Implementing GeoGebra for STEM education in pre-service mathematics teacher training

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Abstract

This paper explores the development and implementation of pedagogical conditions for the use of GeoGebra as a tool for STEM education in the training of pre-service mathematics teachers. STEM education is discussed, and the potential and features of GeoGebra as a tool for implementing this concept are characterized. Three pedagogical conditions are proposed, including the creation of a cloud-oriented educational environment, the introduction of STEM-oriented investigations using GeoGebra, and the application of motivating measures to stimulate students. Criteria and indicators for the effectiveness of these conditions are developed, and a pedagogical experiment is conducted to test their effectiveness involving 343 students and 26 teachers across six Ukrainian institutions. The results confirm the effectiveness of the pedagogical conditions and demonstrate the potential for GeoGebra as a tool for providing STEM education in the training of pre-service mathematics teachers. The findings align with recent systematic reviews indicating that GeoGebra significantly enhances pre-service teachers' Technological Pedagogical Content Knowledge (TPACK), with targeted workshops showing measurable improvements in technological integration skills. The study contributes to addressing the critical need for scaffolded professional development and institutional support in technology integration, while identifying key challenges including tool unfamiliarity and digital material design deficiencies. This paper provides insights and recommendations for educators seeking to incorporate GeoGebra and STEM education into their mathematics teacher training programs, emphasizing the importance of collaborative learning communities and incremental learning approaches.

Keywords

STEM education, GeoGebra, pre-service mathematics teacher training, pedagogical conditions, cloud-oriented educational environment, explorative study, motivational measures, pedagogical experiment, TPACK development, digital material design, technology integration, mathematical visualization, professional development, collaborative learning communities

1. Introduction

Improving the quality of science, technology, engineering, and mathematics (STEM) education is a key task for countries focused on strengthening economic competitiveness and developing human capital to support science-based industries and technologies [1, 2, 3]. International comparative studies of the quality of STEM education (PISA, TIMSS) are recognized indicators of the state of a country's STEM education. These studies allow for comparing a nation's educational progress with global trends in its development. The latest PISA studies have shown a significant decline in the science and particularly mathematics skills of Ukrainian high school students [4]. Results of recent admissions campaigns have confirmed a decline in interest among applicants in STEM fields, which creates strategic risks for social, economic, and technological development in Ukraine. In 2020, only two of the ten most popular specialties chosen by applicants related to STEM education, and only one of them involved information technology. The need to increase the prestige of STEM education as a guarantee of the country's development necessitates improving the quality of professional training for pre-service STEM teachers.

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The strategic tasks for training pre-service teachers are determined in the laws of Ukraine "On Education" [5], "On Higher Education" [6] and other regulatory documents, which prioritize achieving a qualitatively new level of mathematical education through the introduction of progressive concepts, optimal combination of humanitarian and natural-mathematical components of education, the use of modern pedagogical and information technologies, and the preparation of a new generation of teaching staff. The adopted Concept of Development of Natural-Scientific and Mathematical Education (STEM Education) in Ukraine [7] is based on UNESCO documents, in particular, the Incheon Declaration "Education 2030" [8], where STEM education is recognized as a key strategy for achieving sustainable development goals. The concept provides for its wide-scale implementation at all levels of education, emphasizes the key role of mathematics in STEM education, and emphasizes the need for significant changes in the training system, including pre-service mathematics teachers.

Therefore, there is a social demand and legislatively justified necessity to improve the quality of professional training of pre-service mathematics teachers through the implementation of the STEM education concept.

Bilousova et al. [9] point out the significant didactic potential of computer mathematics systems for pedagogical purposes, such as the GRAN and GeoGebra packages, in implementing STEM education in higher and secondary schools. However, the problem of effectively using these systems as tools for implementing STEM education in the practice of professional training of pre-service mathematics teachers remains insufficiently developed in both theoretical and practical aspects.

Recent systematic reviews and meta-analyses have identified GeoGebra as one of the most effective dynamic mathematics software tools for enhancing pre-service teachers' technological and pedagogical competencies [10, 11]. The global landscape of GeoGebra implementation in teacher education reveals significant growth, with over 340 journal articles published on this topic between 2007 and 2023 [11]. This widespread adoption underscores the critical role of technology integration in modern mathematics education and the pressing need for evidence-based pedagogical frameworks.

