1, while in women – 74.4 ± 22.60 beats·min^{-1} ($t = 0.54$; $p = 0.63$), which is also not statistically significant. When moving to an upright body position, the heart rate in men increased to 86.0 ± 12.39 beats·min^{-1}, and in women to 83.2 ± 17.14 beats·min^{-1} ($t = -0.78$; $p = 0.53$), which also does not show significant differences between the sex groups. However, it is worth noting that the orthostatic increase in heart rate, which indicates the adaptation of the cardiovascular system to changes in body position, in men was 13.8 ± 2.11 beats·min^{-1}, while in women it was lower than 8.7 ± 2.19 beats·min^{-1} ($t = -4.81$; $p < 0.001$). Our results indicate a more pronounced orthostatic response in men, possibly due to the peculiarities of physiological adaptation to orthostatic stress.

The results obtained indicate that gender differences exist in the cardiovascular system's response to orthostatic load, which should be taken into account when organising physical activity and training for military personnel of different sexes.

(*Table 2*) shows the results of indicators of the cardiovascular system of military personnel of men and women during the performance of two functional tests, a test with local isometric load and a hypoxic test. According to the data obtained, there are statistically significant ($p<0.05$; $p<0.01$; $p<0.001$) gender differences in the responses of the cardiovascular system, which indicates the specifics of the body's adaptation to different types of exercise in representatives of different sexes.

When performing the test with a local isometric load, men recorded higher systolic blood pressure values of 156.6 ± 24.43 mm Hg compared to women, whose indicator was 143.6 ± 11.85 mm Hg ($t = -2.77$; $p = 0.01$). The results may indicate a more pronounced blood pressure response in men to local static load. Also, diastolic blood pressure in men was significantly higher; the average group result was 107.1 ± 13.95 mm Hg in women; this indicator corresponded to 96.5 ± 6.11 mm Hg ($t = -4.04$; $p < 0.001$). The heart rate during isometric exercise was also statistically significantly higher in men at 95.0 ± 18.66 beats·min^{-1}, compared to 87.1 ± 11.30 beats·min^{-1} in women ($t = -2.10$; $p = 0.04$). The average blood pressure in men was also higher and corresponded to 123.6 ± 16.21 mm Hg in women; this value was 112.0 ± 4.48 mm Hg ($t = -2.11$; $p = 0.04$). The results indicate that in men when performing local isometric loads of 50% of the maximum, mechanisms that contribute to a greater increase in blood pressure may be due to physiological differences or a stressful state.

Comparative results of the hypoxic test analysis also revealed significant differences. The mean Group value of systolic blood pressure in men was significantly higher and was 148.0 ±

20.61 mm Hg; in women, by almost 18 mm Hg, it was smaller and was 130.6 ± 10.84 mm Hg ($t = -3.98$; $p < 0.001$). The average group diastolic blood pressure was also significantly higher in men and was 100.8 ± 14.75 mm Hg compared to 85.6 ± 5.89 mm Hg in women ($t = -5.07$; $p < 0.001$). However, the heart rate in men was 77.4 ± 18.37 beats·min^{-1}, which did not show a significant difference with the indicator in women (72.4 ± 5.87 beats·min^{-1}, $t = -1.34$; $p = 0.18$). It is also worth noting that the average group indicator of average blood pressure in men was also higher (116.5 ± 16.17 mm Hg) compared to women (98.3 ± 2.75 mm Hg, $t = -3.34$; $p = 0.01$).

So, comparative analysis of the results allows us to establish that men show higher average group results in most of the studied indicators during the performance of functional tests, particularly with local isometric and hypoxic load. Reactivity of the cardiovascular system is manifested by a significant increase in systolic and diastolic blood pressure, average blood pressure, and heart rate in response to these loads, which may be due to physiological differences in vascular and neuromuscular control between the sexual groups of military personnel.

Discussion

Undoubtedly, the relevance of the chosen topic of scientific research is due to the growing role of women in the armed forces of Ukraine and the need to develop individual approaches to the intensity of physical activity during practical physical training classes. An analysis of the scientific literature shows that although the physiological adaptations of the cardiovascular system to exercise are similar in men and women, there are significant gender differences that affect their reactivity in response to different types of physical activity and conditions. Some studies point to higher respiratory muscle stability in women (*Guenette et al., 2010*), while others highlight a greater tendency for men to increase systolic pressure during intense physical activity (*Gilbert et al., 1991*). Taking into account such differences is an important aspect that can help optimise approaches to physical training, ensuring individualisation of programs and improving the health safety of military personnel of both sexes. In addition, a review of the scientific and methodological literature allowed us to justify the choice of functional tests that are convenient and accessible for use in military service and provide high information content for the results.

A comparative analysis of the data obtained by the US revealed some gender differences in the response of the cardiovascular system to the orthostatic test. In the horizontal position of the body, there were no significant differences in the indicators of systolic and diastolic blood pressure. In the vertical position of the body, a significant increase in systolic blood pressure was found in men compared to women, which indicates a more pronounced vascular response in men to orthostatic load. The increase in heart rate during changes in the initial body position was also significantly higher in men, which may indicate the specifics of adapting the cardiovascular system to stressful conditions.

With a local isometric load of 50% of the maximum, there were significant gender differences in blood pressure indicators. This indicates a more intense vascular response in men, possibly due to physiological characteristics or the influence of stress factors. Analysis of the hypoxic test also revealed significant gender differences, in particular in the indicators of systolic and diastolic blood pressure, which indicates different levels of adaptation of the cardiovascular system in men and women during hypoxic exercise.

Thus, the study's results confirm the presence of gender differences in the cardiovascular system's responses to different types of physical activity, which should be considered when organising physical training classes for military personnel, especially men.

The prospects for further research will be aimed at studying the gender characteristics of the adaptive capabilities of the body under stress, in particular during physical and psychological stress that occurs in various situations of military activity.

Conclusion

The results obtained in a pedagogical experiment indicate that men's cardiovascular systems adapt to various types of physical activity through more pronounced sympathetic activation, which causes an increase in blood pressure and heart rate. In women, there is a less intense reaction, which can be due to both morphological features and hormonal factors that affect vascular tone and the function of the cardiovascular system.

The scientific data we have obtained are of practical importance, as they emphasise the importance of gender mainstreaming in the planning and implementation of physical training programs in military units. Considering gender differences will allow us to more accurately assess the functional capabilities of military personnel and ensure optimal physical activity. As a result, it will help reduce the risks of overloading the cardiovascular system in men and contribute to improving the effectiveness of the training process.

Conflict of interest

The author declares that there is no conflict of interest.

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Appendix

Table 1. The results of the reaction of the cardiovascular system during the orthostatic test in military personnel of two sex groups, ($n = 63$)

Studied indicators	People, (n=32)		Women, (n=31)		t	p
	$\bar{x}$	S	$\bar{x}$	S		
BP systolic in a horizontal body position, mm Hg	125,4	16,16	121,3	9,55	-1,33	0,19
BP diastolic in a horizontal body position, mm Hg	81,1	12,57	82,3	7,95	0,48	0,63
BP systolic in a vertical body position, mm Hg	149,0	22,27	124,3***	11,78	-5,92	0,001
BP diastolic in a vertical body position, mm Hg	99,9	17,81	86,1***	7,12	-4,33	0,001
HR in the horizontal position of the body, beats·min^{-1}	72,2	8,90	74,4	22,60	0,54	0,63
HR in the vertical position of the body, beats·min^{-1}	86,0	12,39	83,2	17,14	-0,78	0,53
Orthostatic test, beats·min^{-1}	13,8	2,11	8,7***	2,19	-4,81	0,001

Note: Verification of significant differences in the student's parametric t-criterion for independent samples between the results of performing an orthostatic test of military personnel of different sex groups, $^{***}p < 0{,}001$

Table 2. The results of indicators of the cardiovascular system during functional tests in military personnel of two sex groups, ($n = 63$)

Studied indicators	People, (n=32)	Women, (n=31)	t	p

	$\bar{x}$	S	$\bar{x}$	S		
Sample with local isometric load						
BP systolic, mm Hg	156,6	24,43	143,6**	11,85	-2,77	0,01
BP diastolic, mm Hg	107,1	13,95	96,5***	6,11	-4,04	0,001
HR, beats·min^{-1}	95,0	18,66	87,1*	11,30	-2,10	0,04
Average blood pressure, mmHg	123,6	16,21	112,0*	4,48	-2,11	0,04
Hypoxic test						
BP systolic, mm Hg	148,0	20,61	130,6***	10,84	-3,98	0,001
BP diastolic, mm Hg	100,8	14,75	85,6***	5,89	-5,07	0,001
HR, beats·min^{-1}	77,4	18,37	72,4	5,87	-1,34	0,18
Average blood pressure, mm Hg	116,5	16,17	98,3**	2,75	-3,34	0,01

Note: Verification of significant differences in the student's parametric t-criterion for independent samples between the results of performing functional tests of military personnel of different sex groups, $^{*}p < 0{,}05$; $^{**}p < 0{,}01$; $^{***}p < 0{,}001$.

Viktoria V. Veselova [12]

Historical aspects, activities and role of volunteers during multi-sport events [8]

Abstract: The Volunteer Movement has become integral to organising and conducting multi-sport events such as the European Games, the Olympic Games, and the World Beach Games for decades. Volunteers are people of different ages, professions, and faiths who, by their vocation, sacrifice some of their strength, skills, and time for the sake of public interests and achieving a common goal. The study aimed to consider the historical aspects and basic principles of the volunteer movement at international multisport sports events and its components to determine the main areas of activity of volunteers and their motivation to volunteer. The study subject was aspects of volunteer activity in organising sports events. The study object was volunteering to organise and conduct multisport events. Such research methods as analysis and generalisation of sources of unique literature found on the Internet, historical cognition, structural and functional analysis, and observation were used. The scientific novelty of the work consists of substantiating the organisational and methodological foundations for attracting sports volunteers to conduct multisport events, determining the main activities of volunteers and their motivation for this activity. The work's practical significance substantiates ways to attract volunteers to organise and conduct international mass sports events in Ukraine and disseminate information among the population.

Keywords: volunteer, volunteer activity in sports, volunteer activity in multisport events, Olympic Games.

Abbreviations:

EOC is European Olympic Committee

IOC is International Olympic Committee

Volunteering as an international social phenomenon

The volunteer movement has a long history that goes back to ancient times. From simply helping one person or family, it has become an international movement regulated at the legislative level by states and large, world-famous organisations (IOC, EOC).

In modern society, volunteering is a global process that unites people who have the right to benefit from it both in their own country and internationally.

Most people have always been willing to help others by pursuing self-realisation, self-improvement, and activities that benefit others (*Lyakh, 2004*).

Volunteering is inextricably linked to the development of civilisation as a social and cultural phenomenon characterised by voluntary and selfless assistance.

The volunteer movement is a humanistic and socially significant activity aimed at helping others. Volunteering is based on the principles of charity, on a gratuitous basis, does not provide for career growth in the principal place of activity and is aimed at the well-being and prosperity of society as a whole (*Vainola et al., 1999*; *Traktat, 2016*).

Individuals and organisations can perform volunteer activities (French "volontaire" is volunteer, the free expression of will; volō-desire, intention).

The volunteer movement is an integral part of many social processes worldwide, including those in sports.

Volunteer activities are now becoming increasingly popular and crucial in almost all countries. At the same time, today, volunteers are significantly expanding their assistance areas.

Summer and Winter Olympic Games, summer and Winter Youth Olympic Games (*The International Olympic Committee…, 2021*; *The European Olympic Committees…, 2024*), European Games, European Youth Olympic festivals (*The International Olympic Committee…, 2021*; *The European Olympic Committees…, 2024*), other multisport competitions, and even municipal races can not be imagined without the activity of volunteers, their number is constantly growing from games to games, their work is gaining a new quality, some volunteers are already becoming permanent participants in this movement, passing on their skills to newly involved volunteers.

Estimating volunteers' activities, economic, cultural, or political impact is difficult. Significant experience in such activities positively affects the volunteers and the city/state that conducts such sports competitions, which determines the relevance of this work (*Dikhtyarenko et al., 2024*).

Ukraine, we can say, for the first time, attracted large-scale volunteers during the 2012 European Football Championship Euro 2012, which was held in Kyiv, Donetsk, Lviv, and Kharkiv, as well as in the largest cities of the Republic of Poland. Volunteers from Ukraine and representatives of the Ukrainian Diaspora acted as volunteers at the Olympic Games of different years together with representatives of other countries.

Historical milestones in the development of volunteering at the modern Olympic Games

Analysis and generalisation of data from specialised literature suggest that the history of Olympic volunteering is as old as the most modern Olympic Movement (*Levkov & Makuts, 2013*). The first volunteers are considered sponsors of the Athens Games of 1896, revived after a break of almost one and a half thousand years. Since the beginning of the modern Olympic Games, a person's contribution to developing the Olympic movement has been very diverse: selling tickets for sports competitions, participating in a solemn procession, working with athletes and spectators, etc. (*Olikh & Matviychuk, 2013*).

One of the first volunteers could be considered military, and scouts were responsible for spreading information about the games, ensuring order in stadiums, and helping to conduct competitions (in 1907, British Colonel R.S. Baden-Powell founded the World Youth Scout Movement).

In 1924, at the Olympic Games in Paris, Scouts first participated in the opening and closing ceremonies with the honorary mission of flag bearers.

After the end of the Second World War, new areas of activity were added, including assistance in preparing for competitions, providing athletes and spectators with information, restoring order on the field after competitions, assisting the police, working as translators, etc., which has already defined volunteers as an integral team of Olympic Games organisers.

At the 6th Winter Olympic Games of 1952 in Oslo, volunteers began participating in ticket verification, monitoring the situation during competitions, and technical work in various areas.

At the 16th Olympic Games in Melbourne in 1956, 250 female scouts accompanied and provided services to female athletes, and volunteers performed the duties of couriers, security guards, and drivers.

At the 18th Olympic Games in Rome in 1960, recruiting volunteers as translators was rigorous. Only young people with excellent command of French, English, and other languages were selected, and many volunteers contributed to the work of media representatives.

At the games of the 17th Olympic games of 1968 in Mexico, the duties of volunteers were added personal service on the principle of "one to one" of members of the NOC, heads of the Mexican Olympic organising committee, members of international sports organisations, heads of sports and cultural delegations, essential guests, and assistance to media representatives and others.

The official report on holding the 13th Winter Olympic Games in Lake Placid in 1980 stated: "If there were not 6,700 volunteers, the 13th Winter Olympic Games would not have ended" (*Levkov & Makuts, 2013*). The volunteers were people of various specialities, not only from the United States but also from other countries (*Spanoudakis, 2004*). Volunteers worked as translators, stopmasters, couriers, postmen, scribes, proofreaders, secretaries, etc. The work of volunteers was already regulated, uniform uniforms, food and accommodation were provided, and at the end of the Games, volunteers received certificates confirming their participation in the preparation and holding of the Games. It is safe to say that the scheme of volunteer work at the 1980 Olympic Games in Lake Placid later became widely used, especially at the subsequent 1984 Winter Olympics in Sarajevo.

About 30,000 volunteers worked at the 23rd Olympiad in 1984 in Los Angeles. The games largely depended on volunteers' activities.

The organisers of the games of the 29th Olympic Games in Beijing in 2008, among their other achievements, consider the work of the "volunteer team" brought to perfection. Here, the record for the number of volunteers was broken, involving almost the entire Chinese capital population: 70,000 worked at the Olympic Games and 30,000 at the Paralympic Games (*Brettell, 2001*). About 100,000 university students in Beijing, Hong Kong, Aomen, and Taiwan aged 18-25 were selected from 1.2 million applicants, older people and 22,000 foreigners. The main requirement for volunteers was knowledge of a foreign language, especially English, which has always been a big problem for the PRC.

The organising committee of the 21st Winter Olympic Games 2010 in Vancouver (VANOC) attracted about 25,000 volunteers from all Canadian provinces through the online campaign Callforvolunters launched two years before the start of the Games in Canada. The age of 19 as of September 01, 2008, has become mandatory for the selection of volunteers, "flexibility", diligence and enthusiasm, which corresponds to the slogan of these Olympic Games: "with burning hearts". They were involved in the maintenance of sports facilities, ticket sales for competitions, provided service in the Olympic Village, worked as guides for guests of the country, translators and technical staff of the press centre, and so on. About 1% of the volunteers were foreigners.

