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FUNCTIONING OF STEM EDUCATION IN PEDAGOGICAL INSTITUTIONS OF HIGHER EDUCATION OF UKRAINE IN WARTIME CONDITIONS: PROBLEMS AND PROSPECTS FOR DEVELOPMENT

Abstract. The article examines contemporary challenges in the functioning of STEM education within the system of higher pedagogical education in Ukraine under wartime conditions. The relevance of the study is determined by the need to ensure the continuity and quality of professional preparation of prospective teachers of natural sciences, mathematics, computer science, and technology amid the destruction and relocation of educational infrastructure, academic staff losses, unequal access to laboratory and digital resources, accelerated digital transformation, and the need to prepare the Ukrainian education system for post-war recovery. The aim of the article is to comprehensively identify and systematize the key challenges affecting the development of STEM education in Ukrainian pedagogical higher education institutions under wartime conditions, determine the interrelationships among these challenges, and substantiate a conceptual model of STEM teacher education. To achieve this aim, the study employed a systematic analysis of scholarly publications and regulatory and policy documents, comparative-pedagogical, structural-functional, and problem-oriented analysis, as well as methods of systematization, generalization, classification, and modelling. The methodological framework of the study is based on conceptualizing STEM education as an integrated and multidimensional system whose effective functioning depends on the interaction of institutional, human-resource, infrastructural and resource, digital, psychological-pedagogical, and methodological factors. The main results demonstrate the existence of six interrelated groups of challenges affecting STEM education in Ukrainian pedagogical higher education institutions: organizational and institutional, infrastructural and resource, human-resource, digital and technological, psychological and pedagogical, and methodological challenges. The findings indicate that wartime conditions not only exacerbate existing challenges in STEM teacher education but also generate new requirements for the organization of the educational process, particularly regarding flexibility, the provision of distance and blended learning, digital security, the psychological resilience of educational participants, the development of international partnerships, and the continuity of professional preparation. On this basis, a conceptual model for the functioning of STEM education was substantiated, integrating regulatory and legal, organizational, human-resource, infrastructural and resource, digital, psychological-pedagogical, and monitoring and evaluation components. The scientific novelty of the study lies in the systematic structuring of the challenges facing STEM education in Ukrainian pedagogical higher education institutions under wartime conditions, the identification of their interrelationships, and the conceptualization of STEM teacher education as an adaptive, resilient, and digitally oriented system. The novelty also consists in substantiating a model of its functioning that integrates enabling, process-oriented, and outcome-oriented components. The practical significance of the study lies in the potential application of its findings to the modernization of educational and professional programs for prospective STEM teachers, the development of institutional STEM education strategies in pedagogical universities, the planning and renewal of digital and laboratory infrastructure, the professional development of academic and teaching staff, the expansion of international partnerships, and the implementation of innovative educational technologies. The study concludes that the effective

functioning of STEM education in Ukrainian pedagogical higher education institutions under wartime conditions requires a transition from fragmented responses to individual challenges towards a systemic and adaptive model focused on educational resilience, digital transformation, human-resource development, institutional and resource capacity, and the quality of professional preparation of prospective teachers. Such an approach provides a conceptual foundation for the modernization and sustainable development of pedagogical STEM education during both the wartime and post-war periods.

Key words: STEM education, pedagogical institutions of higher education, martial law, professional training, STEM competence, higher education of Ukraine.

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ФУНКЦІОНУВАННЯ STEM-ОСВІТИ У ПЕДАГОГІЧНИХ ЗАКЛАДАХ ВИЩОЇ ОСВІТИ УКРАЇНИ В УМОВАХ ВОЄННОГО ЧАСУ: ПРОБЛЕМИ ТА ПЕРСПЕКТИВИ РОЗВИТКУ