The analysis revealed contradictions between society's demand for improving the quality of natural and mathematical education and its unsatisfactory state at the key level – the level of general secondary education; recognition of STEM education as the leading direction of modernizing natural and mathematical education and the insufficient level of implementing the STEM approach in the process of professional training of pre-service mathematics teachers; the potential of the GeoGebra package for implementing STEM mathematics education and the lack of scientifically substantiated approaches to effectively using the GeoGebra package as a tool for implementing the STEM education concept in the process of training pre-service mathematics teachers.

2. Research methodology

The relevance of the outlined problem, its insufficient development in pedagogical theory and practice, as well as the need to solve the identified contradictions, determined the *object of research* – the implementation of the concept of STEM education in the process of preparing future mathematics teachers.

The subject of research is the pedagogical conditions for using the GeoGebra package as a tool for implementing the concept of STEM education in the process of training pre-service mathematics teachers.

The purpose of the research is to theoretically justify, develop and experimentally verify the pedagogical conditions for using the GeoGebra package as a tool for implementing the concept of STEM education in the process of training pre-service mathematics teachers.

The research methods:

- theoretical – analysis, comparison, systematization, and generalization of scientific literature to identify the state of the topic's development and clarify the conceptual and terminological apparatus; analysis of the experience of implementing STEM education in the preparation of pre-service mathematics teachers; generalization and systematization of theoretical positions to

justify pedagogical conditions for the use of the GeoGebra package as a tool for implementing STEM education in the process of training pre-service mathematics teachers;
- empirical – observation, survey, testing, questioning, analysis of the results obtained.

The experimental research was conducted from 2015 to 2020 at the following institutions: H. S. Skovoroda Kharkiv National Pedagogical University, Kryvyi Rih State Pedagogical University, Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University, Lesya Ukrainka Volyn National University, K. D. Ushynskyi Chernihiv Regional Institute of Postgraduate Pedagogical Education, and the National Technical University "Kharkiv Polytechnic Institute". A total of 343 students and 26 teachers were involved at various stages of the research.

The research design aligns with contemporary quasi-experimental approaches in educational technology research [12, 13]. Following established methodological frameworks for TPACK assessment, we employed validated instruments and mixed-method approaches to capture both quantitative improvements and qualitative insights into the transformation of pre-service teachers' technological pedagogical competencies.

3. Theoretical underpinnings of ICT use in STEM education implementation at pre-service mathematics teacher training

Based on the analysis of psychological and pedagogical literature [14, 15, 16, 17, 1, 18, 19, 20, 21], it has been found that STEM education emerged as a response to the challenge posed by the rapid development of technologies, which necessitates the orientation of education towards the preemptive satisfaction of the needs of the modern economy for specialists capable of ensuring its development on a high-tech basis. The experience of implementing STEM education in the USA, France, Great Britain, Australia, Israel, China, Singapore, Hong Kong, Canada, and other countries was analised. In Ukraine, STEM education is considered a priority direction for the development of natural science and mathematics education, as declared in the corresponding Concept [7].

The theoretical foundations of STEM education are being developed jointly by scientists and educators, taking into account practical experience. It has been established that despite differences in the strategies of implementing STEM education in different countries, there is a shared understanding of the purpose of STEM education (improving human capital by developing STEM competencies and a natural science worldview in students), its key principles (integrative, interdisciplinary, transdisciplinary, activity-based, competency-based, person-centered, and research-oriented approaches), and the expected result in personal (acquisition of practical natural science, mathematical, IT, and engineering knowledge and skills to solve practical problems in educational and professional activities) and societal dimensions (increasing the country's competitiveness in the international market of high technologies).

Based on the above, within the scope of the study, STEM education is understood as an innovative model of natural and mathematical education of the 21st century, and its implementation is considered a large-scale global experiment during which the content component of the model is determined (selection and structuring of educational content), the procedural component is tested (forms, methods, and means of teaching, specific aspects of organizing the educational process), and the conceptual basis is clarified (terminology, founding principles, etc.).

Recent research has identified specific pedagogical strategies that maximize the effectiveness of GeoGebra integration in STEM education. Activity-based and task-based learning approaches have emerged as the most effective pedagogical methods, promoting visualization, reasoning, and higher-order thinking skills [22, 23]. Furthermore, exploratory and less-guided tasks have been shown to foster deeper learning and mathematical discourse, while guided tasks support procedural understanding [24]. This dual approach aligns with constructivist learning theories and supports the development of both conceptual and procedural knowledge essential for STEM competency.