The organisers of the 30th Olympic Games 2012 games in London selected volunteers "from 18 and older", and the upper value did not matter. The management of the organising committee stated that the composition of Olympic volunteers fundamentally reflected the social and age diversity of residents of the United Kingdom, including the involvement of people with disabilities. All candidates must be familiar with the work of the PC, have oral and written communication skills, experience in a team, internal motivation (the embodiment of "passion,

enthusiasm and energy of games"), experience in medicine, working at sports facilities, service, modern technologies, media, logistics and accreditation.

At Pyeongchang's 23rd Winter Olympic Games 2018, almost 42,000 volunteers, including 16,200 residents, were selected. In the Olympic Village, nine assistants (volunteers) worked directly with the Ukrainian team: five Koreans and four Ukrainians.

The number of volunteers involved in the 32nd Olympic Games 2020 games in Tokyo was significantly less than expected. This is due to the introduction of quarantine measures in the land of the rising sun due to the COVID-19 pandemic, the inability of most foreign participants to get to Japan, and the refusal of about 10,000 Japanese people to volunteer. Despite this, the Games were held in 2021 and became a real celebration of Olympism.

The 24th Winter Olympics in Beijing employed more than 18,000 volunteers, of whom 94% were under 35 years of age. Volunteers from China worked with the Ukrainian team in three Olympic villages.

Until 1994, the Winter and Summer Olympic Games were held in Olin in the same year. After this date, the games are held every two years – winter and, two years later, summer (a four-year cycle for the Winter and Summer Olympic Games).

About 40,000 volunteers worked at the games of the 33rd Olympic Games in Paris in 2024.

The number of volunteers (*Table 1*) is approximate and rounded because different sources interpret different numbers.

Summing up the above, we can say that the volunteer sports movement has become very important since the 20th century. Volunteers began to work in a broader range of directions, and their number increased with each Olympic Games. The age of volunteers can be considered significantly younger in percentage terms, but the requirements do not determine the upper age limit of volunteers.

Stages of selection and distribution of volunteers by work area

The organisation and success of multisport events largely depend on volunteers' comprehensive and professional activities.

Several parameters can determine the mission directions of the Olympic movement's volunteer activities. Researchers M. Moragas, A. Moreno and R. Paniagua focus on the following (*Tomenko, 2016*):

- political (unity of actions of subjects united by a common goal, which is a form of participation of citizens in a significant public event);
- economic (the work of volunteers helps to reduce the cost of organising the Olympic Games, and trained volunteers will be able to work in other sectors of the economy);
- cultural (solidarity and cooperation of different people with different cultural frameworks);
- sports (promotion of sports, communication with athletes motivates young people to play sports, in turn, volunteers directly support athletes).

Volunteers make up a massive part of the additional force in all areas of the event's work, significantly affecting any sporting event's success.

The involvement of sports volunteers in organisations is preceded by careful preparation and analysis. The planning allows the event organising committee to fully formulate and specify

its vision and expectations from the work of volunteers. This makes it possible to understand the goals of attracting volunteers, predicting and eliminating potential risks in advance, and responding most adequately to emerging problems and ambiguities while minimising the amount of additional resources spent (*Dikhtyarenko et al., 2024*; *Lyakh, 2004*).

Of course, before you start working on attracting volunteers, you need to develop a clear plan. What age, qualifications, work areas to be responsible for, what time to work, training, selection of volunteers, uniforms, and so on? Also, an important role is played by identifying team leaders who will keep in touch with the Organising Committee of the games, convey the necessary information, and be responsible for the activities of the team's members.

The recruitment strategy depends on the expected volunteer work types and the organisation's programme/project specifics. If this is the holding of the Olympic Games or the European Games, then it is necessary to maximise internet resources and attract the media. This is the most effective way to attract volunteers instead of directly contacting potential candidates, especially regarding international multi-sport events.

Planning the company's start time plays an important role, with the announcement of recruitment of candidates for volunteers, questionnaires, determining their abilities and wishes for areas of work, creating certain groups and their distribution, identifying leaders, etc.

Usually, such work at multisport events, such as the Olympic Games, begins no later than two years before the event starts. Information can be found through search sites, on the official websites of the IOC, EOC or organising committees. The next SVT event will be the 25th Winter Olympic Games and the 2026 Paralympic Games in Milan-Cortina (Italy), and the selection of volunteers has already begun. All information can be found on the official website (*The Organizing Committee…, 2024*).

Each organising committee determines its selection stages. For example, the Organizing Committee of the 3rd European Games 2023 in Krakow (Republic of Poland) defined the following stages of volunteer selection (*Figure 1*) (*The Organizing Committee…, 2023*).

Recruitment of sports volunteers is an essential aspect of the organisation's volunteer management. This aims to select potential participants – volunteers of the organisation's program/project, corresponding to the developed and declared functions and qualities. It allows you to identify the applicant's compliance with the criteria of personal specification and professional and motivational suitability for a specific sports volunteer vacancy (*The Organizing Committee…, 2023*).

The selection of candidates involves obtaining sufficient information about them and deciding whether to invite them to an interview or refuse to.

For the selection of candidates for volunteers, the following methods are used:

(1) observation that can provide visual information about the volunteer candidate, namely the presence of sociability, features of the behaviour and interaction model, and communication style;
(2) questionnaires are the most common survey method in which communication is mediated by the text of a questionnaire aimed at identifying the quantitative and qualitative characteristics of a volunteer candidate;
(3) interviewing is an opportunity to obtain reliable examples that allow us to determine the level of developing the necessary competencies of candidates for sports volunteers;

(4) the interview completes the candidate selection process directly.

For example, volunteers at the 3rd European Games 2023 in Krakow were selected and worked in the following areas: accreditation, Anti-Doping ceremonies, VIP & Hospitality, logistics, marketing, mascot work, Media, NOC Assistant, Medical patrols, sports presentations, promotions, Ticket Sales, Logistics/Transport, venue assistant, Volunteer Center, Welcome desk Information, sports disciplines, Special Tasks, catering (*The Organizing Committee…, 2023*).

So, the volunteer movement needs appropriate organisation, planning, and distribution in areas. Candidates' involvement must be announced in advance due to particular stages in the time and organisation of selection. Each organising committee works out these issues according to the conditions of the event and many other organisational factors, including the number of participants and sports facilities.

Personality qualities of a sports volunteer and motivation

I.O. Kogut notes that volunteerism and voluntary choice reflect personal position – this is the basic principle of volunteering. The most crucial distinguishing feature of volunteering is the social significance of the work performed by volunteers (*Table 1*).

Undoubtedly, sports volunteering is one of the most common and popular types of volunteer activities. This activity aims to help organise and conduct sports events, promote the development of physical culture and sports, and attract the population, especially young people, to sports and physical education.

The social component of volunteers' activities implies the presence of such personal qualities that largely determine the effectiveness and success of their work, in particular:

(1) social activity: a creative, conscious attitude to life, society, and social values, which is reflected in activities that ensure professional self-realisation of the individual;
(2) tolerance: the desire to achieve mutual respect, understanding and agreement of different interests and views without applying pressure through methods of explanation and persuasion;
(3) empathy: the ability to understand the inner world of another person, penetrate their feelings, respond to them and empathise;
(4) altruism: the principle of a person's life orientation, according to which the good of another person is more important and meaningful than their own good and personal interests;
(5) moral responsibility: manifests itself in the tendency to perform their professional and social duties creatively and effectively;
(6) tolerance: the ability to correct your negative emotions and feelings, directing them in a constructive direction for positive motivation for further cooperation;
(7) communication: this is the process of interaction between people during which interpersonal relationships arise, manifest and Form (*Annaeva, 2014*; *Boyko, 2016*).

The basic requirements for a sports volunteer are:

- proactive, responsible and purposeful,
- available for the entire event period,
- positive and full of energy,
- at least 16 years old (18 years old),

- communication skills,
- willingness to help,
- organisational skills,
- team player,
- sufficient level of knowledge of the English language.

Also, in any volunteer environment, team leaders are specially selected to lead volunteers in the following areas.

To successfully work, encourage and motivate volunteers, they use:

- volunteer starter package (volunteer uniforms, gadgets, accreditation),
- accident insurance,
- training package,
- meals on task/work completion days,
- free public transport in the city where the games are held,
- accommodation for visiting volunteers (can be provided free of charge or on preferential commas),
- the Volunteer Center is responsible for the activities and support of volunteers,
- gift packages may include souvenirs provided by the Organising Committee,
- certificate of working at the Games as a volunteer.

During the closing ceremonies, the president of the International Olympic Committee or European Olympic committees thanks the volunteers for their outstanding role and selfless work in making the multi-sport event successful.

Conclusion

The modern sports volunteer movement is integral to organising and conducting multisport events. It is based on the principles of volunteerism, charity, and humanism and aims to improve the efficiency of sports competitions. The theoretical analysis conducted gives grounds to assert that a "sports volunteer" is a person who has received special training and carries out sports volunteer activities by assisting the organisation and conduct of competitions.

The purpose of the volunteer activity is to provide free assistance to improve the quality of the competition. This means that the unique knowledge, skills, and communication skills of sports volunteers are worth understanding, as are the types of volunteer activities and functions that volunteers perform during the preparation and conduct of competitions.

The number of volunteers involved and the range of their activities expands with each subsequent multisport event.

The content of a sports volunteer's functions and direction of activity depends on the level of their qualifications, knowledge of foreign languages, organisational skills, sports, and the specifics of competitions, particularly for people with disabilities.

Research on developing the volunteer movement, according to unique scientific and methodological literature and the Internet, shows that volunteers' activities play an important role because they allow not only to save a significant part of the budget for competitions (about 20%) but also to solve various tasks that the event's organising committee sets.

The mechanism of attracting sports volunteers to the volunteer movement, based on people's motivation to volunteer free work and the level of their special training, has some features compared to other social activities.

In modern conditions, the main ways to attract sports volunteers are television, websites of organising committees, public organisations, internet sources, social networks, information in public places, educational institutions, etc.

Sports volunteer activity affects the formation of personal qualities such as communication skills, social activity, responsibility, and the ability to plan activities and organise one's time.

Conflict of interest

The author declares that there is no conflict of interest.

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Appendix

Table 1. Winter and Summer Olympic Games, date and city/country, number of volunteers involved

Olympic Games	Summer/Winter	Year	Place	Volunteers
XIII	Winter	1980	Lake Placid, USA	6,703
XIV	Winter	1984	Sarajevo, Yugoslavia	10,540
XXIII	Summer	1984	Los Angeles, USA	28,742
XV	Winter	1988	Calgary, Canada	9,498
XXIV	Summer	1988	Seoul, Republic Of Korea	27,221
XVI	Winter	1992	Albertville, France	10,258
XXV	Summer	1992	Barcelona, Spain	34,548
XVII	Winter	1994	Lillehammer, Norway	9,054
XXVI	Summer	1996	Atlanta, USA	60,422
XVIII	Winter	1998	Nagano, Japan	32,578
XXVII	Summer	2000	Sydney, Australia	50,135
XIX	Winter	2002	Salk Lake City, USA	22,000
XXVIII	Summer	2004	Athens, Greece	50,840
XX	Winter	2006	Turin, Italy	25,500
XXIX	Summer	2008	Beijing, China	100,000
XXI	Winter	2010	Vancouver, Canada	25,000
XXX	Summer	2012	London, United Kingdom	70,000
XXII	Winter	2014	Sochi, Russia	25,000
XXXI	Summer	2016	Rio de Janeiro, Brazil	70,000
XXIII	Winter	2018	Pyeongchang, Republic Of Korea	41,350
XXXII	Summer	2020 (2021)	Tokyo, Japan	70,000
XXIV	Winter	2022	Beijing, China	18,000
XXXIII	Summer	2024	Paris, French Republic	45,000

Figure 1. Stages of selection of volunteers for the 3rd European games 2023 in Krakow (Republic of Poland)

Serhii O. Kradozhon [13], *Oleg V. Zamitsky* [14]

Hydro-gas dynamics and thermophysics of two-phase flows: Analysis and current research trends [9]

Abstract: Hydro-gas dynamics and thermophysics of two-phase flows are relevant due to their application in various industrial and energy processes. The study object is two-phase flows involving the interaction of liquid and gas. The study subject is the processes that occur during the simultaneous movement of gas and liquid phases in pipelines and heat engineering systems, like heat exchange mechanisms accompanied by phase transitions. The study aims to analyse current trends in modelling such systems to improve their efficiency. The main objectives are to study flow types, modelling methods, and heat exchange. The methods used include numerical modelling and experimental studies. The article uses the works of leading researchers, such as V.S. Karpov, S.P. Pavlov, and others. The study's main results are optimising heat exchange processes in systems with two-phase flows.

Keywords: two-phase flows, heat exchange, modelling, turbulence, phase transitions.

Introduction

Two-phase flows, including liquids and gases, play a pivotal role in many industrial and natural processes, particularly in power systems, heating plants, and chemical reactors. Studying these flows can improve the energy efficiency and reliability of such systems. The relevance of research in this area is due to the complexity of the interaction processes between phases, which requires the development of new models and modelling methods.

The study object is two-phase gas and liquid flows in pipeline systems and heat exchangers.

The study subject is the processes that occur during the simultaneous movement of gas and liquid phases in pipelines, heat engineering systems, and heat exchange mechanisms accompanied by phase transitions.

The study aims to study the mechanisms of heat exchange and the influence of various factors on the efficiency of heat transfer. It will also analyse the main mechanisms of hydro-gas dynamic interaction and heat exchange in two-phase flows that occur under the joint movement of the liquid and gas phases.

The main objectives are to study flow types, modelling methods, and heat exchange.

The methods used include numerical modelling and experimental studies.

The results of the study

Fundamentals of hydro-gas dynamics of two-phase flows

Hydro-gas dynamics of two-phase flows involve studying the movement and interaction of two phases (gas and liquid) that flow together through pipes or other channels. In this case, there may be different options for interaction between the phases, in particular:

- Parallel flow: liquid and gas flow together in the same pipe;
- Mixed flow: liquid and gas mix to form different flow structures, such as gas bubbles, foam, or aerosol;
- Clearly separated flow: liquid and gas flow in separate layers with minimal interaction.

One of the main challenges that engineers and researchers face when modelling two-phase flows is accurately predicting the effect of interfacial interactions on various flow parameters, such as velocity, pressure, temperature, and energy losses.

Models of hydrodynamics of two-phase flows can be based on such approaches as:

- "Uniform flow" models: assume that gas and liquid have the same speed and move as a single medium. Such models are useful for general estimates.
- "Inhomogeneous flow" models: consider the difference in the velocities and behaviour of each phase separately, allowing you to predict the flow dynamics more accurately.

Thermophysics of two-phase flows

Two-phase flow thermophysics studies heat transfer and thermodynamic processes that occur during the interaction of the gas and liquid phases. Due to the complexity of such systems, significant aspects are:

- One of the key processes in the thermophysics of two-phase flows is the transition phase between liquid and gas (e.g., boiling, condensation), accompanied by intense changes in the thermal properties of the medium;
- Convective heat exchange mechanism: in such systems, heat exchange often occurs due to convection, which is a complex process due to phase mixing and the formation of turbulent structures;
- The effects of surface phenomena, such as surface tension, capillary forces, and interfacial interactions at the microscopic level, can significantly affect heat transfer in two-phase flows.

Modern computational models of thermophysical processes of two-phase flows consider both phenomena at the macroscopic level (temperature distribution, velocity) and the microscopic level (interaction of molecules and phase transitions).

Analytical resume

Studying two-phase flows is a significant part of scientific research, and many papers have been devoted to developing new models and methods for calculating such processes. Here are a few areas that have received significant attention in the past and present century:

- Modelling of boiling and condensation in two-phase flows: one of the significant research topics since many power plants and industrial processes involve boiling processes (e.g., in nuclear reactors or cooling systems). The use of the two-phase flow model makes it possible to accurately predict temperature and heat losses, like determining the efficiency of such systems;
- Development of numerical methods for modelling two-phase flows: many dissertation studies focus on improving numerical methods (hydrodynamic and thermophysical modelling methods), such as finite element methods and methods for solving Navier-Stokes equations for two-phase media. They help to create more accurate models for predicting the behaviour of such flows in real-world conditions;
- Experimental studies of two-phase flows in various geometries allow us to assess the influence of pipeline geometry, flow rate, and other parameters on heat exchange efficiency

and flow dynamics. This is significant for developing new designs of heat exchangers and other heat engineering devices.