Анотація. У статті досліджено сучасні проблеми функціонування STEM-освіти у системі вищої педагогічної освіти України в умовах воєнного часу. Актуальність дослідження зумовлена необхідністю забезпечення безперервності та якості професійної підготовки майбутніх учителів природничих наук, математики, інформатики й технологій в умовах руйнування та релокації освітньої інфраструктури, кадрових утрат, нерівного доступу до лабораторних і цифрових ресурсів, посилення цифрової трансформації та необхідності підготовки системи освіти до післявоєнного відновлення України. Метою статті є комплексне визначення та систематизація ключових проблем розвитку STEM-освіти у педагогічних закладах вищої освіти України в умовах воєнного часу, встановлення взаємозв'язків між ними та обґрунтування концептуальної моделі функціонування STEM-підготовки майбутніх педагогів. Для досягнення поставленої мети використано систематичний аналіз наукових публікацій і нормативно-правових документів, порівняльно-педагогічний, структурно-функціональний та проблемно-орієнтований аналіз, методи систематизації, узагальнення й класифікації, а також моделювання. Методологічною основою дослідження визначено розгляд STEM-освіти як цілісної багатокомпонентної системи, функціонування якої забезпечується взаємодією інституційних, кадрових, ресурсних, цифрових, психолого-педагогічних і методичних чинників. Основні результати дослідження засвідчили наявність шести взаємопов'язаних груп проблем STEM-освіти педагогічних закладів вищої освіти України: організаційно-інституційних, матеріально-технічних, кадрових, цифрово-технологічних, психолого-педагогічних та методичних. Установлено, що воєнні умови не лише посилюють традиційні проблеми STEM-підготовки, а й формують нові вимоги до організації освітнього процесу, зокрема щодо його гнучкості, забезпечення дистанційної та змішаної взаємодії, цифрової безпеки, психологічної стійкості учасників освітнього процесу, розвитку міжнародного партнерства та забезпечення безперервності професійної підготовки. На цій основі обґрунтовано концептуальну модель функціонування STEM-освіти, що інтегрує нормативно-правовий, організаційний, кадровий, матеріально-технічний, цифровий, психолого-педагогічний та моніторингово-оцінювальний компоненти. Наукова новизна одержаних результатів полягає у системному структуруванні комплексу проблем STEM-освіти педагогічних закладів вищої освіти України в умовах війни, установленні їх взаємозалежності та концептуалізації STEM-підготовки як адаптивної, стійкої й цифрово орієнтованої системи, а також в обґрунтуванні моделі її функціонування, яка поєднує забезпечувальні, процесуальні та результативні компоненти. Практичне значення дослідження визначається можливістю використання запропонованих положень під час модернізації освітньо-професійних програм підготовки майбутніх учителів STEM-дисциплін, розроблення стратегій розвитку STEM-освіти педагогічних університетів, планування цифрової та лабораторної інфраструктури, підвищення кваліфікації науково-педагогічних працівників, розвитку міжнародного партнерства та впровадження інноваційних освітніх технологій. Висновок полягає у тому, що ефективне функціонування STEM-освіти у педагогічних закладах вищої освіти України в умовах воєнного часу потребує переходу від фрагментарного розв'язання окремих проблем до системної адаптивної моделі, орієнтованої на стійкість, цифрову трансформацію, кадровий розвиток, ресурсну спроможність та якість професійної підготовки майбутніх учителів, що створює концептуальні передумови для модернізації педагогічної STEM-освіти у воєнний і післявоєнний періоди.

Ключові слова: STEM-освіта, педагогічні заклади вищої освіти, воєнний стан, професійна підготовка, STEM-компетентність, вища освіта України.

Problem Statement. The rapid development of science, digital technologies, artificial intelligence, robotics and engineering systems necessitates the modernization of the higher education system in accordance with the modern requirements of the innovative economy and knowledge society. In this context, STEM education is considered one of the key areas of training competitive specialists capable of interdisciplinary thinking, scientific research, engineering design, digital creativity and solving complex practical problems. The development of STEM education in pedagogical institutions of higher education is of particular importance, since it is they who provide the training of future teachers of natural sciences, mathematics, computer science and technology, on whose professional competence the further implementation of STEM approaches in secondary education institutions depends.

At the same time, the functioning of the higher pedagogical education system of Ukraine takes place in conditions of a full-scale war, which significantly complicated the implementation of the educational process and actualized the need to revise traditional models of professional training of future teachers. The destruction of educational infrastructure, damage to educational buildings and laboratories, relocation of higher education institutions, forced migration of students and teachers, shortage of material and technical resources, unstable energy supply, psychological stress and the need to organize training in blended and distance formats significantly affect the quality of training of future teachers of STEM disciplines.

These challenges are particularly acute in pedagogical universities, since STEM education is based on the widespread use of laboratory equipment, experimental research, digital measuring systems, engineering modeling, robotics complexes, modern software and project-based teaching methods. In wartime conditions, access to such resources is significantly limited, which negatively affects the formation of professional competencies of future teachers and requires the search for new organizational, methodological and technological solutions.

At the same time, modern challenges have become a powerful incentive for the accelerated digital transformation of pedagogical education. Higher education institutions are actively implementing distance learning platforms, virtual laboratories, cloud technologies, computer modeling tools, computer-aided design systems, digital educational resources, and artificial intelligence tools. However, the effectiveness of their use largely depends on the level of digital competence of teachers, the availability of modern infrastructure, methodological support for STEM education, and the creation of a safe educational environment.

An analysis of current practice shows that most research is devoted to individual aspects of the development of STEM education, the digitalization of the educational process, or the organization of distance learning. At the same time, the complex problems of the functioning of STEM education in pedagogical institutions of higher education in Ukraine in wartime conditions remain insufficiently studied. Further scientific substantiation of the issues of the relationship between organizational, personnel, material and technical, psychological and pedagogical and digital and technological factors that determine the quality of professional training of future teachers of STEM disciplines, as well as the development of conceptual models for adapting pedagogical STEM education to crisis conditions, is required.

Thus, the relevance of the study is due to the objective need for a comprehensive analysis of modern problems of the functioning of STEM education in pedagogical institutions of higher education in Ukraine in wartime conditions, identification of key factors of its effectiveness and substantiation of scientific and practical approaches to the modernization of professional training of future teachers in accordance with the needs of the post-war reconstruction of the state, digital transformation of education and integration of Ukraine into the European educational and research space.

Analysis of recent research and publications.