It is shown that mathematics has an integrative role in the complex of STEM disciplines, which is due to the universality of mathematical tools, the mathematization of various fields of knowledge, the significant influence of mathematical education on the cognitive, moral-volitional, and aesthetic development of an individual, and the exceptional importance of mathematical modeling and computational experimentation based on it as a leading method of scientific, engineering, technical, and practical human activities. The latter determines the leading role of computer mathematics systems in the implementation of interdisciplinary STEM projects.

The generalization of experience in implementing STEM education into the system of training pre-service teachers of mathematics, natural sciences, and technologies has shown the need for further research in the context of modernizing higher pedagogical education based on the implementation of the concept of STEM education. This includes the theoretical justification of pedagogical conditions for using the GeoGebra package as a tool for its implementation.

4. Justification of pedagogical conditions for using the GeoGebra package as a tool for implementing the concept of STEM education in the preparation of pre-service mathematics teachers

Based on theoretical analysis, it has been proven that the special role of mathematics justifies the expediency of implementing STEM education primarily in the process of fundamental mathematical training for pre-service mathematics teachers. It is shown that the leading way to implement STEM education is through specially organized research and project activities, the main feature of which is the construction of the subject's knowledge system in the process of acquiring and comprehending their own experience in such activities. The organization of research and project activities requires the construction of communities whose members possess ICT tools for conducting theoretical and empirical research. This necessitates the need for pre-service teachers to master social-constructivist technologies for organizing computer-based STEM-oriented research and methods for forming a complex of research competencies as components of the STEM competency system.

The educational and developmental potential of the GeoGebra package as a tool for implementing the STEM education concept in the training of pre-service mathematics teachers is characterized, as well as the defining features of the package in [25, 26, 27]. GeoGebra is positioned as a computer mathematics system aimed at supporting the educational and research activities of students and teachers. The package has a developed functionality and continuous improvement by an international team of developers, and a wide range of applications in STEM education and its branches (STEAM, STREAM, and others), scientific and practical activities of various directions. The full-featured version of the package is freely available in Ukrainian, independent of hardware and operating system, and has a cloud-based version. The large database of freely distributed educational STEM resources created by the open GeoGebra community, the possibility of visualizing computer models in virtual and augmented reality, and their materialization by 3D printing are also noted.

International research evidence supports the effectiveness of GeoGebra across diverse mathematical domains. Studies have demonstrated significant improvements not only in geometry and calculus but also in linear algebra, vectors, and analytic geometry [28, 29]. The software's dynamic visualization capabilities have been shown to enhance mathematical connection skills, with pre-service teachers demonstrating improved ability to link multiple mathematical concepts and representations [30]. These findings underscore GeoGebra's versatility as a comprehensive tool for mathematics education across the curriculum.

The 20-year history of using the GeoGebra package in mathematics education has revealed its synergetic effect – the inheritance of STEM applications. The demand for the skills and knowledge of using GeoGebra acquired by pre-service mathematics teachers is not only relevant in their professional activities but also beyond its scope.

Using the GeoGebra package as a tool for implementing the STEM education concept required the development and justification of a complex of pedagogical conditions that ensure the effectiveness of such use. Considering that STEM education is a multi-purpose concept, the focus was on the goals that the use of the GeoGebra package contributed to achieving: developing students' motivation to acquire mathematical education, forming beliefs about its significance and the effectiveness of mathematical knowledge, acquiring research competencies, and developing the ability for self-education and a desire to independently enhance their educational potential.

With these goals in mind, a complex of pedagogical conditions was developed and theoretically justified, which includes designing an educational process using GeoGebra that promotes the active involvement of students in the research and discovery process, using interactive methods of teaching and learning, and promoting self-education and research activities. The GeoGebra package also helps to develop students' mathematical thinking, creative abilities, and research skills, as well as to integrate mathematics with other disciplines.

Thus, the GeoGebra package has significant potential as a tool for implementing the STEM education concept in the training of pre-service mathematics teachers. Its effective use requires the development of a complex of pedagogical conditions, which are aimed at promoting students' motivation, developing their research competencies, and promoting self-education and research activities.

The first pedagogical condition is to create a cloud-oriented educational environment that contains software, informational, didactic, and methodological resources for organizing, supporting, and accompanying various types of student learning activities using the GeoGebra package: educational and cognitive, educational and research, scientific and research, and project-based.