Recent studies, particularly dissertations (*Martynenko, 2022*), focus on a deeper study of turbulent two-phase flows, where intense turbulence significantly changes the heat transfer and dynamics of phase transitions. In particular, researchers such as V.S. Karpov and S.P. Pavlov (*2018*) offer new numerical models for predicting the behaviour of such flows under high temperatures and pressures, which are critical for nuclear and thermal power plants.

Interaction between phases and thermodynamic processes: I.V. Kozlov's work (*2019*) develops a detailed model of phase transitions and heat transfer in two-phase flows based on statistical methods. These studies allow us to create more accurate predictions for systems with high thermodynamic changes, such as boiling and condensation.

New approaches to heat exchange optimisation: modern works in thermophysics of two-phase flows, in particular, the dissertations of V.A. Kostenko (*2020*), devoted to improving heat exchange installations by numerical modelling and experiments with new materials that increase the efficiency of heat exchange in two-phase flows.

Modelling of two-phase flows on a microscopic scale: M.R. Nazarov's work (*2021*) uses molecular dynamical models to study phase transitions in bounded geometries, such as nanochannels, which opens up new horizons for developing technologies in microelectronics and nanotechnology.

A.V. Stepanov's article (*2019*) presents numerical methods for modelling phase transitions in two-phase flows, particularly boiling and condensation. Using finite element methods, the author develops new approaches to mathematically modelling flow behaviour in actual conditions. Special attention is paid to temperature gradients and the influence of pipe geometry on the phase distribution.

Yu. Baklanov's monograph (*2021*) presents complex mathematical models of two-phase flows used to predict their behaviour in various types of pipelines. The author focuses on numerical experiments and comparing them with actual data, especially regarding energy losses and phase dynamics.

V.P. Volkov's article (*2022*) examines the effect of turbulence on heat exchange processes in two-phase flows. The author uses modern approaches to modelling turbulent processes under various pressure and temperature conditions, particularly for power plants. The research focuses on improving understanding of the behaviour of two-phase flows in industrial systems and improving their efficiency.

Despite significant progress in understanding the hydro-gas dynamics and thermophysics of two-phase flows, there are still many unresolved problems and difficulties (*Lapin, 2017*):

- *In-depth modelling of complex two-phase flows*: for accurate prediction, it is necessary to develop more detailed models that take into account microscopic details, such as bubble structures and their interaction with the liquid (*Smirnov, 2019*);
- *Stimulating more efficient heat exchange methods*: creating new materials and designs for heat exchangers that interact effectively with two-phase flows can significantly improve the efficiency of energy systems;

- *Applications in new fields*: Expanding two-phase flow research into new areas, such as renewable energy, quantum thermodynamics, or even space technology, could lead to breakthroughs in science and technology.

Influence of pipeline geometry. Pipeline geometry has a decisive influence on heat exchange characteristics and flow dynamics (*Orlov, 2020*). The main parameters are the shape of the cross-section, the length of pipes, the presence of bends, and the diameter and roughness of the walls.

Pipeline diameter. Changes in the pipeline diameter can significantly affect the flow dynamics. During the study, it was found that with an increase in the pipe diameter, the flow resistance decreases, leading to a decrease in pressure losses. Still, at the same time, the intensity of heat exchange decreases due to a decrease in the contact surface between the flow and the pipe walls.

Roughness of the walls. High roughness contributes to turbulence, improving convective heat exchange by increasing heat transfer between the pipe walls and the flow. However, excessively high roughness increases hydrodynamic losses and energy costs for maintaining the flow.

Pipeline bends. The simulation results showed that bends and changes in the direction of flow movement lead to developing turbulence in areas of change in direction, increasing the heat transfer coefficient. At the same time, this increases hydraulic losses due to local supports. In systems with a large number of bends, it is necessary to find an optimal balance between heat exchange and energy losses.

Influence of the flow rate. The flow rate is one of the critical factors affecting the efficiency of heat exchange. Studies have demonstrated the following patterns:

- *Low speeds*. At low flow rates, laminar flow modes occur, in which convective heat exchange is low due to insufficient mixing of the flows. However, energy losses due to friction and local resistances are also reduced at low speeds.
- *High speeds*. As the flow rate increases, heat exchange increases due to developing turbulence, contributing to more efficient heat transfer from the walls to the flow. However, significant speeds also increase pressure losses and energy costs for pumping the medium.

Influence of the medium's phase state. In the case of two-phase flows (gas-liquid), the efficiency of heat exchange significantly depends on the phase ratio, the type of flow, and the dynamics of interaction between gas and liquid.

Phase transitions. Phase transitions, particularly boiling and condensation, are significant processes that affect heat exchange. Boiling a liquid in a two-phase stream significantly increases the heat transfer coefficient since there is an active mass exchange between the phases, and local zones of intense heat transfer are formed.

Structures of two-phase flows. The flow structure – bubble, film, or jet – also plays a significant role. Phase mixing and interaction increase heat transfer efficiency but complicate flow dynamics due to the need to consider the phase distribution over the pipe cross-section.

Influence of temperature gradients and thermodynamic conditions. The temperature gradient also determines the efficiency of heat exchange. Increasing the temperature difference between the liquid and the pipe walls contributes to an increase in heat flow. However, high-temperature gradients can cause instability of the flow, particularly the formation of bubbles or steam plugs in two-phase systems, which reduces the uniformity of heat exchange.

Influence of pipe diameter on heat transfer coefficient: as the pipe diameter increases, the heat transfer coefficient decreases, indicating a decrease in heat transfer efficiency at larger diameters due to less contact between the pipe walls and the flow.

Influence of flow rate on pressure loss: As the flow rate increases, pressure losses increase, which indicates an increase in energy costs to maintain the medium's movement at high speeds.

The graphs (*Figure 1*) show the importance of choosing the optimal parameters for efficient heat exchange in pipelines.

Discussion

The study's relevance is due to the complexity of the behaviour of two-phase flows and the need for accurate modelling of phase transitions (such as boiling and condensation), the influence of geometric features of pipelines on the efficiency of heat transfer and reduction of energy losses. Although capable of considering basic physical parameters, modern two-phase flow models need further improvement to improve accuracy under real-world operating conditions. In particular, considering microscopic effects (such as capillary forces and molecular interactions) is a significant challenge and opens up prospects for future research.

Further areas of work may include:

(1) Developing more detailed microscopic models of two-phase flows that consider capillary phenomena and interactions at the molecular level. This will allow us to better understand the processes of heat and mass transfer under high temperatures and pressures, especially for micro- and nanochannels.

(2) Optimising heat exchange systems by developing new pipeline materials and structures. Using materials with improved thermal conductivity characteristics and special coatings that contribute to improving heat transfer efficiency is a promising area of research for improving two-phase heat exchange systems.

(3) Introducing numerical models of two-phase flows into engineering practice to predict the behaviour of flows under non-standard conditions, such as renewable energy, heat pumps, and Microelectronics. Studying the specifics of such applications will help specialists and scientists improve design solutions and increase the energy efficiency of new systems.

Conclusion

The study's results show that heat exchange efficiency in pipelines largely depends on the geometric parameters, flow rate, and Phase state of the medium. Optimising the pipeline geometry and selecting appropriate flow modes and phase ratios allows you to achieve maximum efficiency with minimal energy and resource losses.

Hydro-gas dynamics and thermophysics of two-phase flows are significant and dynamically developing branches of science that play a key role in energy, chemical, and technological processes. Modern research in this area makes a significant contribution to developing new models, methods, and technologies that can improve the efficiency and reliability of such systems.

Conflict of interest

The author declares that there is no conflict of interest.

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Appendix

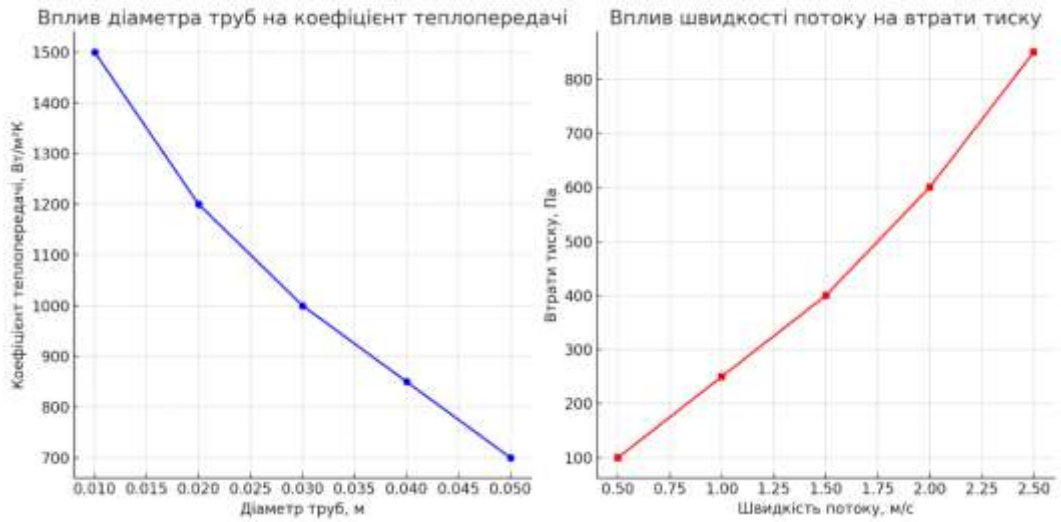

Figure 1. Graphs of optimal parameters

Oksana S. Bohomolova [15], *Vadim I. Mossakovskyi* [16]

Approach to determining the remaining lifetime of power transformers [10]

Abstract: Insulation of the power transformer windings is the main element which determines the condition and possibility of further operation of the transformer. There is a need to renew the main funds of the electric power industry. Improving the methods of monitoring the condition of the transformer to carry out timely repair work and extend the service life is an urgent task. The residual service life of the transformer is determined based on the combined approach of the probability of failure of the transformer. The probability is determined by assessing the current state and the factors affecting this state, like information about the load and duration of work. The study object is a power transformer. The study aims to develop a fuzzy logic controller for determining the residual life of a transformer based on the physical modelling of thermal processes in the transformer. The article reflects the approach to determining the coordinates of the most heated point of the insulation of the power transformer winding, depending on the mode and temperature of the surrounding environment. Based on this information, a structural diagram of the device based on the fuzzy logic controller was developed to monitor the transformer's residual resource. Transformer load factor, oil temperature and ambient temperature are accepted as input variables for the fuzzy logic controller. At the output, we get the coordinates of the most heated point of the transformer and the remaining service life. The proposed approach will make it possible to determine with high accuracy the remaining service life of the transformer and accordingly plan the date of repair or replacement.

Keywords: the most heated point of the transformer, remaining service life, fuzzy logic controller, winding insulation.

Abbreviations:

$TLGU$ is transformer load graph unit,

RSL is residual service life,

$MHPC$ are the most heated point coordinates,

FLC is fuzzy logic controller,

$FOTOTS$ is fiber-optic transformer oil temperature sensors,

OPC is operator's personal computer,

ATU is ambient temperature unit.

Introduction

Power transformers are a significant part of power transmission and distribution networks, and their condition directly affects the network's reliability and stability. The process of operating the transformer is undoubtedly accompanied by a change in its technical condition and a decrease in its physical and structural properties. Today, many power transformers in Ukraine's energy facilities have exceeded the standard service life.

Maintenance and replacement of failed transformers can be time-consuming and capital-intensive. Considering the market conditions of power companies, a system for diagnosing the state of the transformer and its residual life with minimal monetary investment is necessary.

The remaining life of a power transformer is the actual time it can operate at a particular load until it is repaired or replaced. Analysis of static information about transformer failure indicates that most equipment failures are related to wear, humidity, and/or insulation contamination (*Rozvodyuk & Vdovichenko, 2019*). In this case, the main reason for the deterioration of insulation is the temperature effect due to the overload of the Transformer (*Palaniuk, 2022*).

According to the research conducted (*Rubanenko et al., 2017*), detecting the development of a defect at the initial stage reduces the cost of repair work by 75% and losses from under-discharge of electric energy by 63%.

A transformer's residual life is usually assessed based on several factors, such as its service life and mode, insulation condition, and wear level. Cellulose insulation is a crucial resource-defining element of a transformer, and its service life depends on many factors, such as temperature, humidity, and the quality of transformer oil. It was found that with increasing temperature, the rate of ageing of cellulose insulation increases (e.g., at a temperature of 98°C – ageing occurs in 20 years, and at a temperature of 110°C – the rate of ageing will be 4 times higher and the operational life of the insulation will work out in 5 years) (*Tenbohlen et al., 2016*). It can be concluded that their replacement after the established service life may not be justified under the regular operation of power transformers.

The scientific community has developed many methods and mathematical models for the diagnostics of power transformers: chromatographic analysis of gases, measurement of partial discharges, analysis of the thermal state, determination of the state of high-voltage transformer inputs, etc. (*Pritiskach, 2017*; *Cao et al., 2024*), which have a different set of the number of detected defects and means of measuring transformer parameters. However, the most significant parameter during transformer insulation ageing is the temperature of the most heated point of the winding. To date, various approaches to determining the thermal parameters of a transformer have been proposed. For example, in (*Grabko et al., 2021*), a mathematical model is formed based on the law of thermal conductivity and a mathematical formula for determining the temperature of the most heated point of the transformer winding. However, to accurately analyse the state of the transformer, you need to use an actual thermal model of the transformer.

One of the leading international standards for determining the residual service life of a transformer is IEC 60076-7 (*2005*). This standard sets out recommendations for determining the residual service life of a transformer based on monitoring its condition, diagnostics and analysis of test results. The basic model of the standard assumes that the most significant ageing of the insulation will be on the side of the winding with the maximum temperature. The temperature of the most heated point on the insulation surface of the power transformer winding θ_h is determined as follows:

$$\theta_h = \theta_a + \Delta\theta_{bt} + \Delta\theta_w,$$

where:

θ_a is ambient temperature;

$\Delta\theta_{bt}$ is excess of the oil temperature over θ_a at the bottom of the tank at a time t;

$\Delta\theta_w$ is exceeding the temperature of the hottest point above $\Delta\theta_{bt}$.

However, the standard's model has several assumptions that do not fully reflect the reality of the transformer's physical processes. For example, the model contains a linear profile of

changes in the oil temperature in the middle and along the winding; the sinusoidal dependence of the ambient temperature over time indicates a difference in the maximum and minimum temperatures in the range of 12 hours, which is not valid. There is also an underestimation of the effect of transformer loading.

The temperature of the windings' most heated points determines the reduction of their service life. Data on the temperature of the most heated points at any given time of the transformer's operation under changing load and environmental conditions can be used to perform diagnostics of the transformer's actual exact state.

Most use the methods described in regulatory documents (IEEE and IEC), but equations and methods do not accurately consider processes. Existing regulatory documents are based on statistical data on the maximum load of each day and the average monthly or average daily temperatures during operation. At the same time, significant short-term overloads are not considered.

Therefore, to determine its service life, it is necessary to consider all the features and factors of a particular type of transformer and its operating conditions and use more accurate models and techniques that reflect the actual physical processes occurring in the transformer. You also need to be able to assess the transformer's condition online. M.P. Bolotnyi (*2019*) notes that today, there is a problem of inconsistency in the methods of processing diagnostic information received from monitoring, information measurement, and control systems.

The study object is a power transformer.

The study aims to develop a fuzzy logic controller for determining the residual life of a transformer based on the physical modelling of thermal processes in the transformer.

Based on the purpose of the study, the following tasks were set and solved:

- create a power transformer model in the SolidWorks software environment;
- perform a simulation study of thermal processes in the transformer under different loads and obtain the trajectory of movement of the most heated point of insulation of the winding;
- create an adaptive knowledge base and a fuzzy logic controller to define and fix.

The results of the study

To correctly predict the reduction in the transformer's service life, changes in the transformer's most heated point under various operating conditions were modelled and researched using the SolidWorks computer-aided design software package.

The transformer simulation was performed for the following parameters: the load of the transformer windings varied from 50% to 200% (in increments of 10%), the ambient temperature – from -15°C to +40°C, which corresponds to the actual physical conditions of transformers in Ukraine. As a result of modelling and thermal calculation, it was found that depending on the load factor of the transformer, the ambient temperature, and the presence of symmetry or non-symmetry of the load, the coordinates of the most heated point move. At the same time, for symmetric modes, this point is located on the low-voltage winding, and for unbalanced loads on the high-voltage winding side and at the same time starting from the transformer load by more than 150% and the temperature above 10°C, the coordinates of the most heated point remain unchanged.

Practical approaches to diagnosing electric power system equipment have been widely developed and implemented. These approaches include expert systems, fuzzy logic, and neural networks.