Systematic literature review: foreign research on STEM education issues in higher pedagogical education (2020–2026)

Analysis of modern scientific literature shows that during 2020–2026, STEM education research shifted from considering individual methods of integrated learning to a comprehensive study of university STEM ecosystems, professional training of future teachers, digital transformation, the use of artificial intelligence, and ensuring the sustainability of education in crisis conditions. The most cited works of this period are indexed in Scopus and Web of Science and published in the journals *International Journal of STEM Education*, *Journal of Science Education and Technology*, *Education Sciences*, *Frontiers in Education*, *Humanities and Social Sciences Communications*, *European Journal of STEM Education*, and others.

1. Professional training of future STEM educators

The problem of forming professional competence of future teachers of STEM disciplines is most actively studied. A systematic review published in *Frontiers in Education* (2026) summarized the results of 26 empirical studies selected according to the PRISMA 2020 recommendations from the Scopus and Web of Science databases [34]. The authors

proved that the most effective training models are the integration of project-based learning, engineering design, digital technologies and practice-oriented activities. At the same time, the main barriers remain insufficient interdisciplinary teacher training, limited technological infrastructure and rigidity of university curricula.

Similar conclusions were reached by Segarra-Morales and Rodríguez-Miranda, who in their systematic review *Teacher Training and Conceptual Dimensions for the Implementation of STEAM Education* identified six conceptual components of the training of a modern STEM/STEAM teacher: pedagogical, technological, engineering, research, digital and socio-communicative [37]. The authors emphasize that the effectiveness of STEM training is determined not by the number of integrated disciplines, but by the quality of interdisciplinary interaction.

2. Professional development of STEM teachers

A separate direction is research on the professional development of teachers. A systematic review by Rehman et al. (2025), published in *Humanities and Social Sciences Communications*, summarized current models of professional development for STEM teachers [35]. The authors found that long-term professional development programs that combine mentoring, practice, digital tools, and professional communities are the most effective. At the same time, short-term courses without pedagogical support demonstrate low effectiveness and do not provide sustainable changes in teaching practice.

3. Digital transformation of STEM education

After the COVID-19 pandemic, digitalization has become one of the leading research areas. In most modern works, digital laboratories, cloud services, virtual and augmented reality are considered as integral components of modern STEM education. At the same time, the authors note that digital technologies cannot completely replace real laboratory experiments, especially when training future teachers of natural sciences [12].

4. Artificial Intelligence in STEM Education

A new scientific trend in 2024–2026 was research into the use of generative artificial intelligence. A systematic review by Memari and Ruggles, which covered 258 studies, showed significant potential for intelligent learning systems, automated assessment and adaptive learning [27]. At the same time, the authors identified significant risks: fragmented implementation, problems with academic integrity, unequal access to digital infrastructure and insufficient integration of AI with interdisciplinary STEM practices.

5. STEAM and transdisciplinary approach

The review of STEAM in Tertiary and Teacher Education demonstrates the current trend of transition

from the classical STEM model to STEAM, which involves the integration of art, design and humanities [18]. The authors emphasize that modern teacher training is increasingly based on design thinking, research-based learning, culturally sensitive practices and the use of artificial intelligence as a tool to support learning. At the same time, the problems of institutional support, assessment of results and preparation of teachers for interdisciplinary interaction remain.

6. STEM education in times of crisis and military conflict

Starting from 2024, a new direction has been formed in the international literature dedicated to the functioning of STEM education in crisis conditions. The work *Resilience through Crisis* proposes the concept of sustainable STEM education for countries affected by military conflicts [38]. The authors argue that universities should combine digital transformation, entrepreneurial education, international partnerships, and flexible learning models to maintain the quality of teacher training.

In parallel, research on the training of future teachers in Ukraine in wartime conditions shows the need to integrate trauma-informed pedagogy, psychological support, and resilience development as mandatory components of modern teacher education [7].

Critical analysis of foreign studies

The systematization of modern literature allows us to identify several patterns.

First, most foreign studies consider STEM as a holistic ecosystem that integrates education, science, digital technologies, entrepreneurship and innovative activities of universities, while Ukrainian studies often focus on individual methods or disciplines.

Second, in international literature, priority is given to the development of professional competence of the teacher, while the issue of adapting STEM education to the conditions of protracted military conflicts is only beginning to receive systematic coverage.

Third, most reviews emphasize that digitalization, the use of artificial intelligence and distance learning significantly expand the capabilities of STEM education, but are unable to fully compensate for the loss of experimental learning, laboratory activities and direct interaction of students with modern equipment.

Thus, foreign studies demonstrate a high level of theoretical and methodological elaboration of the problems of professional training of STEM teachers, digital transformation, and the development of university STEM ecosystems. At the same time, the issues of the functioning of pedagogical universities in countries experiencing full-scale war remain insufficiently covered, which opens up prospects for further research into the Ukrainian experience.

Systematic review of Ukrainian research on STEM education problems in pedagogical higher education institutions of Ukraine (2020–2026)

The analysis of Ukrainian scientific publications in 2020–2026 indicates a significant increase in interest in the problems of developing STEM education in higher education institutions [16; 2; 4; 6; 13]. If until 2022 most of the research was devoted to the conceptual principles of STEM, the methodology of integrated learning and the digitalization of the educational process, then after the start of the full-scale war, the main attention of scientists shifted to the problems of the functioning of pedagogical education in conditions of martial law, the academic stability of universities, the digital transformation of teaching and the preparation of future teachers for professional activity in crisis conditions [14; 15].