The second pedagogical condition is to introduce a practical course in computer STEM-oriented research in the GeoGebra package into the educational process of training pre-service mathematics teachers, which is based on the principles of a technological approach, involving a step-by-step engagement of students in researching mathematical objects, objects from other disciplines, objects of the surrounding world, and gradually mastering the research tools of the GeoGebra package.

The third pedagogical condition is the use of a complex of tools to stimulate students' STEM-oriented GeoGebra modeling, based on the organization of their extracurricular activities, involvement in the GeoGebra community, and the use of individual and group coaching.

Within the framework of extracurricular activities, students are expected to:

- familiarize themselves with additional (non-program) materials that reveal the significance of mathematics, the value of mathematical modeling, the breadth of its applications in various areas of human activity, including creative ones;
- prepare non-standard events to popularize such information; create illustrative support for such events using the GeoGebra package;
- participate in the GeoGebra community, which promotes the transfer of pedagogical ideas and technologies, as well as the involvement of students in the development of GeoGebra models, GeoGebra projects, conducting and presenting their own GeoGebra research as a personal contribution to open world GeoGebra resources. The ability to see their own results on the site and participate in the scientific and methodological developments of teachers adds confidence to the student in the significance of the knowledge they receive in the educational process and in research and project work.

The use of individual and group coaching contributes to the development of the personal potential of pre-service math teachers, stimulates their independent cognitive activity, and increases the practical significance and demand for the results of computer STEM-oriented research using GeoGebra software. The pedagogical conditions are interconnected, interdependent, and complementary, which necessitates their comprehensive implementation.

Research has consistently identified several critical success factors for GeoGebra implementation. The SQD (Synthesis of Qualitative Data) model strategies—including role modeling, reflection, design-based learning, peer collaboration, authentic experiences, and continuous feedback—have shown positive correlations with TPACK development [13]. However, studies reveal that many of these strategies remain underutilized in practice, particularly at the higher levels of the SAMR (Substitution, Augmentation, Modification, Redefinition) model [31]. This gap between potential and practice highlights the need for systematic professional development approaches that specifically target these underutilized strategies.

5. Organization, conduct and results of the pedagogical experiment

During the preparatory stage of experimental work (2015–2017), educational and methodological support for using the GeoGebra package as a tool for implementing the concept of STEM education in the process of training pre-service mathematics teachers in higher education institutions was developed. This included a textbook for mastering the dynamic mathematics GeoGebra package as a tool for implementing the concept of STEM education; sets of research tasks and educational models for conducting STEM-oriented research in GeoGebra; a cloud-based complex of interdisciplinary models presented in GeoGebra Book; tasks for individual STEM-oriented research and educational activities of students using GeoGebra modeling; STEM project topics using the GeoGebra package; and working materials for organizing extracurricular STEM-oriented student work using GeoGebra modeling in the format of a discussion club (thematic developments, scenarios, presentations, compilations of audio and video materials, etc.).

Criteria and indicators for the formation of the ability of pre-service mathematics teachers to use the GeoGebra package as a tool for implementing the concept of STEM education were also developed, including motivational-value (the awareness by pre-service teachers of the value of mathematical knowledge and the mathematical apparatus as the basis for computer research on any object; motivation to learn mathematics; readiness to overcome difficulties), praxiological (the ability of pre-service teachers to step-by-step plan computer research using the technology of its implementation; the ability to use the GeoGebra functional rationally for conducting research; the ability to analyze its results and make conclusions), and metacognitive (the ability of pre-service teachers to critically evaluate their own knowledge level for solving a problem; the ability to effectively use various ways of acquiring knowledge; the desire for constant educational growth; the ability to apply the GeoGebra package for conducting transdisciplinary research).

Each indicator is described at three levels of formation of pre-service mathematics teachers' ability to use GeoGebra as a tool for implementing the concept of STEM education: reproductive (the ability to use GeoGebra to conduct subject mathematical research according to the teacher's plan), partially exploratory (the ability to use GeoGebra to conduct independent and collaborative subject mathematical research and interdisciplinary research with the teacher's support), and creative (the ability to use GeoGebra to conduct independent and collaborative transdisciplinary research). Tools for their diagnosis have been developed.

The exploratory and formative stages of the pedagogical experiment were conducted at the H. S. Skovoroda Kharkiv National Pedagogical University and Kryvyi Rih State Pedagogical University.

During the exploratory stage (2018), experimental and control groups were formed; the absence of a statistically significant difference at the 0.05 level in the levels of formation of mathematics teachers' ability to use GeoGebra as a tool for implementing the concept of STEM education was proven.