Many scientific papers use neural networks to predict and determine transformer parameters. For example, in the work of Vasylevskyi et al. (*2019*), the neural network is used to predict the humidity of transformer oil in power oil-filled transformers.

As a tool for organising a system for monitoring the technical condition of the transformer, an ANFIS adaptive neural network of neural output is used. This five-layer neural network of direct signal propagation of a particular type has a structure that works as a system of fuzzy logical output Sugeno with appropriate settings for the base of rules and functions of belonging (*Subbotin & Oliinyk, 2019*).

The results obtained from modelling the thermal process and the dependence of the movement of the most heated point of the power transformer are the basis of the neural network model. The appendix (*Figure 1*) shows the dependences of the coordinate displacement of the most heated point of the transformer (KorX, KorY, KorZ) on the ambient temperature and the load factor of the transformer.

Due to the obtained thermal calculation, the value of the coordinates of the most heated point of the transformer is obtained. The corresponding temperature value depends on the transformer load and ambient temperature (*Figure 2*). Thermal modelling of the transformer condition makes it possible to identify internal defects in the windings by installing local heating in the transformer tank, which is associated with local overheating of individual transformer coils. Thanks to the obtained result, it becomes possible to monitor the spent and remaining life of the transformer. When using the proposed approach, it becomes possible to determine the residual service life of the transformer with high accuracy, make an objective forecast of the date of exit from operation, and accordingly plan repairs or replacement.

According to the simulation, the service life of the transformer corresponds to the rated value of 25-30 years (depending on the type of transformer) when the transformer is loaded by no more than 140%, while the temperature value of the most heated point will not exceed 98°C. When the transformer is loaded more than 140%, the temperature of the most heated point increases, and the insulation's thermal ageing rate increases.

According to the reference literature, in the heating range from 80°C to 140°C, an increase in temperature by 6°C reduces the service life of the transformer insulation by almost half (*Rubanenko et al., 2017*).

There are two ways to implement a model for determining the residual life of a transformer, where the temperature of the most heated point is required as input data:

(1) measurements using fibre-optic sensors (Luxtron, ABB, General Electric Co), which will reduce the number of calculations and make it possible to obtain real-time information about the remaining resource;

(2) use the SOLIDWORKS CAD thermal calculation model, which will allow for more straightforward technical means but provides for an increased amount of calculations

The appendix (*Figure 3*) shows a block diagram of the transformer residual life monitoring device, which includes TLGU, RSL, MHPC, FLC, FOTOTS, OPC, and ATU.

For the first method, the operation of the complex involves collecting, processing and receiving data to the input of a fuzzy logic controller relative to the temperature of the transformer windings via a wireless communication channel from measuring devices. The controller input also provides information about the ambient temperature.

For the second option, the controller input must include information about the actual Transformer load graph and ambient temperature.

As a result of information processing, the fuzzy logic controller provides the operator with information about the transformer's residual life, like the coordinates of the point (s) where the greatest thermal ageing of the insulation occurred. Therefore, first of all, during repair work, it is necessary to pay attention to these places.

Discussion

Power transformer condition Diagnostics is a process that uses various methods and technologies based on statistical data and operational experience to determine the transformer's technical condition and assess its remaining life. The main purpose of diagnostics is to ensure the transformer's reliable and safe operation, such as maintenance and repair.

Despite numerous studies of thermal processes and diagnostic systems for power transformers, modern trends lead to further improvement of models and the use of the latest technologies. In order to increase the efficiency of transformer operation, simulation modelling must be combined with accurate monitoring data. A promising approach is using fuzzy logic methods, which allow you to get optimal solutions in conditions of uncertainty or incompleteness of data. Combining simulation results in the SolidWorks software environment with monitoring data provides a synergistic effect. Simulation results can refine the input rules of a fuzzy system, improving the accuracy of its predictions, and actual data allows you to verify the model and improve its parameters. Thus, the proposed approach is the basis for forming adaptive state control systems for transformers. The research results can be used to develop new methods for diagnosing the state of a power transformer, considering both static, i.e., design, and dynamic (operational) factors.

Conclusion

The temperature of the most heated point of the transformer has a significant impact on the residual service life due to the degradation of materials under the influence of high temperatures. Temperature overheating and changes in the transformer windings reduce the service life of insulation, lead to premature failures of power transformers, and cause short circuits.

An approach to determining the most heated point of a transformer and its movement along the windings based on the thermal modelling of SOLIDWORKS CAD is proposed. A 3D model of the transformer was created, considering the geometry and parameters, and thermal modelling algorithms were used to determine the temperature distribution inside the transformer.

From the simulation results, it is concluded that when the transformer is loaded by no more than 140%, the temperature value of the most heated point will not exceed 98°C and the service life, depending on the type of transformer, corresponds to the passport value of 25-30 years.

Under transformer overload conditions of more than 140%, the temperature of the most heated point increases and the insulation's thermal ageing rate increases.

In this article, a fuzzy logic controller is formed to analyse the technical condition and continuously determine the residual life of the transformer, considering the transformer load and ambient temperature. The controller also includes the ability to receive transformer temperature data from fibre-optic transformer oil temperature sensors, data from which will help form decisions about the need to maintain the transformer replacement unit. Fuzzy controller rules are formed by considering experts' knowledge and analysing 3D modelling data.

The proposed diagnostic method will extend the service life of power transformers and help personnel obtain complete operational information to make appropriate, timely decisions, increasing transformer reliability and safety.

Conflict of interest

The author declares that there is no conflict of interest.

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Appendix

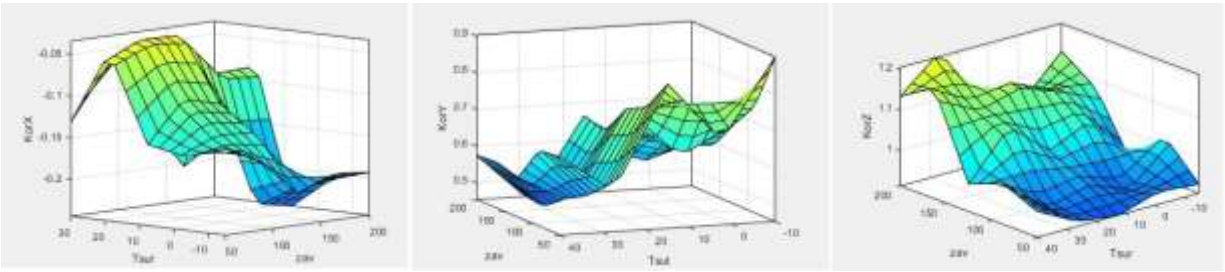

Figure 1. The dependences of the coordinate displacement of the most heated point of the transformer (KorX, KorY, KorZ) on the ambient temperature and the load factor of the transformer

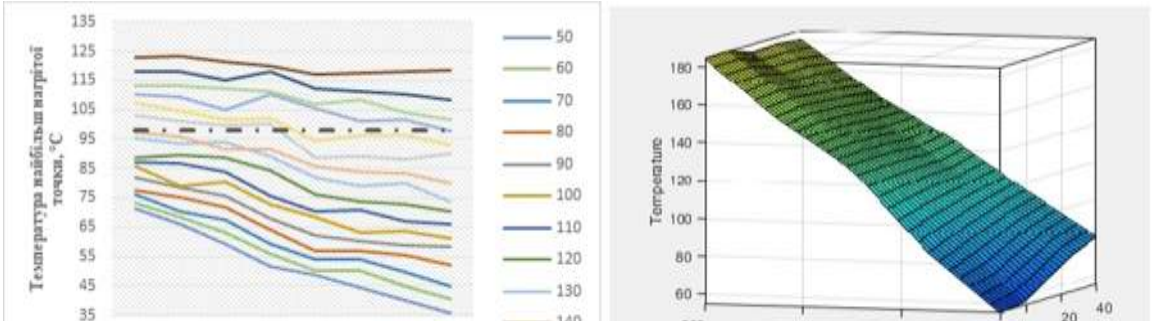

Figure 2. Dependence of the corresponding temperature value on the transformer load and ambient temperature (In Ukrainian)

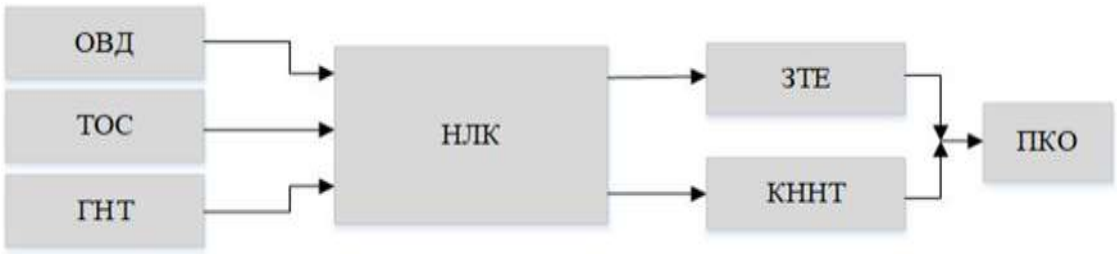

Figure 3. A block diagram of the transformer residual life monitoring device (In Ukrainian)

Larysa S. Kaykan [17]

Magnetite-based hybrid cathode material for advanced lithium-ion batteries [11]

Abstract: This research focuses on the synthesis, structural characterization, and electrochemical performance of a hybrid cathode material based on nano-dispersed magnetite for advanced lithium-ion batteries. The material was synthesized using a hydrothermal method that enabled the integration of magnetite into a mesoscopic framework, resulting in a hybrid structure optimized for electrochemical applications. Structural analysis using X-ray diffraction confirmed the X-ray amorphous nature of the compound, indicating a highly disordered atomic arrangement. Mössbauer spectroscopy further revealed the absence of a magnetically ordered state of iron, with paramagnetic doublets indicating Fe^{3+} cations in a symmetric oxygen coordination environment. These findings highlight the structural uniqueness of the material, with its nanoscale dispersion and amorphous properties playing a critical role in its electrochemical behavior. The electrochemical characterization demonstrated a stable discharge curve with an operating voltage of approximately 2.2 V, making it well-suited for low-voltage energy storage systems. The material exhibited a specific electrochemical capacity of ~350 A·h/kg, consistently maintained over three discharge cycles, reflecting its robust cycling stability and excellent structural durability. Potentiodynamic measurements and electrochemical impedance spectroscopy were used to calculate the lithium-ion diffusion coefficient, which ranged from ($3.0\ 10^{-13}$) to ($8.9\ 10^{-13}$) cm^2/s. These high diffusion values suggest efficient ionic transport facilitated by the amorphous structure and nanoscale distribution of magnetite within the composite. The hybrid material's structural features, such as its mesoscopic organization and enhanced lithium intercalation pathways, provide a strong basis for its performance. As indicated by the flat discharge profile, the absence of significant polarization effects during cycling demonstrates the material's capability for efficient charge transfer and reduced resistance at the electrode-electrolyte interface. The high stability of the lithium intercalation process, supported by the disordered yet stable structure, ensures consistent energy delivery over multiple cycles.

Keywords: lithium-ion batteries, nanomaterials, hybrid composites, electrochemical studies, XRD studies, Mössbauer studies, energy storage.

Abbreviations:

EIS is electrochemical impedance spectroscopy,
LIB is lithium-ion batteries,
SEI is solid electrolyte interphase,
XRD is X-ray diffraction.

Introduction

The continuous advancements in portable electronics, electric vehicles, and renewable energy systems have necessitated the development of energy storage devices with higher capacity (*Heydari Gharahcheshmeh & Chowdhury, 2024*; *Mendonça et al., 2025*; *Su et al., 2024*), longer lifespans, and improved safety. LIBs remain at the forefront of these efforts due to their superior energy density, efficiency, and rechargeability compared to other energy storage technologies (*Yang et al., 2024*; *Hou et al., 2025*). Central to the performance of LIBs is the development of novel electrode materials that can accommodate rapid ion diffusion, sustain high charge-discharge rates, and exhibit stability over extended cycling.

Nano-dispersed magnetite (Fe_3O_4) has garnered substantial interest in this context (*Li et al., 2024*) owing to its unique physicochemical properties and the broad spectrum of potential applications. Magnetite's versatility lies in its ability to be synthesized in various morphologies and sizes, tailored to specific requirements by adjusting production methods and conditions. For instance, as highlighted in (*Jonak & Borah, 2021*; *Adi & Taniguchi, 2022*), the combination of mechanochemical synthesis and ultrasonic dispersion can yield hollow spherical magnetite nanoparticles with an average size of 6-12 nm. These features make magnetite attractive for energy storage and open avenues for its use in diverse fields such as biology and medicine, where specific nanoparticle geometries play a critical role.

In LIB applications, magnetite demonstrates promising electrochemical properties as an electrode material. Its high theoretical capacity (924 mAh g^{-1}) (*Zeng et al., 2025*) surpasses many conventional cathode materials. Studies (*He et al., 2022*; *Xie, 2022*) have explored the dual use of magnetite in LIBs, where pure magnetite serves as a cathode, and magnetite coated with conductive or protective layers functions as an anode. These investigations underscore magnetite's potential to enhance battery performance when employed in electrode design. Furthermore, magnetite synthesized through sol-gel techniques has been shown to form a highly porous framework after annealing, facilitating efficient lithium-ion intercalation during the battery discharge process (*Qi et al., 2024*). This porous nature is critical for ensuring a high surface area and effective ionic transport pathways, essential for achieving high capacity and rate performance.

Despite these advantages, pure magnetite faces limitations, such as volume expansion and aggregation during cycling, which can compromise structural integrity and result in capacity fading. Researchers have turned their attention to hybrid structures that integrate magnetite with other materials to overcome these challenges. Hybrid cathodes provide structural stability and exploit the combined phases' synergistic properties to enhance ionic conductivity and lithium-ion storage. Heterogeneous systems that combine nanosized magnetite particles with a second phase capable of lithium intercalation hold immense potential for improving battery performance (*Xie et al., 2024*).

Building on these insights, the present study focuses on synthesizing a hybrid cathode material incorporating magnetite as nanotubes within a sulfur-containing phase. This "colloidal" system aims to achieve a dual benefit – improved ionic conductivity due to the sulfur-containing phase and enhanced lithium storage capacity due to the nanosized magnetite. Additionally, the tubular morphology of magnetite is expected to provide a robust framework that accommodates volume changes during cycling while maintaining structural integrity.

The objectives of this work are twofold: (1) to synthesize and characterize the hybrid cathode material and (2) to investigate the diffusion behavior of lithium ions during the electrochemical intercalation process. By addressing the current challenges associated with pure magnetite and exploring the potential of hybrid structures, this study aims to contribute to developing next-generation cathode materials for advanced lithium-ion batteries.

Materials and methods

Following a carefully controlled protocol, a nano-dispersed composite of magnetite and sulfur-containing compounds was synthesized using a hydrothermal method. A 20 mL aqueous

ferric sulfate solution ($Fe_2(SO_4)_3$, 0.05 M) was mixed with 5 mL of albumin using magnetic stirring for 5 minutes, yielding a homogeneous orange solution. Subsequently, 8 mL of ethanol (CH_3CH_2OH) was introduced into the solution. To this mixture, 10 mL of 80% hydrazine hydrate ($N_2H_4 \cdot H_2O$) was added dropwise under continuous stirring. After an additional 10 minutes of stirring, the mixture was transferred to a Teflon-lined autoclave and subjected to hydrothermal treatment at 140°C for 24 hours. Upon completion, the autoclave was cooled to room temperature alongside the oven. The inclusion of albumin during synthesis facilitated the formation of magnetite particles with a nanotubular morphology.

The synthesized composite was characterized using X-ray diffraction (XRD), thermogravimetric analysis (TGA), and Mössbauer spectroscopy. XRD patterns were recorded on a DRON-3 diffractometer, while thermal properties were examined using a synchronous thermal analyzer (STA 449 F3 Jupiter). Mössbauer spectra of ^{57}Fe were acquired at 300 K on an MS1104 spectrometer. The isomeric shift values were calibrated relative to α-Fe, employing a 57Co source embedded in a Cr matrix. Spectral analysis and parameter extraction were performed using the Univem MS-2.07 universal software package, ensuring precise decomposition and quantification of spectral components.

The synthesized composite was employed as a cathode material in a custom-designed electrochemical cell featuring a lithium metal anode. The electrolyte utilized was a 1 M solution of lithium tetrafluoroborate ($LiBF_4$) dissolved in γ-butyrolactone (*Nandika et al., 2019*).