1. Conceptual principles of the development of STEM education

The first group consists of studies devoted to the theoretical substantiation of STEM education [1]. Ukrainian scientists consider STEM as the basis of competency-based modernization of education, which ensures the integration of natural sciences, technologies, engineering and mathematics through research and project-based learning. Considerable attention is paid to interdisciplinary integration, the development of critical thinking, digital literacy, engineering thinking and innovative culture of the future teacher. However, most of such works are theoretical in nature and do not sufficiently take into account the specifics of the functioning of pedagogical universities under martial law.

2. Digital transformation of STEM education

After 2022, the number of works devoted to the digitalization of STEM education has increased significantly. The analytical review «Digital trends of STEM education in the system of professional pedagogy» systematizes modern digital trends in the development of the STEM approach in Ukraine [3]. The authors note the active use of distance learning platforms, digital laboratories, simulators, cloud services, open educational resources and online courses for advanced training of teachers. At the same time, it is emphasized that digitalization cannot fully compensate for the loss of the practical laboratory component, which is key to high-quality STEM training.

Studies devoted to the use of gaming technologies, digital modeling, and interactive educational platforms deserve special attention. They demonstrate the positive impact of digital tools on student motivation, but at the same time point to the uneven level of digital competence of teachers and unequal access of universities to modern material and technical resources [36].

3. Training of future teachers

A separate area of modern research is related to the professional training of future teachers [19]. Considerable attention is paid to the integration of STEM components into educational programs of pedagogical specialties, the development of research competence, the use of project-based learning, and interdisciplinary methods [11].

In particular, research on the integration of STEM education into primary school teacher training programs demonstrates that most Ukrainian universities already include individual STEM components in educational programs. However, integration is mainly carried out at the level of individual disciplines and does not form a holistic interdisciplinary model of training a future teacher. The authors emphasize the need to update curricula, strengthen the practical component and develop students' digital competence.

4. STEM education in pedagogical universities during the war

The most significant empirical study of recent years is the work «STEM education through the eyes of teachers from various specialties in Ukrainian Pedagogical University», carried out on the basis of the Berdiansk State Pedagogical University after its relocation [31; 33]. The study showed that teachers positively assess the potential of the STEM approach, but its implementation is significantly limited by war conditions.

Among the main problems, the authors highlight:

- relocation of universities;
- loss of laboratory facilities;
- lack of modern equipment;
- full or partial transition to distance learning;
- psychological stress of teachers and students;
- power and Internet outages;
- limited opportunities for conducting experimental work.

At the same time, the study demonstrates a high level of adaptability of Ukrainian teachers and their readiness to integrate STEM technologies even under martial law.

5. Academic sustainability of universities

After 2022, a separate research area was formed dedicated to ensuring the academic sustainability of higher education institutions. Scientists analyze the consequences of the destruction of educational infrastructure, the relocation of universities, the loss of human resources and the need for rapid digital adaptation of the educational process. It has been established that the support of international partners, digital platforms, open educational resources and academic mobility have become key factors in preserving the quality of higher education in Ukraine [32; 15; 10].

Critical analysis of Ukrainian research

A comparative analysis of Ukrainian publications allows us to highlight several characteristic features.

Firstly, most works focus on individual aspects of STEM education – digital technologies, the integration of disciplines or modernization of individual educational programs [17]. Much less research offers comprehensive organizational and pedagogical models of the functioning of STEM education in pedagogical universities.

Secondly, only after 2022 did Ukrainian scientific literature begin to systematically analyze the impact of military operations on the training of future teachers. The most frequently studied issues are distance learning, psychological support [23; 28] digital transformation and relocation of universities, while the problems of organizing laboratory training, engineering training and assessing STEM competencies remain insufficiently developed.

Thirdly, most Ukrainian works lack a comparative analysis with international models of STEM teacher training [9]. Only some authors analyze the possibilities of adapting foreign experience to Ukrainian realities, which complicates the formation of scientifically based recommendations for the modernization of pedagogical education [14].

Thus, modern Ukrainian research demonstrates significant progress in the development of digital and methodological aspects of STEM education. At the same time, the issues of creating a comprehensive model of STEM education functioning in pedagogical institutions of higher education under martial law, mechanisms for ensuring the quality of professional training of future teachers, criteria for assessing STEM competencies, and tools for integrating

best international practices into the post-war modernization of Ukrainian pedagogical education remain insufficiently researched.

A systematic analysis of current research (2020–2026) shows that the development of STEM education in the world is taking place in several inter-related directions: professional training of teachers, digital transformation of universities, integration of artificial intelligence, interdisciplinary learning, development of STEM/STEAM ecosystems, formation of engineering thinking and ensuring academic sustainability of educational institutions (see Table 1).

The Ukrainian scientific school demonstrates the positive dynamics of the development of STEM research, but their thematic structure differs significantly from international trends. The foreign studies are increasingly using systematic reviews, bibliometric analysis, PRISMA methodology and meta-analysis, which ensures a high level of evidence of the results obtained [20; 24]. A significant part of Ukrainian works is devoted to the theoretical justification of the STEM approach, the methodology of integrated learning, the digitalization of education, the development of the competencies of future teachers, and the use of certain digital technologies. After 2022, the number of studies devoted to the functioning of education in conditions of war, the digital adaptation of universities and ensuring the continuity of education has increased significantly.

A systematic review identifies several key trends in international research.

First, there is a shift from the traditional understanding of STEM as an integration of four disciplines to the concept of a university STEM ecosystem that combines education, research, entre-

Table 1

Comparative analysis of Ukrainian and foreign scientific and pedagogical research and identification of scientific gaps

Direction of research	Foreign research	Ukrainian research	Scientific gap
The theory of STEM education	STEM as a university ecosystem, interdisciplinarity, innovations	STEM as an integrated learning and competence approach	Organizational models of pedagogical universities in wartime conditions are insufficiently researched
Training of teachers	TPACK, digital competences, engineering design, professional development	Formation of STEM competence of future teachers	There are not enough models of training teachers specifically for working in martial law
Digitization	AI, XR, VR, digital laboratories, adaptive learning	LMS, cloud services, online platforms	There are almost no studies on the integration of AI in the STEM training of Ukrainian teachers
STEM laboratories	Active development of digital and physical laboratories	Limited material and technical base	Missing models of virtual STEM laboratories for pedagogical higher education institutions
Education in times of crisis Mainly analysis of distance learning during war	Educational sustainability, continuity of learning, support of teachers	Lack of comprehensive models of functioning of STEM education in war conditions	There is a lack of comprehensive models of how STEM education functions in wartime

preneurship, digital infrastructure and collaboration with employers.

Second, there is a rapid increase in the number of studies devoted to the use of generative artificial intelligence, adaptive educational systems, digital laboratories and automated assessment of learning outcomes. At the same time, the authors emphasize that the effectiveness of such technologies largely depends on the digital competence of the teacher and the availability of appropriate infrastructure.

Third, significant attention is paid to the professional development of STEM teachers. Systematic reviews demonstrate that long-term professional development programs based on mentoring, project-based learning and professional communities are the most effective, while short-term courses have limited impact.

Ukrainian research is characterized by a predominantly applied focus. The most frequently analyzed issues are the digitalization of education, the integration of STEM into educational programs, the development of professional competence of future teachers, and the use of certain information and communication technologies.

After the start of the full-scale war, a new thematic direction was formed related to ensuring the sustainability of the education system. The main attention is paid to distance learning, academic mobility, international cooperation, relocation of universities, and the use of digital platforms to support the educational process. At the same time, the issue of organizing full-fledged STEM training of future teachers in wartime conditions has been studied only fragmentarily.

The comparative analysis allowed us to identify the following main scientific gaps:

1) There is a lack of comprehensive studies of the functioning of STEM education in pedagogical institutions of higher education in Ukraine in conditions of full-scale war.

2) The impact of war factors (destruction of infrastructure, relocation of universities, security risks, psychological stress) on the formation of STEM competencies of future teachers has not been sufficiently studied.

3) There are practically no scientifically substantiated organizational and pedagogical models for adapting international experience in STEM training to Ukrainian realities of wartime.

4) There is limited coverage of the issue of using generative artificial intelligence, digital laboratories, robotics and virtual experiments in the training of future teachers of natural and mathematical disciplines.

5) Criteria and indicators for assessing the formation of STEM competencies of future teachers in

conditions of blended and distance learning have not been sufficiently developed.

6) There are no long-term empirical studies of the effectiveness of various models of STEM training of teachers in the war and post-war periods.

The generalization of modern Ukrainian and foreign research shows that the international scientific community is gradually moving towards a model of integrated STEM ecosystems, centered on interdisciplinarity, digital technologies, artificial intelligence, university-industry partnerships, and continuous professional development of teachers. Ukrainian science demonstrates significant progress in the development of theoretical foundations of STEM education and digitalization of pedagogical education; however, the full-scale war has actualized a new set of organizational, methodological, and technological problems that have not yet received sufficient scientific justification. It is the need to develop an adaptive model of STEM education in pedagogical institutions of higher education of Ukraine under martial law that determines the relevance of further research.

The purpose of the article is a comprehensive analysis of the current problems of the functioning of STEM education in the higher education system of pedagogical institutions of Ukraine in wartime conditions, identification of the main organizational-institutional, personnel, material-technical, psychological-pedagogical, digital-technological and methodological factors that affect the quality of professional training of future teachers of STEM disciplines, as well as substantiation of the conceptual model of the functioning of STEM education aimed at ensuring the stability, adaptability and efficiency of the educational process in the conditions of war challenges and post-war reconstruction of Ukraine.

To achieve the set goal, the following research tasks were defined:

1. To analyze the current state of development of STEM education in pedagogical institutions of higher education of Ukraine in wartime conditions based on a systematic review of domestic and foreign scientific research.

2. To identify key problems of the functioning of STEM education, in particular organizational-institutional, material-technical, personnel, psychological-pedagogical, digital-technological and methodological.

3. To investigate the impact of martial law on the quality of professional training of future teachers of natural sciences, mathematics, computer science and technology in pedagogical institutions of higher education.