Potentiostatic discharge experiments were conducted under a constant current density of j=10 μA to evaluate the cell's performance. Electrochemical impedance spectroscopy (EIS) measurements were performed using an Autolab PGSTAT 12/FRA-2 spectrometer over a frequency range of 0.01 Hz to 100 kHz to assess the system's charge transfer and ionic conductivity. Potentiodynamic studies were performed in the voltage range of 1.0-4.0 V, with voltage sweep rates varying between 0.01 and 0.005 mV/s, to analyze the electrochemical behavior and cycling stability of the cathode material.

This comprehensive suite of electrochemical analyses provided critical insights into the performance characteristics of the synthesized composite as a cathode material in lithium-ion battery systems.

Results and discussion

The first figure (*Figure 1*) presents the results of thermogravimetric analysis (TGA), providing insights into the synthesized composite's thermal stability and decomposition behavior. The initial mass loss of approximately 10 wt.% begins at around 50°C, which can be attributed to the desorption of physically adsorbed water molecules and residual moisture from the powder dried at room temperature. This step is commonly observed in materials with surface-bound water or hygroscopic properties.

A more pronounced mass loss, approximately 33.79 wt.%, is observed within the 200–380°C. This is associated with the thermal decomposition of iron (III) hydroxides $Fe(OH)_3$ into iron oxides (Fe_2O_3) (*Taneja et al., 2023*). This transformation involves the release of water molecules as $Fe(OH)_3$ decomposes into a more thermodynamically stable oxide phase. This process is accompanied by an exothermic peak at ~250°C, indicating the energy release due to

the formation of oxide bonds. Such exothermic behavior is characteristic of decomposition reactions leading to stable oxide formations.

In the temperature range of 600–700°C, a further mass loss of ~11.20 wt.% is observed, likely due to the formation of volatile sulfur-containing compounds, such as sulfur trioxide (SO_3). This step suggests the involvement of sulfur in the material's thermal decomposition pathway, possibly arising from the sulfur-containing phase integrated during synthesis. The release of SO_3 may indicate the partial decomposition or volatilization of sulfur-containing moieties within the composite.

Notably, no distinct exothermic peaks are observed beyond 700°C, suggesting that the synthesized compound does not undergo first-order phase transitions in this temperature range. This thermal behavior implies that the material's crystalline framework remains stable at elevated temperatures, which is advantageous for its potential applications in environments requiring high thermal stability.

X-ray diffraction (XRD) analysis, as illustrated in the appendix (*Figure 2*), indicates that the synthesized powder is X-ray amorphous. This conclusion is based on the absence of sharp, well-defined diffraction peaks in the pattern, typically indicative of a crystalline structure with long-range periodic atomic arrangement. Instead, the XRD profile exhibits a broad diffuse halo, which is characteristic of materials with a disordered or amorphous atomic structure.

The Mössbauer spectra of the synthesized material, presented in the appendix (*Figure 3*), reveal the absence of a magnetically ordered state for iron, as evidenced by the lack of hyperfine splitting typically observed in ferromagnetic or antiferromagnetic phases. Instead, the spectra display a series of paramagnetic doublets indicative of iron in a paramagnetic state. This behavior is consistent with a disordered structure where iron cations are not magnetically coupled, likely due to the fine dispersion of the material.

Among the observed doublets, the parameters of Doublet_2 (*Table 1*) are particularly noteworthy. Its high isomer shift (I_S = 1.6075 mm/s) and quadrupole splitting (Q_S = 2.5739 mm/s) suggest that Fe^{3+} cations are in a symmetric oxygen coordination environment. This symmetric environment implies that the iron centers are stabilized within a chemically homogeneous matrix, which aligns with the amorphous nature of the material as identified by X-ray diffraction analysis.

The doublets' relative area percentages (S%) and line widths (G) provide further insight into the material's structural characteristics. Doublet_1, representing most of the spectral contribution (S=57.45%), corresponds to Fe^{3+} in a less distorted environment. At the same time, the remaining doublets (Doublets 2–5) reflect iron cations in environments with varying degrees of asymmetry and electronic interactions. This distinct quadrupole splitting across the doublets suggests the presence of multiple iron sites with diverse local geometries, indicative of a non-crystalline, heterogeneous matrix.

The absence of a magnetically ordered component corroborates the X-ray diffraction results, which identified the material as X-ray amorphous. This lack of magnetic ordering underscores the nanoscale dispersion of the iron-containing phases, as the spatial separation and structural disorder prevent the establishment of magnetic interactions necessary for long-range ordering.

The SEM images presented in the appendix (*Figure 4*) reveal that the synthesized material consists of magnetite nanotubes embedded within agglomerated complexes. These complexes form compact globular structures characterized by a relatively uniform distribution of Fe_3O_4 throughout the volume. The observed morphology suggests effective integration of the magnetite phase within the colloidal system, contributing to the material's overall structural homogeneity.

The X-ray diffraction data further supports the presence of a complex colloidal structure, which confirms the material's X-ray amorphous nature. The lack of distinct crystalline features in the diffractogram aligns with the disordered arrangement of the magnetite nanotubes and their incorporation into the agglomerates, emphasizing the nanoscale dispersion and amorphous characteristics of the synthesized compound.

The figure (*Figure 5*) displays the discharge curves of the first three cycles for an electrochemical cell employing the synthesized material as the cathode. The discharge profiles exhibit a relatively stable operating voltage of approximately 2.2 V throughout the cycles. This voltage is acceptable for developing a 2-volt energy storage device, demonstrating the material's potential for practical applications.

The stability of the operating voltage during discharge indicates consistent electrochemical behavior (*Table 2*) and suggests a reversible lithium-ion intercalation process within the cathode material (*Taneja et al., 2023*). The observed voltage plateau is likely associated with redox reactions involving Fe^{3+}/Fe^{2+} transitions, characteristic of magnetite-based systems. Such stable discharge characteristics are critical for maintaining energy density and ensuring reliable performance in applications requiring low-voltage sources.

The absence of significant voltage fluctuations over the three cycles implies good cycling stability and efficient charge transfer kinetics at the electrode-electrolyte interface. This behavior suggests that the synthesized material exhibits low polarization and retains its structural integrity during repeated lithium-ion insertion and extraction (*Wang et al., 2016*), which are essential properties for long-term operational stability.

The discharge curves and associated parameters demonstrate that the synthesized cathode material combines high specific capacity and energy density with good cycling stability. The initial variations in performance metrics are consistent with typical behavior observed in newly developed materials and could be mitigated by optimizing the synthesis process or material composition. These results position the synthesized material as a strong candidate for cathode applications in lithium-ion batteries, with further investigations into long-term cycling performance and impedance characteristics recommended to understand and enhance its capabilities thoroughly.

The results of the discharge cycles indicate that the synthesized material exhibits promising electrochemical performance, with specific capacity, specific energy, stoichiometric factor, and efficiency showing consistent trends across the first three cycles. The specific capacity C is 365.1 A·h/kg in the first cycle, which decreases slightly to 345.1 A·h/kg in the second cycle before recovering to 363.5 A·h/kg in the third cycle. This initial drop is likely due to stabilization processes within the material, such as structural rearrangement or forming a SEI layer. The recovery in the third cycle demonstrates that the material retains its capacity for reversible lithium-ion intercalation, suggesting good cycling stability.

Similarly, the specific energy E follows a comparable pattern, starting at 790.2 W·h/kg in the first cycle, decreasing to 697.1 W·h/kg in the second, and stabilizing at 695.4 W·h/kg in the third cycle. This decrease aligns with the slight reduction in specific capacity and may result from minor irreversibility in lithium-ion intercalation and deintercalation or resistive losses at the electrode-electrolyte interface. Despite this, the values indicate that the material is capable of providing significant energy density, which is critical for practical applications.

The stoichiometric factor x, which reflects the extent of lithium-ion intercalation, remains relatively stable across the cycles, with values of 2.7, 2.6, and 2.8. These results indicate the efficient utilization of lithium ions, further supported by the material's ability to maintain its structural integrity throughout the cycles. The efficiency η is initially high at 96% but drops to 83% in the second cycle before partially recovering to 85% in the third cycle. The initial drop in efficiency may be attributed to resistive losses or side reactions, such as electrolyte decomposition or partial capacity fading due to structural changes in the cathode material. The slight recovery in the third cycle suggests that these processes stabilize, highlighting the material's durability.

To evaluate the kinetics and extent of lithium-ion intercalation within the synthesized cathode material, the lithium diffusion coefficient D_{Li} was determined using potentiodynamic curves (*Figure 6*). These curves were recorded at varying scan rates, ranging from 0.01 to 0.005 mV/s. The discharge region of the curves exhibits a distinct cathodic peak, characteristic of the electrochemical reduction process associated with lithium-ion intercalation into the host material.

As the scan rate increases, notable changes in the peak behavior are observed. Specifically, the cathodic peak becomes less pronounced and shifts to lower voltages. This behavior indicates kinetic limitations during faster scanning, reducing the time lithium ions can diffuse into the active material. The peak shift also suggests an increase in overpotential at higher scan rates, likely due to the effects of slower charge transfer kinetics and the diffusion limitations of lithium ions within the material.

The cathodic peak current and scan rate relationship provide additional insight into the intercalation mechanism. As shown in the appendix (*Figure 7*), the cathodic current at the peak value varies systematically with the scan rate, reflecting the influence of diffusion processes on electrochemical performance. By analyzing this dependence, the lithium diffusion coefficient can be extracted using the Randles-Sevcik equation (*Huang et al., 2012*) for semi-infinite linear diffusion.

The equation (*Huang et al., 2012*),

$$i_p = (2 \times 10^5) n^{3/2} A D_{Li}^{1/2} C v^{1/2}$$

relates the peak current i_p to the scan rate v, diffusion coefficient D_{Li}, active electrode surface area A, and the lithium-ion concentration C.

The observed peak shifts and the current's scan rate dependence suggest that lithium-ion diffusion is the rate-limiting step at higher scan rates. This behavior highlights the importance of optimizing the material's structure to enhance ionic conductivity and minimize resistance to lithium transport. The nanoscale and amorphous nature of the synthesized material likely contributes to its overall lithium storage capacity by providing abundant intercalation sites and

shorter diffusion pathways. However, further structural refinement and compositional tuning could improve the material's performance under dynamic conditions.

The lithium-ion diffusion coefficient D_{Li} was calculated from potentiodynamic measurements using the Randles-Sevcik equation, which correlates the peak current (i_p) to the electrochemical and physical properties of the electrode material and the experimental conditions (*Prosini, 2002*). The relationship is expressed as:

$$i_p = \frac{n^{3/2}F^{3/2}}{R^{3/2}T^{1/2}} D^{1/2} A_{C_{Dx}} v^{1/2}$$

where i_p is the peak current obtained from the cyclic voltammogram, R is the universal gas constant (8.314 J mol−1 K−1), T is the absolute temperature (298 K for room temperature), n is the number of electrons transferred during the electrochemical reaction (for lithium-ion intercalation, n=1), A is the contact area between the cathode and the electrolyte (approximated as the geometric area of the electrode), C is the concentration of lithium ions within the cathode (0.024 mol cm−3), calculated from the unit cell volume of the active material), and v is the potential scan rate.

In the context of the cathodic process, the initial concentration of vacancies in the intercalation host c_0 serves as the critical parameter, while for the anodic process, c_0 corresponds to the initial concentration of lithium ions within the intercalation matrix. Assuming that the intercalation and deintercalation processes are reversible under standard conditions, the lithium diffusion coefficient D_{Li} at room temperature (T = 298K) was calculated as

$$i_p = (2.69 \cdot 10^5) n^{\frac{3}{2}} A D_{Li^+}^{\frac{1}{2}} c_{Li} v^{\frac{1}{2}}, D = 1.4 \cdot 10^{-13}, cm^2/s.$$

To further validate and refine this value, the lithium diffusion coefficient was independently determined using the method of EIS (*Han et al., 2024*). EIS is a powerful tool that measures the frequency-dependent impedance of an electrochemical cell, providing insights into the kinetic and transport processes governing the system. The analysis is based on the construction of Nyquist plots (impedance hodographs) and their subsequent interpretation through equivalent circuit modeling.

The method incorporates the Warburg impedance, which is sensitive to the diffusion of lithium ions in the electrode (*Cruz-Manzo & Greenwood, 2020*). In the low-frequency region of the Nyquist plot, the Warburg impedance appears as a linear segment with a slope of 45°, representing the diffusive contribution. The Warburg constant W is extracted from the impedance data and is related to the lithium diffusion coefficient D_{Li} by the following relationship:

$$D_{Li} = \frac{R^2T^2}{2A^2n^4F^4C_0^2W^2}$$

where R is the universal gas constant 8.314 J mol−1 K−1), T is the absolute temperature, A is the active electrode surface area, n is the number of electrons transferred during the reaction, F is the Faraday constant (96,485 C mol-1), C_0 is the bulk lithium-ion concentration in the electrode, and W is the Warburg constant.

The Warburg constant W is determined by fitting the linear portion of the low-frequency region of the Nyquist plot.

$$-ImZ = \frac{W}{\sqrt{4\pi f}}.$$

The slope of this segment reflects the contribution of diffusion-controlled processes, allowing the calculation of D_{Li}. This method's accuracy relies on proper circuit modeling and precise measurement of impedance across a broad frequency range.

The Warburg constant, in turn, is related to the dependence of the equilibrium potential on the concentration of the diffusing element c:

$$W = \frac{\frac{-dE}{dc}}{F\sqrt{D}}$$

where D is the diffusion coefficient of lithium in the cathode.

The relationship between E and c is determined from the quasi-equilibrium discharge curve (dependence on the amount of transferred charge Q):

$$dQ = \frac{dcnF}{\rho}$$

where ρ is the density of the cathode material.

So, based on the equations, we can obtain an expression for the diffusion coefficient D:

$$D = \frac{\left(\frac{dE}{dQ}\right)^2}{2\rho^2 W^2} = \frac{\left(\frac{dE}{dQ}\right)^2}{4\pi f \rho^2 (Im)^2}$$

The diffusion coefficient value calculated by the electrode impedance spectroscopy method for three discharge cycles is

$$D \approx 3.0 \times 10^{-13} - 8.9 \times 10^{-13} cm^2/s.$$

The D values obtained based on independent methods coincide with an accuracy of an order of magnitude, which is evidence of the correctness of the obtained results.

Conclusions

This study demonstrates the successful synthesis and electrochemical characterization of a mesoscopic compound featuring nano-dispersed magnetite as the active cathode material for lithium-ion batteries. The cathode exhibited a flat discharge curve with a stable operating voltage of approximately 2.2 V, making it suitable for low-voltage energy storage systems. Its specific electrochemical capacity, measured at ~350 A·h/kg, remained consistent over the three discharge cycles investigated, highlighting the material's excellent cycling stability and structural integrity.

The lithium-ion diffusion coefficient, determined through potentiodynamic measurements and impedance spectroscopy, ranged between ($3.0\ 10^{-13}$) and ($8.9\ 10^{-13}$) cm^2/s. These values are notably high for systems of this type, indicating efficient ionic transport within the material. The nanoscale dispersion of magnetite and the amorphous nature of the synthesized compound likely contribute to its superior diffusion kinetics and reversibility during lithium intercalation and deintercalation.

The material's performance, including its stable discharge behavior, high-capacity retention, and favorable diffusion properties, positions it as a promising candidate for cyclic operation in lithium current sources. These results suggest that further optimization of the synthesis process and structural properties could unlock additional improvements, enhancing the material's suitability for advanced energy storage applications.

Conflict of interest

The author declares that there is no conflict of interest.

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Appendix

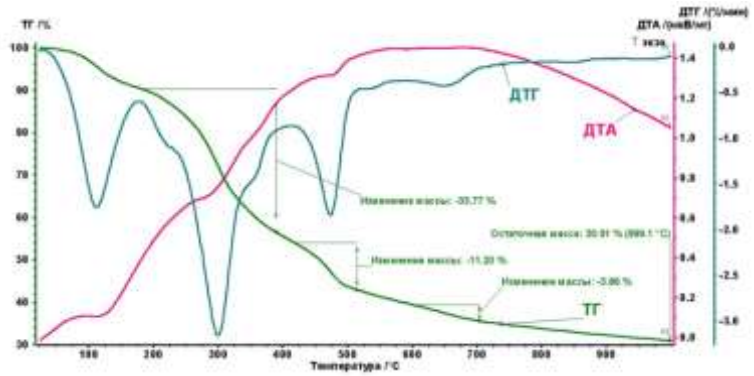

Figure 1. Thermogravimetric analysis of the composite, showing mass losses from water desorption (~50°C), iron (III) hydroxide decomposition (200-380°C), and volatile sulfur compound formation (600–700°C), with an exothermic peak at ~250°C indicating oxide formation.

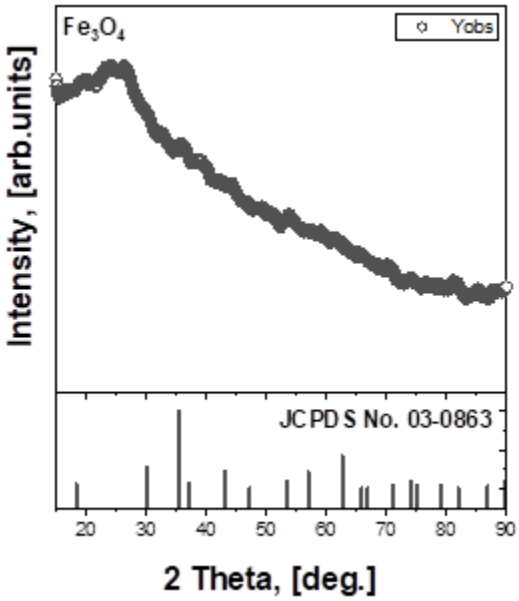

Figure 2. X-ray diffraction pattern of the synthesized material, exhibiting a broad diffuse halo characteristic of an X-ray amorphous structure, indicative of a disordered atomic arrangement and the absence of long-range crystallinity

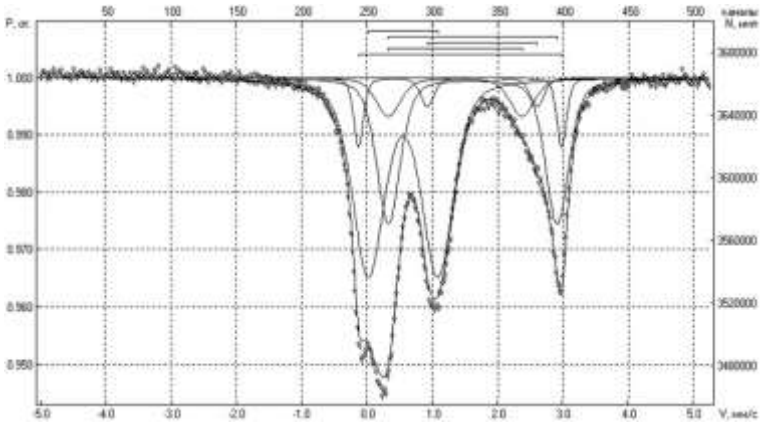

Figure 3. Mössbauer spectrum of 57Fe at room temperature, showing paramagnetic doublets indicative of Fe3+ cations in a disordered environment, with no evidence of magnetically ordered states

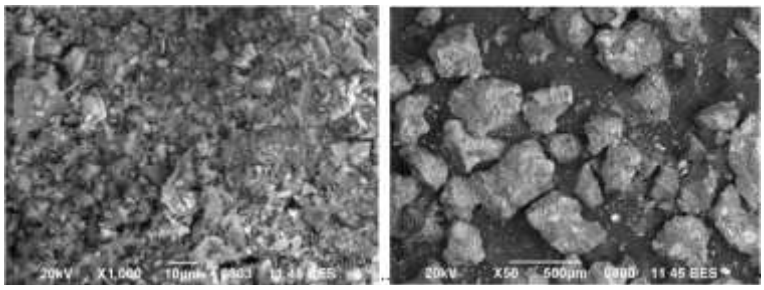

Figure 4. SEM images of the synthesized material, highlighting the structural features and morphology

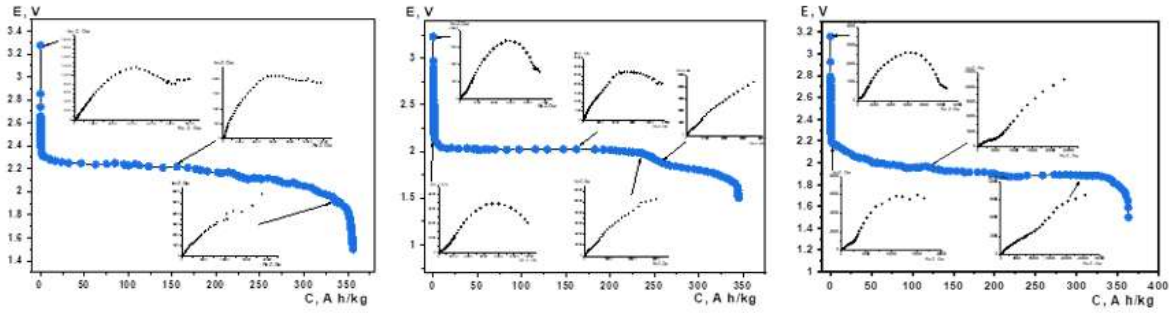

Figure 5. Discharge curves for the 1st, 2nd, and 3rd cycles of the electrochemical cell, accompanied by the corresponding impedance spectra

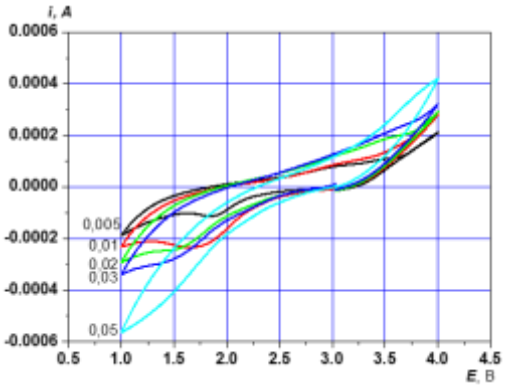

Figure 6. Cyclic voltammetry curves of the composite electrode, recorded at various potential sweep rates at 25°C, illustrating the electrode material's electrochemical behavior and kinetic responses

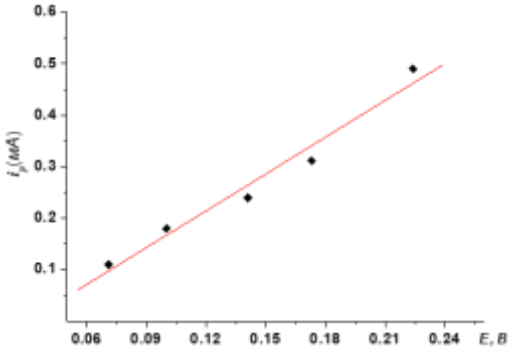

Figure 7. Dependence of the cathodic peak current on the square root of the potential sweep rate from cyclic voltammetry measurements. The solid line represents the linear fit to the experimental data, indicating a diffusion-controlled process

Table 1. Parameters of RT Mössbauer spectra of ^{57}Fe

Component	IS, mm/s	QS, mm/s	S, %	G, mm/s
Doublet_1	0.5839	0.9946	57.45	0.6491
Doublet_2	1.6075	2.5739	24.58	0.3754
Doublet_3	1.7115	1.6035	2.31	0.2203
Doublet_4	1.3819	1.9649	7.08	0.4241
Doublet_5	1.4313	3.1012	8.57	0.2160

Table 2. Electrochemical discharge characteristics of the synthesized material

No. of discharge cycle	Specific Capacity, C, A·h/kg	Specific Energy, E, W·h/kg	Stoichiometric Factor, x	Efficiency, η
1	365.1	790.2	2.7	96
2	345.1	697.1	2.6	83
3	363.5	695.4	2.8	85

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Genetic diversity of bread wheat and durum wheat varieties at the *Ppd1*- and *ZCCT1* loci and identification genotypes by DNA markers [12]

Abstract: The study of growth type and rate of development alleles gene of valuable cereal species, in particular wheat, determination of single alleles and their combinations in specific genetic material, identification of genotypes – carriers of different functional allelic variants is significant for the creation of varieties adapted to cultivation in specific climatic condition. In this regard, it is relevant to conduct molecular genetic analysis using DNA markers, which can identify allelic variations of *Vrn*- and *Ppd*-genes and their carriers in wheat, which is vital for the selection of genotypes and practical breeding of high-yielding varieties in certain climatic regions. The study object is the molecular genetic polymorphism of wheat varieties at the loci of growth type and rate of development. The study aimed to research the allelic diversity at the *Ppd-1* and *ZCCT-1* loci of bread wheat (*T. aestivum*) and durum wheat (*T. durum*) varieties of different origins and identification of genotypes carrying the corresponding alleles based on DNA markers. The objectives of the work included marker analysis of wheat varieties (*T. aestivum, T. durum*) at these loci and identification of the corresponding alleles and genotypes. Methods: DNA extraction, allele-specific PCR, agarose and polyacrylamide gel electrophoresis. Statistical analysis was performed using Microsoft Excel software. The genetic variability of 46 spring wheat varieties (25 – *T. aestivum*, 21 – *T. durum*) of various origins was analyzed at the *Ppd-1* and *ZCCT-1* loci. Possible combinations of alleles for each of the studied loci in bread and durum wheat varieties were identified, and the most common variants were determined. Among the studies of bread wheat varieties, eleven *Ppd-1* genotypes were identified. Two mutant recessive alleles were low-frequency in bread wheat varieties, whereas one was widely distributed in durum wheat. The *ZCCT-1* locus in the studied varieties is represented mostly by two genes. Absence of *ZCCT-B1* (null allele) is standard. In bread wheat varieties, only one gene (double null allele) and all three ZCCT-1 genes were detected once. The frequency of the null allele for *ZCCT-B1* is comparable to that of varieties carrying two other genes (*ZCCT-D1, ZCCT-A1*) of the *ZCCT-1* locus. The combination of *ZCCT-1* with the alleles *Ppd-A1b* or *Ppd-A1_del2ex7* is also comparable in the frequency of distribution in varieties. The distribution frequency in the combination *ZCCT-1* varieties with the alleles *Ppd-A1b* or *Ppd-A1_del2ex7* is also comparable. The analysis results can be used in genetic and plant breeding research to select genotypes and predict agronomically important traits in wheat.

Keywords: bread wheat (T. aestivum. L), durum wheat (T. durum. Desf.), Ppd1, ZCCT1, DNA polymorphism, DNA markers.

Abbreviations:

PRR is Pseudo-Response-Regulator,

FT is Flowering Time,

Vrn is Vernalization,

Ppd is Photoperiod,

$ZCCT$ is Zinc Finger CCT,

DNA is Deoxyribonucleic Acid,

$CTAB$ is Cetyltrimethylammonium Bromide,

PCR is Polymerase Chain Reaction.

Introduction

Increasing the adaptive potential of created genotypes of valuable cereal species, particularly wheat, due to optimal development rates in a specific growing region continues to attract significant attention. It is one of the essential directions of modern plant breeding programs (*Hasan et al., 2021*). In wheat, as in other cereal crops, the *Ppd* and *Vrn* gene systems are the main ones in controlling the adaptive responses of the plant organism to the environment. By controlling the duration and rate of the initial stages of organogenesis, the alleles of the *Vrn* and *Ppd* genes have a direct effect on many important traits, in particular, the level of formation of yield components, the resistance of genotypes to adverse conditions caused by the action of biotic and abiotic factors.

Ppd-1 genes of wheat are localized in the short arm of chromosomes of the second homeologous group. They belong to the family of *PRRs* (*Beales et al., 2007*; *Cockram et al., 2007*), whose protein products directly influence the activity of other genes, in particular *FT*, which are responsible for the induction of flowering (*Turck et al., 2008*; *Fernandez-Calleja et al., 2021*). There is a direct relationship, particularly in wheat, between the expression of dominant *Ppd-1* alleles, the transcriptional activity of the *FT* (*Vrn 3*) locus, and heading time. (*Nishida et al., 2013*).

Ppd-1 genes are important regulators of flowering in cereals. Thus, varieties that weakly respond to photoperiod are more adapted to growing conditions in areas with short winter, early spring, and high summer temperatures (*Law et al., 1997*; *Worland et al., 1998*). Photoperiod-insensitive alleles became widespread in bread wheat varieties after the "green revolution." Mutations identified in dominant alleles of *Ppd-1* are due to deletions or insertions in the promoter region, such as an increase in the number of copies of this gene (CNV mutants) (*Diaz et al., 2012*).

The influence of dominant alleles of *Ppd-1* from homeologous A, B, and D genomes of wheat on the reduction of sensitivity to photoperiod and heading time is not equivalent. Thus, the dominant allele *Ppd-D1a* is less sensitive to photoperiod and is associated with the earliest flowering in short days. Lower expression levels were shown for dominant alleles of the *Ppd-A1* and *Ppd-B1* genes (*Bentley et al. 2013*).

PPD-1 proteins induce the *Vrn* 3 flowering locus, the repressor of which is the *Vrn2* locus, as one of the important elements of the adaptive regulatory mechanism of vernalization (*Kippes et al., 2016*).

It is known that the *VRN2* locus in wheat contains genes that encode transcription factors of the ZCCT type with the so-called "zinc finger" structure and the CCT motif, which is similar to other proteins in *A. thaliana* (*Kinmonth-Schultz et al., 2019*).

ZCCT genes were first mapped in the diploid wheat genome in the region of the long arm of chromosome 5A (translocation from 4A). In hexa- and tetraploid wheat, in addition to chromosome 5A, they are also localized in the long arms of chromosomes of the fourth homologous group of B- and D-genomes. Each polyploid wheat genome contains three copies of the *ZCCT* gene. One of these copies (*ZCCT-3*) is reduced and not functional. Only the *ZCCT-1* and *ZCCT-2* genes retain functional activity. In addition, duplication of the *ZCCT-B2* gene is frequently observed (*ZCCT-B2a* and *ZCCT-B2b* copies) (*Distelfeld et al., 2009*; *Zhu et al., 2011*).

The primary attention in wheat is paid to the study of *ZCCT-1*, which, according to many studies, is the most influential on the rate of development and the reduction of the response to

vernalization. A dose-dependent effect on development rates characterizes the number of functional *ZCCT1* genes and, according to existing knowledge about epistatic interaction with other *VRN* genes, can potentially affect agronomic traits (*Yan et al., 2015*).

Decreased sensitivity to vernalization due to mutations in the *ZCCT* gene sequence encoding the CCT domain or the presence of null alleles for these genes (*Distelfeld et al., 2009*; *Zhu et al., 2011*). Recent studies have found that the *VRN-B2* gene has more influence on the need for vernalization in wheat than its homologous gene *VRN-D2* (*Kippes et al., 2016*).

The study aimed to research the allelic diversity at the *Ppd-1* and *ZCCT-1* loci of bread wheat (*T. aestivum*) and durum wheat (*T. durum*) varieties of different origins and identification of genotypes carrying the corresponding alleles based on DNA markers.

Since the rate of passage of the stage from germination to heading is controlled by the genes of these two genetic systems, obtaining data on the variability of both *Ppd* and *Vrn* loci, in particular *ZCCT-1*, is of scientific and practical interest. The use of molecular markers significantly increases the efficiency of identification of a large amount of genetic material, providing valuable information for understanding the adaptive value of single alleles or their combinations in specific wheat cultivation conditions.

Materials and methods

Genetic material for research

Analysis of DNA polymorphism in the *Ppd-1* and *ZCCT-1* loci was carried out using 46 spring wheat varieties of different origins, in particular, 25 varieties of *T. aestivum* (Anshlag, Vetka, Heroinya, Katyusha, Skorospelka 95; Skorospelka 99; Svitanok, Srebryanka, Kharkovskaya 30; Etud/UKR; Apu/FIN; Herakles, Capta /FRA; Chanate, Loros/USA; Ciano 67; Opata 85; Turaco/MEX; Norin 29; Norin 17; Konosu 25/JPN; Balaganka, Duvanka, Sarrubra, Saratovskaya 29; Sibiryachka 4; Shortandinka, Strela, Poltavka/RUS) and 21 varieties of *T. durum* (Chornokoloska, Gordeiforme 3; Kharkovskaya 1; Kharkovskaya 3; Kharkovskaya 15; Kharkovskaya 21; Kharkovskaya 33; Kharkovskaya 37; Kharkovskaya 39; Kharkovskaya 51; Kuchumovka 46; Luganskaya 7; Mestnaya, Narodnaya /UKR; Beloturka/RUS; Trems, Presto de taviro/PRT; Merliuri, Tbilisuri 9/GEO; Shirvan 5/AZE; Gumillo/ITA).