4. To summarize the current international experience in ensuring the continuity of STEM

education in crisis conditions and determine the possibilities of its adaptation to the Ukrainian system of higher pedagogical education.

5. To develop a conceptual model of the functioning of STEM education in pedagogical institutions of higher education of Ukraine in wartime conditions, which integrates organizational, personnel, digital, material and technical and psychological and pedagogical components.

6. To identify promising directions for the modernization of STEM education aimed at improving the quality of professional training of future teachers, developing a digital educational environment, strengthening the academic sustainability of higher education institutions and ensuring their effective functioning in the conditions of post-war reconstruction of Ukraine.

Presentation of the main material of the study.

Theoretical and methodological principles of the functioning of STEM education in pedagogical institutions of higher education of Ukraine in wartime conditions

The current stage of development of the system of higher pedagogical education of Ukraine is characterized by the simultaneous influence of two interrelated processes. The first is associated with the global transformation of education, caused by digitalization, the development of artificial intelligence, automation of production, the concept of Industry 4.0 and the transition to a knowledge economy. The second is determined by the consequences of full-scale military aggression against Ukraine, which significantly changed the conditions for the functioning of higher education institutions, especially pedagogical universities that train future teachers of natural and mathematical disciplines [26; 30; 10].

In these conditions, STEM education takes on a new meaning. If until 2022 its main goal was the formation of interdisciplinary competencies, the development of research skills and the training of competitive specialists, now it also performs the functions of ensuring educational sustainability, maintaining continuity of education, developing digital adaptability and forming human resources for the post-war restoration of the state [31; 38].

A feature of pedagogical institutions of higher education is the dual mission of STEM training. On the one hand, the university must form modern subject, digital, research, engineering and technological competencies in students. On the other hand, the future teacher must be able to implement the STEM approach in professional activities, integrating it into the educational process of general secondary education institutions. Thus, the pedagogical university acts not only as a consumer of innovative educational

technologies, but also as a generator of new learning models [21; 29; 5].

Martial law has significantly changed the conditions for the implementation of STEM education. The destruction of educational buildings and laboratories, damage to research infrastructure, forced relocation of universities, migration of teachers and students, constant security threats, power outages and Internet connections, psychological stress and economic constraints have significantly affected the quality of professional training of future teachers [22; 39]. At the same time, these challenges have become a catalyst for the active digital transformation of pedagogical education. Universities have significantly expanded the use of learning management systems (LMS), video conferencing platforms, cloud services, electronic libraries, digital laboratories, simulators, virtual modeling and open educational resources. Interactive environments for modeling physical, mathematical, chemical and technological processes have become widespread, which partially compensate for limited access to traditional laboratory classes [25; 8].

At the same time, the results of the analysis of modern research indicate that the effectiveness of STEM education is determined not only by the level of digitalization, but primarily by the balance of five interrelated components:

- 1) organizational and managerial;
- 2) personnel;
- 3) material and technical;
- 4) digital and technological;
- 5) psychological and pedagogical.

Violation of the functioning of at least one of these components negatively affects the effectiveness of professional training of future teachers.

In order to systematize the results obtained, we proposed a conceptual model of the functioning of STEM education in pedagogical institutions of higher education in Ukraine in wartime conditions (Fig. 1).

The proposed model demonstrates that modern STEM education in a pedagogical university should function as an open adaptive system, capable of quickly responding to changes in the external environment. Unlike traditional models, it involves the integration of digital technologies, flexible organizational forms of learning, international cooperation and mechanisms for ensuring academic sustainability.

The analysis also allowed us to determine that the effectiveness of STEM education depends on the coordination of actions of the state, university administration, scientific and pedagogical workers, employers and international partners. Only a comprehensive combination of regulatory and legal support, modern material and technical base, digital