Molecular genetic analysis

Total DNA from wheat grains and seedlings was isolated using the CTAB method. Gene marker analysis was carried out according to recommendations in the literature: *Ppd-A1* (*Wilhelm et al., 2009*), *Ppd-A1_del303*, *Ppd-A1_del2ex7* (*Takenaka et.al., 2012*), *Ppd-B1a* (*Diaz et.al, 2012*), *Ppd-D1, Ppd-B1c* (*Beales et.al, 2007*), *Ppd-D1a*, *Ppd-D1b*; *Ppd-D1c* (Show et.al, 2013), *Ppd-D1d* (*Guo et.al., 2010*), *ZCCT-1* (*Zhu et al., 2011*).

Samples of isolated DNA from the studied varieties were amplified by allele-specific PCR. PCR amplification products were tested using electrophoresis in agarose and polyacrylamide gels. The sequences of PCR primers, the composition of the reaction mixture, the conditions for PCR amplification, electrophoresis, and visualization of PCR products are also given in the above literature.

The DNA marking data analysis was performed using Microsoft Excel.

The results of the study

DNA markers analyzed the variability of 25 spring bread wheat (*T. aestivum*) varieties and 21 spring durum wheat (*T. durum*) varieties at the *Ppd-1* and *ZCCT-1* loci.

The study of the Ppd-1 locus

DNA marking of *Ppd-1* alleles was carried out, in particular *Ppd-D1a*, *Ppd-D1b, Ppd-D1c*, *Ppd-D1d*, *Ppd-B1c, Ppd-B1a, Ppd-A1b, Ppd-A1_del303, Ppd-A1_del2ex7*.

Marker fragments are 288 bp -*Ppd-D1a*, 414 bp - *Ppd-D1b,* 672 bp - *Ppd-D1c*, 174 bp - *Ppd-D1d*, 223 bp -*Ppd-B1a*, 452 bp – *Ppd-A1b*, 425 bp - *Ppd-B1c*, 220 bp - *Ppd-A1_del303,* 170 bp - *A1_del2ex7*.

Ppd-1 (T. aestivum)

Nine alleles were found at the locus *Ppd-1* due to the DNA marking analysis of the studied bread wheat varieties, based on the combination of which 11 *Ppd-1* genotypes were identified (*Table 1*). The most common allele in the studied sample of spring varieties is *Ppd-D1c*. This allele was detected in 10 (40%) of the studied varieties (*T. aestivum*) of different origins, including four of Ukrainian plant breeding.

The *Ppd-D1c* allele carriers were varieties Anshlag, Heroinya, Skorospelka 95, Kharkovskaya 30, Herakles, Balaganka, Duvanka, Saratovskaya 29, Poltavka, Sarrubra.

Nine out of 10 varieties with the *Ppd-D1c* allele also had the most common genotype in this sample, *Ppd-D1cPpd-B1Ppd-A1b*, the frequency of which was 36±9.6%. This genotype was identified in representatives of different origins, including four Ukrainian varieties: Anshlag, Heroinya, Skorospelka 95, and Kharkovskaya 30.

The genotype *Ppd-D1aPpd-B1bPpd-A1b* was present in the sample with a frequency of 20±8.0. This genotype was identified in varieties of different origins, including two Ukrainian varieties, Katyusha and Skorospelka 99, and in varieties Capta, Chanate, and Norin 17 from France, the USA, and Japan.

The *Ppd-B1* gene multicopy alleles are presented in various combinations with alleles of two other photoperiod genes as part of nine other genotypes, occurring in one or two varieties from the sample with a frequency of 4±3.9 and 8±5.4, respectively.

Varieties with dominant *Ppd-A1* have not been identified, but carriers of mutant recessive alleles *Ppd-A1_del303* and *Ppd-A1_del2ex7* are present.

Single cases of mutant alleles were identified in the *Ppd-1* genotypes of the Mexican varieties Ciano 67 (*Ppd-D1aPpd-B1bPpd-A1_del303*), Opata 85 (*Ppd-D1aPpd-B1bPpd-A1_del2ex7*), and the Eastern European variety Sarrubra (*Ppd-D1cPpd-B1bPpd-A1_del2ex7*).

Ppd-1 (T. durum)

Two Ppd-1 genes control the photoperiodic response in durum wheat. The main differences in the trait manifestation are associated with the *Ppd-A1* gene.

It is known that *T. durum* has two dominant alleles, *Ppd-A1a.2* and *Ppd-A1a.3*, the first of which has a higher expression level. In the set of spring varieties of durum wheat, the *Ppd-A1a.2* and *Ppd-A1a.3* alleles were detected in Luganskaya 7 and Merliuri, respectively (*Bentley et.al., 2011*).

In tetraploid wheat species, the *Ppd-A1* gene is highly polymorphic. According to the data of some authors (*Takenaka et.al., 2012*), it is considered to be more than 60 haplotypes, including haplotypes with a 303 bp deletion in exons 5,6 and a 2 bp deletion in exon 7. The *Ppd-A1_del303* allele was not detected in durum wheat varieties, unlike in bread wheat, which is consistent with literary sources. Royo et al. (*2018*) reported the presence of this allele only in ancient varieties of durum wheat and its absence in modern commercial ones. On the contrary, the *Ppd-*

A1_del2ex7 allele is widely distributed in durum wheat. The mutant allele in the sample studied was detected in 10 (47.6%) from 21 varieties of various origins, including seven Ukrainian (Kuchumovka, Chornokoloska 46; Kharkovskaya 21; Kharkovskaya 39; Kharkovskaya 33; Kharkovskaya 37; Narodnaya) and three others (Beloturka, Tbilisuri 9; Trems).

The *Ppd-A1b* allele was detected in nine (43%) of the *T. durum* studied varieties, including 6 Ukrainian (Gordeiforme 3; Kharkovskaya 1; Kharkovskaya 15; Kharkovskaya 3; Kharkovskaya 51; Mestnaya).

Thus, marker analysis made it possible to identify varieties of bread and durum wheat carriers of specific alleles of the *Ppd-1* genes and determine their *Ppd-1* genotypes. The indicated varieties can be used in plant breeding programs as donors of these or other alleles of photoperiod sensitivity genes or their various combinations.

The study of the ZCCT-1 locus

ZCCT-1 (T. aestivum)

Based on the results of the analysis, it was established that the ZCCT-1 locus in the studied spring bread wheat (T. aestivum) varieties is mainly represented by the *ZCCT-D1* and *ZCCT-A1* genes.

It was shown that most varieties have a null allele for ZCCT-B1 at this locus, similar to the theoretical data presented in the literature (*Zhu et al., 2010*).

The double null allele *ZCCT-A1 ZCCT-B1* was identified in the Skorospelka 99 variety. All three genes were present in two Russian-bred varieties, Balaganka and Duvanka.

ZCCT-1 (T. durum)

In durum wheat varieties (*T. durum*), the *ZCCT-1* locus is also represented by two genes. A combination of two genes, *ZCCT-A1* and *ZCCT-B1*, was detected in 11 studied varieties. Some of these varieties (Kharkovskaya 33; Kharkovskaya 37; Narodnaya, Kharkovskaya 3; Kharkovskaya 51; Mestnaya) are from Ukraine, and five varieties (Beloturka, Shirvan 5; Gumillo, Merliuri, Tbilisuri 9) are of other origin.

The null allele *ZCCT-B1* was detected in 10 (47.6%) varieties, including eight Ukrainian (Kuchumovka, Chornokoloska 46; Kharkovskaya 21; Kharkovskaya 39; Gordeiforme 3; Kharkovskaya 1; Kharkovskaya 15; Luganskaya 7) and two (Trems, Presto de Tavira) of another origin.

In combination with the *Ppd-A1_del2ex7* allele, the null allele for *ZCCT-B1* was detected in 5 varieties (Kharkovskaya 33; Kharkovskaya 37; Narodnaya, Beloturka, Tbilisuri 9), in combination with *Ppd-A1b* it was found in 4 varieties (Gordeiforme 3; Kharkovskaya 1; Kharkovskaya 15; Presto de Tavira), which amounted to 23.8% and 19.0% in this sample, respectively.

The combination of *ZCCT-A1ZCCT-B1/Ppd-A1_del2ex7* and *ZCCT-A1 ZCCT-B1/Ppd-A1b* was found in ten varieties and equal numbers. (*Table 2*).

Therefore, varieties with different *Ppd-1* and *ZCCT-1* genotypes can create the genetic material necessary to study the effect of single specific alleles and their combinations on development rate and other traits.

Discussion

A wide range of studies of photoperiodic response in spring varieties of bread wheat indicate the predominance of carriers with recessive *Ppd-1*. In particular, carriers of recessive

alleles are varieties from Scandinavian countries (Sweden, Finland), where spring comes late and daylight hours in summer are 18-19 hours.

Since multiple alleles were found for the *Ppd-1* genes, and each gene represents a series of sensitive and insensitive alleles, marking of recessive mutant alleles of the *Ppd-D1* and *Ppd-A1* genes made it possible to identify high variability in combinations of alleles of photoperiod genes.

Marking of *Ppd-1* loci was performed in 25 varieties of spring bread wheat (*T. aestivum*) of different origins, which allowed the identification of eleven *Ppd-1* genotypes with different combinations of *Ppd-1* alleles. In this sample, the most common genotype was *Ppd-D1cPpd-B1bPpd-A1b*. At the same time, in the sample of varieties, another genotype was detected with the most common allele among the studied varieties *Ppd-D1c* and with a rare allele *A1_ del2ex7* (*Ppd-D1cPpd-B1bPpd-A1_ del2ex7*), which has a corresponding mutation in *Ppd-A1*.

The decrease in photoperiodic response due to the influence of dominant alleles increases in temperate climate zones and, especially at low latitudes. In the total sample of varieties, the *Ppd-D1a* allele and the *Ppd-D1aPpd-B1bPpd-A1b* genotype were found with high frequency, detected in 20% of the varieties. The dominant *Ppd-D1a* allele is also present in a variety of four other *Ppd*-genotypes, including, in some, combinations with the dominant *Ppd-B1a* and *Ppd-B1c*.

In low-latitude varieties, in Mexico and Japan, where daylight hours are shortened and amount to 13-14 hours, varieties with a low reaction to photoperiod predominate. Among Japanese varieties, spring and winter varieties often have digenic dominant *Ppd* control. Only Norin 29 had the *Ppd-D1bPpd-B1cPpd-A1b* genotype in the Japanese varieties studied. A monogenic control involving the *Ppd-B1a* allele was not detected, most likely due to the small sample size. The Mexican variety Turaco with the genotype *Ppd-D1bPpd-B1aPpd-A1b* was one of the parents in creating the Ukrainian variety Etud, which inherited two dominant *Ppd* alleles. The high variability of *Ppd-1* genotypes is also due to allelic differences in the *Ppd-A1* gene, although the *Ppd-A1b* allele was mainly detected in the varieties presented in the sample. The *Ppd-A1_del303* allele was found only in the Mexican variety Ciano 67 in combination with *Ppd-D1a*. It can be noted that, unlike winter wheat, which often has mutant recessive alleles of the Ppd-D1 gene, including in combination with Ppd-A1_del303, in spring wheat, the allele of the *Ppd-A1* gene with a deletion in exons 5,6 is rare.

In the sample of durum wheat varieties, this mutant allele was not detected. However, according to literature data, *Ppd-A1_del303* was detected in ancient European varieties but not in modern commercial ones (*Royo et al., 2018*).

The data on marking the *Ppd-A1_del2ex7* allele in bread wheat and durum wheat are particularly interesting. According to the marking results, the allele with a deletion in exon 7 is widely represented in the *T. durum* but is rare in common wheat. The *Ppd-A1_del2ex7* allele was detected in the Sarrubra (RUS) and Opata 85 (MEX) varieties. The Sarrubra variety was obtained from a combination of crossing the spring variety Poltavka (*T. aestivum, PpdD1cPpdB1bPpdA1b*) and Beloturka (*T. durum, Ppd-A1_del2ex7*). The Sarrubra variety inherited a mutant recessive allele of the *Ppd-A1* gene from a durum wheat variety, which resulted in the formation of the *PpdD1cPpdB1bPpdA1_ del2ex7* genotype. With such an allelic combination, it can be assumed that this variety has a later heading.

Mutations in the *ZCCT* gene encoding the *CCT* domain or the presence of null alleles for these genes cause decreased sensitivity to vernalization (*Distelfeld et al., 2009*; *Zhu et al., 2011*).

No polyploid wheat representative has been identified that simultaneously contains null alleles or non-functional variants of all *ZCCT* genes (*Distelfeld et al., 2009*; *Zhu et al., 2011*). Some known mutations lead to changes in amino acid sequences in the CCT domain of ZCCT1 proteins, which are associated with changes in heading time (*Distelfeld et al., 2009*).

Each of the polyploid wheat genomes contains three *ZCCT* genes, of which the primary attention is paid to the study of *ZCCT-1*, which, according to many studies, has more on the rate of development and the reduction of the response to vernalization (*Yan et al., 2015*). According to the results of this study at the *ZCCT-1* locus, it was found that among the analyzed of spring bread wheat genotypes of different development types and origins, there is a significant spread of the variant with a null allele for the *ZCCT-B1* gene, which correlates with literature data. It should be noted that the absence of *ZCCT-B1* is widely found, as is already known, in Ukrainian varieties and other European genotypes. At the same time, there is evidence in the literature of a relatively low frequency of the null allele for *ZCCT-B1* in bread wheat varieties of American and Chinese origin. However, double mutants were found in them (*Zhu et al., 2011*).

It is known that varieties lacking *ZCCT-B1* are more common among spring wheat genotypes than winter wheat genotypes and durum wheat genotypes of different growth types. As shown in this study, the *ZCCT-1* locus in spring durum wheat varieties was represented by two genes, and 47.6% of them had a null allele at *ZCCT-B1*. The presence of null alleles results in the absence of the translation product of the corresponding *ZCCT1* gene, which eliminates any competitive interaction with other proteins containing the *CCT* domain. It can be assumed that the presence of null alleles of *ZCCT1* genes can affect the indicators of traits directly or indirectly regulated by genes encoding *CCT*-domain-containing proteins that enter into competitive interaction with *ZCCT* proteins. Identifying and assessing the prevalence of null-allele mutants for the *ZCCT1* genes in hexaploid and tetraploid wheat is particularly interesting in this connection.

Since the rate of passage of the stage from germination to heading is controlled by genes of two genetic systems, *Vrn* and *Ppd*, information on the variability of both *Ppd*-genotypes and *Vrn*-genotypes, in particular the genes of the *ZCCT-1* locus, is necessary and valuable.

Using molecular markers significantly increases the efficiency of identifying large amounts of genetic material, providing initial information for understanding the adaptive value of single alleles or their combinations in specific wheat cultivation conditions (*Fait & Balashova, 2022*).

Conclusion

Variability of *Ppd-1* genotype varieties of two commercial wheat species (*T. aestivum*, *T. durum*) is shown.

The allele *Ppd-D1c* and the genotype *Ppd-D1cPpd-B1bPpd-A1b* were the most common in spring-bread wheat varieties.

The *Ppd-D1a* allele, which became widespread as a result of the green revolution, is presented in five combinations with alleles of two other photoperiod genes, of which the *Ppd-D1aPpd-B1bPpd-A1a* genotype is predominant.

A rare presence of mutant recessive alleles *Ppd-A1_del303* and *Ppd-A1_del2ex7* encoding non-functional proteins was detected in spring bread wheat varieties and a broad prevalence of the one latter in durum wheat varieties.

The *ZCCT-1* locus in *T. aestivum* varieties is mainly represented by the *ZCCT-D1* and *ZCCT-A1* genes (null alleles for *ZCCT-B1*). In the *T. durum* varieties, the proportion of carriers of the *ZCCT-A1* genotypes (null alleles for *ZCCT-B1*) and *ZCCT-B1ZCCT-A1* is comparable.

Varieties with different *Ppd-1* and *ZCCT-1* genotypes can be used in genetic and plant breeding research to study the effects of single alleles and allelic combinations, create new genetic material, and in wheat breeding practice.

Conflict of interest

The authors declare that there is no conflict of interest.

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Appendix

Table 1. *Ppd*-genotypes of spring bread wheat (*T. aestivum*) varieties

Ppd-genotype	Varieties	n	$P \pm S_p$
Ppd-D1cPpd-B1bPpd-A1b	Anshlag, Heroinya, Skorospelka 95, Kharkovskaya 30, Herakles, Balaganka, Duvanka, Saratovskaya 29, Poltavka	9	36±9,6
PpdD1d Ppd-B1bPpd-A1b	Apu, Sibiryachka 4	2	8±5,4
Ppd-D1aPpd-B1bPpd-A1b	Capta, Chanate, Katyusha, Norin 17, Skorospelka 99	5	20±8,0
Ppd-D1aPpd-B1bPpd-A1_del303	Ciano 67	1	4±3,9
PpdB1a Ppd-D1aPpd-B1cPpd-A1b	Konosu 25	1	4±3,9
Ppd-D1aPpd-B1aPpd-A1b	Etud, Turaco	2	8±5,4
PpdD1d Ppd-B1aPpd-A1b	Loros	1	4±3,9
PpdD1d Ppd-B1cPpd-A1b	Strela	1	4±3,9
Ppd-D1bPpd-B1cPpd-A1b	Norin 29	1	4±3,9
Ppd-D1aPpd-B1bPpd-A1_del2ex7	Opata 85	1	4±3,9
Ppd-D1cPpd-B1bPpd-A1_ del2ex7	Sarrubra	1	4±3,9

Total		25	100

Table 2. *Ppd-A1* and *ZCCT-1* genotypes of spring durum wheat (*T. durum*) varieties

Variety	*Ppd-A1*	*ZCCT-1*	n	$P \pm S_p$
Kuchumovka, Chornokoloska 46, Kharkovskaya 21, Kharkovskaya 39, Trems	*PpdA1_del2ex7*	*ZCCT-A1*	5	23,8±9,29
Gordeiforme 3, Kharkovskaya 1, Kharkovskaya 15, Presto de taviro	*PpdA1в*	*ZCCT-A1*	4	19,0±8,56
Beloturka, Kharkovskaya 33, Kharkovskaya 37, Narodnaya, Tbilisuri 9	*PpdA1_del2ex7*	*ZCCT-A1* *ZCCT-B1*	5	23,8±9,29
Kharkovskaya 3, Kharkovskaya 51, Mestnaya, Shirvan 5, Gumillo	*PpdA1в*	*ZCCT-A1* *ZCCT-B1*	5	23,8±9,29
Luganskaya 7	*PpdA1a.2*	*ZCCT-A1*	1	4,8±4,66
Merliuri	*PpdA1a.3*	*ZCCT-A1* *ZCCT-B1*	1	4,8±4,66
Total		21		100

Yevhen S. Neseniuk [21]

Formation of a Marketing Strategy in the Context of Digitalisation, Entrepreneurship and Innovation Management [13]

Abstract: The article performs a thorough analysis of modern approaches to the formation of a marketing strategy in the context of digitalisation, entrepreneurship development and implementation of innovative management. It is determined that digital transformation changes the essence of marketing activities: marketing ceases to be an exclusive tool for promoting products and services, and is transformed into a strategic function that permeates all aspects of enterprise management. Particular attention is paid to the impact of innovation and entrepreneurial activity on the effectiveness of strategic decisions in marketing. The expediency of using an interdisciplinary approach that combines marketing tools, methods of innovative management and digital technologies to increase the adaptability of enterprises to dynamic changes in the market environment is substantiated. The author's vision of marketing as an integration centre for commercialisation of innovations, a driver of digital transformations and a source of sustainable competitive advantage of an enterprise is proposed. The paper analyses modern concepts, in particular, interaction marketing, crowd marketing, personalisation and an analytically-oriented approach to the consumer, as examples of tools that can form innovative marketing strategies. Examples of successful implementation of such strategies in the activities of enterprises in various industries are provided. The article may be useful for scholars, practitioners and managers interested in developing effective marketing strategies in the digital age.

Keywords: marketing strategy, digitalisation, entrepreneurship, innovation management, personalisation, customer experience, interaction marketing, digital technologies, strategic marketing, competitive advantage.

Introduction

In today's economy, characterised by dynamic changes, global competition and growing digitalisation, businesses are forced to adapt quickly to new conditions. At the same time, innovation is becoming increasingly important as a key driver of economic growth and competitiveness. In this context, marketing, management and entrepreneurship should be seen as interrelated components of strategic business development.

However, in practice, for many businesses, marketing is often perceived as an advertising or sales tool, separated from overall strategic management and innovation activities. This leads to low flexibility of enterprises, loss of potential markets and inefficient use of their resources. That is why an integrative approach to forming a marketing strategy as part of the system of innovation management and entrepreneurial development is relevant.

In the current digital transformation environment, marketing strategy is becoming not only a tool for promoting goods and services, but also a key element of the overall business strategy. Digitalisation opens up new opportunities for collecting and analysing data, personalising communications with target audiences, and improving the efficiency of sales channels. According to F. Kotler, digital technologies are transforming marketing into a strategic function that directly affects product innovation and value (*Kotler et al., 2021*).

At the same time, entrepreneurship in the digital era requires flexibility, speed of decision-making, and the ability to generate innovation. According to P. Drucker, the entrepreneurial

function is not only to create a new business, but also to constantly search for new opportunities in a changing environment (*Drucker, 2007*). In this context, the marketing strategy should consider the innovative potential of the enterprise, digital resources and the specifics of changes in consumer behaviour.

Modern research emphasises the need to integrate marketing, entrepreneurship and innovation management into a single strategic management system. In particular, J. Tidd and J. Bessant emphasise the role of innovation orientation in marketing planning as a means of creating long-term competitive advantages (*Tidd & Bessant, 2020*). This requires an interdisciplinary approach to building strategies that can ensure not only the efficiency of current operations but also sustainable development in the future.

Thus, the formation of a marketing strategy in the context of digitalisation should be based on modern concepts of entrepreneurship and innovative management, which allows businesses to adapt to a changing environment, create new value for consumers and achieve sustainable growth.

Materials and methods

The study used a comprehensive interdisciplinary approach that combines methods of strategic, marketing, innovation and entrepreneurial analysis. The methodology is based on a systematic approach to studying the relationship between marketing, digitalisation, entrepreneurship and innovation management in the strategic development of enterprises. The theoretical and methodological framework of the study included modern concepts of strategic marketing (*Kotler et al., 2021*), innovation management (*Tidd & Bessant, 2020*), entrepreneurial dynamics (*Drucker, 2007*), and digital business transformation (*Digital Marketing Institute, 2024*; *Solomon, 2020*). To substantiate the relationship between marketing and management processes, the scientific works of M. Porter, R. Kaplan, D. Norton, and others were analysed.

The content analysis method was used to systematise literature sources, including scientific publications, analytical reports, digital platforms (*ResearchGate, PubMed, StreamGo*), as well as practices of leading companies implementing modern marketing strategies in the context of digital transformation.

The comparative analysis made it possible to compare classical and modern models of marketing activities, identify their limitations in the context of digitalisation and the advantages of the latest approaches, such as interaction marketing, personalised marketing, and the strategy of emotional customer engagement.

The method of systematisation and generalisation is used to form the author's own concept of an integrated marketing strategy based on a triune management relationship: 'enterprise—personnel—consumer'.

The method of case analysis is used to study practical examples of marketing strategies implemented by leading digital companies, as well as domestic enterprises that are actively implementing innovations in their business models.

The empirical basis of the study consists of secondary statistical data, the results of industry reports on the digital transformation of the market, the level of use of CRM systems, platform models and data analytics tools in marketing management.

In general, the chosen methods allowed not only to describe current trends in marketing and innovation management, but also to form a holistic scientific basis for developing an effective marketing strategy adapted to the conditions of the digital economy and entrepreneurial dynamics.

Results

The development of an enterprise in the 21st century is impossible without an effective management system that includes not only organisational management but also strategic planning, innovative solutions and adaptive marketing. Successful businesses are distinguished by their ability to combine marketing functions with management approaches to value creation that consider both customer needs and market opportunities.

The central element of a marketing strategy should be to achieve a competitive advantage through innovation—in products, services, technologies, and management. This advantage ensures a stable market position and customer loyalty.

According to the modern researcher R. Kaplan and his co-author D. Norton, the strategy in the digital economy should be integrated into all enterprise processes, and marketing should be not only a function but also a way of thinking (*Kaplan & Norton, 2004*).

Michael Porter, in his turn, emphasises that competitiveness is formed not only by reducing costs, but by creating unique value for the consumer (*Porter, 1985*). In today's environment, this value can only be created through innovation.

Modern strategic management is increasingly focused on project-oriented entrepreneurship, in which each innovation is seen as a separate business project with clearly defined goals, timeframes, and a performance evaluation system. In such a system, marketing ceases to be a mere communication function and takes on the role of a link between market opportunities and management decisions, forming the basis for effective commercialisation of innovations.

This connection is realised through a number of strategic marketing functions that ensure the integration of the market, product, and business processes within an innovation project:

- identification of innovative market needs. Marketing analytics helps to identify new trends, consumer expectations, and unmet demand, which becomes the starting point for the formation of an innovation project;
- creating a value proposition. Market insights are transformed into product or service concepts that meet the real needs of target consumers, which increases the chances of successful commercialisation;
- innovation life cycle management. Marketing accompanies the innovation from the hypothesis stage (e.g., MVP or prototype) to its launch, scaling and positioning in the competitive environment;
- ensuring the commercialisation of the innovation. Through communication channels, distribution, digital platforms, and customer feedback, marketing turns an innovative solution into a real profitable asset.

Therefore, the marketing function should be transformed into a strategic centre of innovation management that not only accompanies innovations but also initiates them through

an understanding of changing consumer needs and market dynamics. A modern marketer is no longer just an analyst or communicator, but a strategist and architect of consumer experience who combines the business goals of the enterprise with customer expectations in real time.

In today's digitalised and innovative management environment, marketing strategy development requires not only a revision of traditional paradigms, but also a deep integration of technological, behavioural and managerial factors. The evolution of marketing activities is no longer linear, but rather ecosystemic, where each element interacts with others in real time, creating a unique experience for the consumer and new opportunities for business.

Today, classical marketing models (production, commodity, sales) are losing their effectiveness due to too narrow specialisation, product focus or mass consumption without taking into account the complex dynamics of consumer behaviour. Instead, newer models, such as relationship marketing and engagement marketing, are coming to the fore, as they allow for flexible response to customer needs, involvement in the value creation process, and building long-term relationships (*Solomon, 2020*).

According to the scientist S. Vikstrom, the modern consumer is not just an object of influence, but an active participant in the process of creating a product, service and experience, which changes the very essence of marketing activities (*Vikstrom, 2019*). Ignoring this approach leads to a loss of relevance of marketing decisions and marginalisation of the brand in the eyes of the target audience.

An essential factor in the formation of a modern marketing strategy is the use of digital technologies, data analytics, and CRM systems. They allow businesses to accurately identify consumer needs, segment audiences, predict behaviour, and optimise decision-making processes. In the context of business digitalisation, companies need to change their approach to communication with customers—from unidirectional to interactive, personalised interaction.

Thus, an effective marketing strategy today should be based on three basic principles:

1. Integration of customer experience—creating a holistic, multi-channel interaction, taking into account the context, communication history and emotional involvement of the consumer;
2. Personalisation—offering relevant content, goods and services based on behavioural patterns;
3. Flexibility and adaptability—the ability to respond quickly to changes in the market, technology, and customer needs.

Innovative technologies such as artificial intelligence, machine learning, augmented reality (AR), voice search, chatbots, etc. play a significant role in this (*Digital Marketing Institute, 2024*). AI (artificial intelligence) allows automating data analysis, identifying hidden patterns of behaviour, creating personalised content, predicting the results of marketing campaigns, and effectively managing communication channels.

New business models based on digital platforms, crowdsourcing, agile hypothesis testing (lean models), and MVP development are creating a fundamentally new environment for implementing marketing strategies. For example, the use of A/B testing, rapid sprints, and real-time analysis allows businesses to optimise their operations based on customer behaviour.

According to M. Solomon, engagement marketing is based on the idea of two-way communication, where the consumer seeks not just to buy a product, but to be part of the

brand, to participate in shaping its identity (*Solomon, 2020*). The author believes that this model is the basis for the most successful strategies of our time, focused on creating a community around the brand and emotional engagement of customers.

In addition, it is necessary to emphasise the importance of the brand's ethical responsibility and its positioning as a social agent that shares the values of its target audience. In a world where consumers are becoming more and more conscious, it is the value-based identification with a brand that ensures long-term loyalty.

Therefore, a modern marketing strategy is not a set of tools, but a philosophy of customer experience management, where innovation, analytics and emotions interact in a single system. Thus, the future of effective marketing lies in dynamic adaptation, strategic thinking, high technology and a deep understanding of people as the main element of the market.

As for innovation management, it involves not only technological innovations, but also changes in the organisational structure, approaches to human resources management, corporate culture and motivation systems. Particular attention should be paid to communications, both internal (human resources management) and external (customer and partner marketing).

According to the author, innovation management is now transforming from a purely technological to a systemic one, where priority is given not so much to the introduction of new products as to the creation of an environment for continuous change. This environment should be built on trust, openness to feedback, and the ability to learn within the organisation.

In this context, the relationship between 'enterprise—consumer—staff' becomes strategically important. The author believes that the future of marketing lies in close integration with the HR function, as the key competitive advantage is formed not only through product innovation, but also through innovation in human interaction. Customer loyalty begins with employee loyalty: it is employees who are the brand ambassadors, who convey its values, shape customer experience and create an atmosphere of trust, which is a prerequisite for sustainable customer relations.

The formation of an enterprise's marketing strategy in the context of innovation and entrepreneurship should be based on three key management relationships:

- enterprise—consumer: personalisation of the value proposition according to the behavioural and emotional patterns of the client;
- enterprise—staff: managing an innovative culture that stimulates creativity, initiative and teamwork;
- staff—customer: creating a unique customer experience as a result of emotional engagement and professional competence of employees.

These links are not worth viewing as isolated management areas, but as a single system of marketing and organisational synergy, where people act as catalysts for change.

It is also important to ensure:

- implementation of standards of staff behaviour within the quality management system (in particular, ISO 10002:2018, which regulates customer satisfaction management);
- creating an inclusive consumer environment that considers not only economic but also social, cultural and emotional characteristics of target segments;

- application of entrepreneurial tools in marketing practice, including hypothesis testing, MVP creation, crowdsourcing, A/B testing, which provide a quick feedback loop and allow to test assumptions at early stages.

Thus, an effective strategy in a volatile market should be based on the principle of 'test fast—learn faster'. Success is no longer guaranteed by detailed planning, but is achieved through continuous experiential learning, flexible management, and deep empathy for the user. These are the approaches that ensure marketing that matches the pace of modern transformations—fast, dynamic, adaptive.

Conclusions

To summarise the results of the study, it is worth noting that marketing in the modern digital and innovative environment is losing its traditional function of being just a means of promoting a product or service. It is transforming into a strategic management philosophy that permeates all aspects of the business model of an enterprise—from identifying consumer needs to forming a value proposition, innovative development and commercialisation of ideas.

The future of an effective marketing strategy lies not in the number of advertising channels or the creativity of companies, but in the ability of the company to

- flexibly adapt to changes;
- integrate digital technologies into management practices;
- think systematically, combining the interests of business, customers and society.

The key challenge of today is the need to combine technological rationality with the human dimension. In this context, marketing becomes not only an analytical tool but also a carrier of emotions, values and brand culture. While the customer used to be the final stage of the process, today it is the starting point for all strategic decisions.

In today's environment, marketing can no longer be limited to classical concepts or an isolated approach to advertising, promotion or sales. It is evolving into an integrative management function that combines analysis, creativity, technology and entrepreneurial thinking. It is in this synergy that the potential for sustainable business development lies. The role of the marketer is gradually shifting from an executor to a strategic business architect who creates lasting value at the intersection of consumer needs, digital tools and innovative solutions.

It is worth noting that the success of innovative activities without appropriate marketing support is unlikely. Innovations do not create value by themselves—it is only formed by their correct positioning, communication, and integration into the customer's real experience. That is why marketing should become a central part of innovation management, not just a consequence of it.

Consequently, businesses that fail to review their marketing strategies through the prism of digitalisation, personalisation and entrepreneurial thinking risk losing market relevance. Instead, those who manage to combine analytics, innovation and emotional interaction into a single value system will create a new quality of customer relations and gain a sustainable competitive advantage.

Thus, considering all of the above, we can conclude that an effective marketing strategy in the 21st century is not a tool, but a worldview. It is the ability to think in terms of ecosystems, holistic customer experience and long-term interaction, where every action of the company has an ethical, emotional and strategic basis.

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