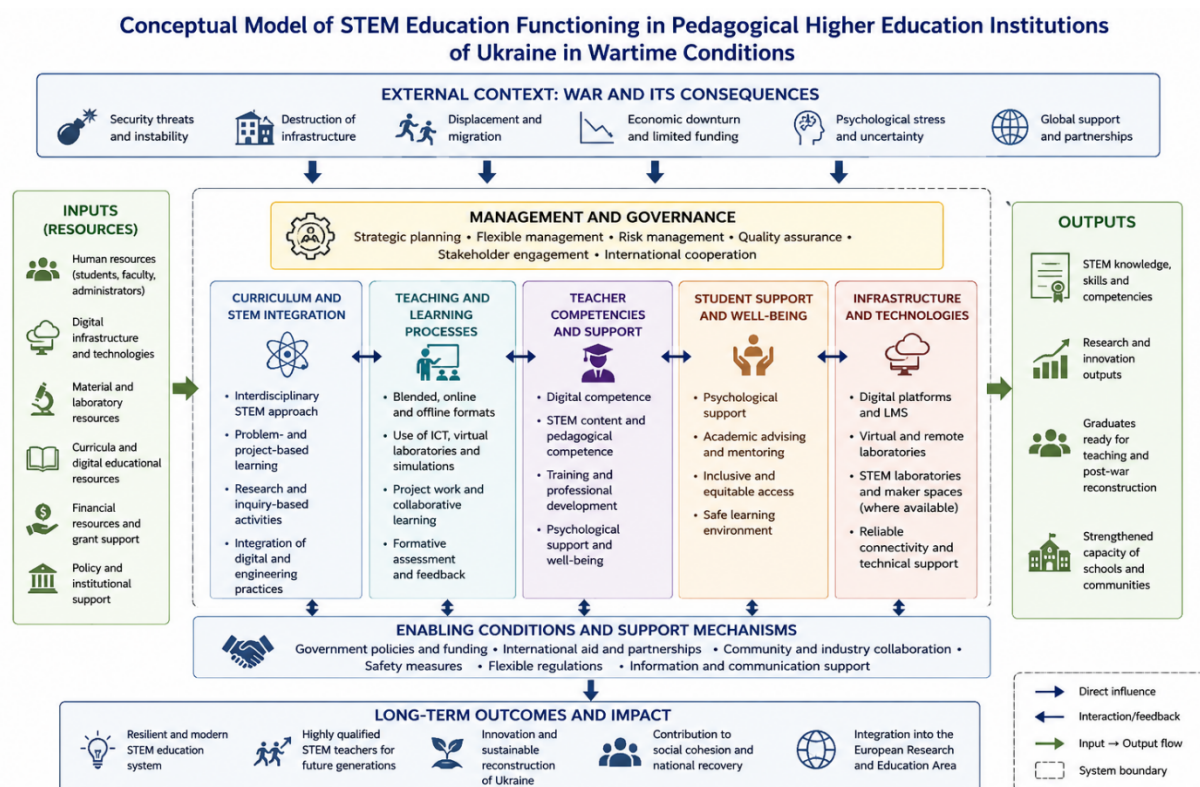


Fig. 1. Conceptual model of STEM education functioning in Pedagogical institutions of higher education of Ukraine in wartime conditions

infrastructure, continuous professional development of teachers and international academic cooperation ensures the proper level of training of future teachers of STEM disciplines even in conditions of martial law.

Thus, the modern model of STEM education in pedagogical higher education institutions of Ukraine should be considered as a dynamic system that combines pedagogical innovations, digital technologies, an interdisciplinary approach, psychological support, and principles of educational sustainability. It is this model that creates the prerequisites for training a new generation of teachers capable of working effectively in conditions of uncertainty, post-war reconstruction, and further integration of Ukraine into the European Higher Education Area.

Personnel, psychological-pedagogical and methodological problems of the development of STEM education in pedagogical institutions of higher education of Ukraine in wartime conditions

Along with organizational and institutional difficulties, personnel, psychological-pedagogical and methodological factors have a significant impact on the quality of STEM training of future teachers. It is the human potential that determines the ability of pedagogical institutions of higher education to ensure the continuity of the educational process, introduce innovative technologies and adapt to prolonged crisis conditions.

One of the most acute problems is the reduction of the human potential of universities. As a result of military operations, some scientific and pedagogical workers were forced to evacuate, go abroad or move to other areas of professional activity. An additional factor was the mobilization of individual teachers to the ranks of the Defense Forces of Ukraine, which increased the pedagogical load on the staff of the departments and complicated the implementation of educational programs.

The shortage of personnel is especially noticeable in the specialties of physics, mathematics, chemistry, computer science and technology. These areas have traditionally been characterized by an insufficient number of young teachers, and martial law has only exacerbated the problem of aging scientific and pedagogical personnel and the shortage of specialists capable of teaching modern STEM disciplines.

An equally important challenge is the psychological state of participants in the educational process. Constant air alarms, risks to life, forced displacement, loss of housing, prolonged uncertainty and emotional exhaustion negatively affect the concentration of attention, motivation for learning, productivity of scientific activity and professional activity of teachers and students. Under such conditions, the importance of psychological support, the development of

emotional self-regulation skills and the formation of academic resilience increase significantly.

The analysis shows that traditional approaches to organizing STEM education have proven to be insufficiently adapted to crisis conditions. A significant part of the curricula was developed for classroom teaching and provided for the regular use of laboratory equipment, specialized rooms and direct interaction between students and the teacher. The transition to a blended or distance format required a rapid revision of the content of disciplines, teaching methods and systems for assessing results.

The problem of developing digital competence of teachers has become particularly relevant. A modern STEM teacher must have a wide range of digital tools, be able to organize a remote experiment, use computer modeling systems, digital measuring complexes, cloud environments, collaboration platforms and integrate elements of artificial intelligence into the educational process.

At the same time, the results of the analysis show that the level of digital readiness of teachers of different departments differs significantly. The highest level of digital competence is characteristic of teachers of computer science and information technology, while representatives of natural disciplines often need additional training in the use of modern digital laboratories, modeling systems, data analysis programs and virtual experiment platforms.

A new challenge for pedagogical education has become the rapid spread of generative artificial intelligence. The use of intelligent systems opens up wide opportunities for personalizing learning, automated creation of didactic materials, analysis of educational achievements, modeling of complex natural processes and support of individual educational trajectories. At the same time, new risks arise related to academic integrity, critical assessment of results, information security and the need to form an ethical culture of using artificial intelligence.

An urgent problem remains the insufficient level of interdisciplinary integration. In many pedagogical

universities, natural science, mathematics, engineering and technology disciplines continue to be taught in isolation, which contradicts the modern concept of STEM education. As a result, students are not sufficiently involved in complex interdisciplinary projects, engineering design, research activities and teamwork.

To summarize the results obtained, an expert assessment of the impact of the main factors on the quality of STEM training of future teachers was conducted (Table 2).

Based on the analysis, the author's classification of the problems of developing STEM education in pedagogical institutions of higher education in Ukraine is proposed, which includes five interrelated groups:

- 1) organizational and institutional (relocation of universities, disruption of management processes, security restrictions);
- 2) material and technical (destruction of laboratories, shortage of equipment, insufficient digital infrastructure);
- 3) personnel (lack of teachers, professional burnout, need for advanced training);
- 4) methodological (insufficient interdisciplinary integration, limited use of modern STEM technologies, adaptation of curricula);
- 5) psychological and pedagogical (emotional exhaustion, stress, the need to develop academic resilience and psychological support).

The proposed classification demonstrates that the effectiveness of STEM education is determined not by individual factors, but by their interaction. That is why the modernization of pedagogical education in wartime conditions should be based on a comprehensive approach, which simultaneously covers the renewal of the material and technical base, the development of digital infrastructure, the improvement of teacher training, the improvement of methodological support, the introduction of artificial intelligence technologies and the creation of a safe psychological educational environment.

Table 2

Expert assessment of the impact of key factors on the quality of STEM training of future teachers in pedagogical higher education institutions of Ukraine

Factor	Degree of impact	Main consequences
Destruction of material resources	Very high	Reduction in the volume of laboratory classes
Staff shortage	Very high	Increase in pedagogical workload
Psychological workload	High	Decrease in motivation and productivity
Digital competence of teachers	High	Quality of distance learning
Financial constraints	High	Slowing down the modernization of the STEM environment
Level of international cooperation	Medium	Expanding access to resources and grants
Use of artificial intelligence	Medium	Increasing the personalization of learning with methodological support
Academic mobility	Medium	Exchange of experience and development of professional competences

Thus, personnel, psychological, pedagogical and methodological problems are determining factors in the effectiveness of STEM education in pedagogical institutions of higher education in Ukraine. Their solution requires systematic interaction between the state, universities, international partners and the professional pedagogical community, which will ensure the training of competitive teachers of STEM disciplines for the post-war restoration and sustainable development of Ukrainian education.

Conclusions. The conducted research allowed for a comprehensive analysis of the current problems of the functioning of STEM education in the system of higher pedagogical education of Ukraine in wartime conditions and to identify the main directions of its further development. The results of the analysis of scientific literature, regulatory documents, international experience and modern trends in the digital transformation of education indicate that the war has become a powerful factor in the transformation of the activities of pedagogical institutions of higher education, while at the same time actualizing the need to modernize the system of training future teachers of STEM disciplines.

It was established that the current problems of the development of STEM education are complex in nature and cover the organizational-institutional, material-technical, personnel, psychological-pedagogical, digital-technological and methodological levels. The most critical challenges include the destruction of educational infrastructure, forced relocation of universities, reduced access to laboratory equipment, insufficient funding, uneven access to digital resources, professional burnout of teachers, a shortage of science and mathematics teachers, and the need to adapt the educational process to blended and distance learning formats.

It has been proven that the effectiveness of STEM education in wartime is determined by the level of integration of digital technologies, modern laboratory equipment, interdisciplinary learning, project-based research activities, international academic partnerships, and the development of digital competencies of teachers and students. The use of cloud services, virtual laboratories, computer modeling tools, distance learning platforms, and artificial intelligence technologies is of particular importance, which ensure the continuity of the educational process and increase its adaptability to crisis conditions.

As a result of the study, a conceptual model of the functioning of STEM education in pedagogical institutions of higher education of Ukraine in wartime conditions was proposed, which combines interrelated structural components: regulatory and legal support, organizational and management system, human

resources, material and technical base, digital educational environment, psychological and pedagogical support, international partnership, innovative STEM technologies and education quality monitoring system. The proposed model can be used as a methodological basis for the modernization of educational programs for the training of future teachers of natural and mathematical disciplines in the post-war period.

The practical significance of the results obtained lies in the possibility of their use by the Ministry of Education and Science of Ukraine, administrations of pedagogical institutions of higher education, scientific and pedagogical workers and developers of educational programs during the improvement of the system of professional training of future teachers of STEM disciplines, the development of the digital infrastructure of universities, the creation of modern STEM laboratories and the formation of a safe, sustainable and innovative educational environment.

Prospects for further research should be linked to the development of models for assessing the effectiveness of STEM education in pedagogical institutions of higher education, empirical verification of the proposed conceptual model, creation of tools for monitoring the formation of STEM competencies of future teachers, research into the possibilities of integrating artificial intelligence technologies, digital twins, virtual and augmented reality into the educational process, as well as a comparative analysis of the experience of Ukraine and the European Union countries in the post-war modernization of pedagogical STEM education.

Use of artificial intelligence (AI). The authors did not use artificial intelligence tools in the preparation of this work.

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