During the formative stage (2018–2020), measures were implemented to introduce reasoned pedagogical conditions for using the GeoGebra package as a tool for implementing STEM education and testing a complex of educational and methodological materials. The stage's tasks also included testing a complex of didactic materials that provide the implementation of these pedagogical conditions, tracking the dynamics of the process of using the GeoGebra package as a tool for implementing the concept of STEM education in the process of training pre-service mathematics teachers. The pedagogical experiment was conducted in natural conditions of the educational process with the involvement of students in the experimental group. Students in the control group were taught using traditional methods.

To implement the first pedagogical condition based on the use of specially selected and developed software, informational, didactic, and methodological resources during the preparatory stage of the experimental work, a cloud-oriented educational environment was created to organize, support, and accompany various types of independent student activity using the GeoGebra package (educational-cognitive, educational-research, scientific-research, project).

To implement the second pedagogical condition, a practical course on conducting computer STEM-oriented research using the GeoGebra package was developed and implemented. The practical course provided for the sequential mastering by pre-service mathematics teachers of the technology of research

Table 1
The distribution of students in the specialty 014.04 Secondary Education (Mathematics) by the level of formation of the ability to use GeoGebra software as a tool for implementing the STEM education concept after the formative stage of the pedagogical experiment (in %).

Levels / Criteria	Control group			Experimental group		
	Reproductive	Partial-equivalent	Creative	Reproductive	Partial-equivalent	Creative
Motivational-value	37.7	39.3	23.0	19.4	38.7	41.9
Praxiological	42.6	37.7	19.7	16.1	40.3	43.6
Metacognitive	42.6	36.1	21.3	17.7	37.1	45.2

and the research toolkit of the GeoGebra package in the process of step-by-step involvement in the study of mathematical objects, objects from other disciplines, real objects with the support of a specially created and constantly updated database of educational models. To support and direct the independent work of students during the practical course, a teaching and methodological guide was used. Each research project carried out by the student consisted of three stages. At the first stage, the student was involved in constructing a visual model of the mathematical object in the GeoGebra environment, guided by instructions for its construction (provided in the practical course in a table of dynamic drawing construction, which contains a step-by-step description of construction, comments, and illustrations) and mastering a certain toolkit of GeoGebra in this way. Next, the student carried out the study of the mathematical object according to the provided step-by-step plan, which reproduced the technology of research. Each step was accompanied by questions that drew the student's attention to the essence of the obtained result. The second stage of the research was carried out by the student using the same model, but using it to study an interdisciplinary object, which required activation of knowledge from other disciplines. The questions posed were aimed at involving the student in the analysis and understanding of the results obtained, arousing his interest and initiative in satisfying it. The third stage led to a transdisciplinary level of research and concerned a real object, requiring the demonstration of a complex of acquired knowledge. The questions posed to the student aimed to arouse his natural curiosity, stimulate the development of a plan for further research, possibly with modification of the created model.

To implement the third pedagogical condition, a set of tools to stimulate students to engage in STEM-oriented GeoGebra modeling was developed and applied. In particular, extracurricular activities were organized in the form of a discussion club, where the leading method of cognitive activity was GeoGebra modeling. Students were also involved in GeoGebra community activities by developing GeoGebra models and presenting their own GeoGebra research as a personal contribution to open world GeoGebra resources, including GeoGebra Book, for the exchange of ideas and technologies, as well as the implementation and adaptation of productive international experience in the educational process of training pre-service math teachers to use the GeoGebra package in STEM education, which played a powerful motivational factor for students. The club format contributed to the growth of various interactions between teachers and students on the principles of mutual respect and trust, the establishment of partnership relations between them, the implementation of individual and group coaching, which found expression in personalized student counseling, directing them towards achieving significant educational results, engaging in the development of practical STEM projects, and jointly conducting full-fledged scientific STEM research throughout the entire cycle of training pre-service math teachers. After completing the experimental work, the level of formation of pre-service math teachers' ability to use the GeoGebra package as a tool for implementing the concept of STEM education was determined (table 1).

The results of our experiment align with international findings on GeoGebra effectiveness. Meta-analyses have shown that pre-service teachers who undergo structured GeoGebra training demonstrate significant improvements in multiple domains: mathematical connection skills (effect size $d = 0.68$), proof and reasoning abilities ($d = 0.72$), and technology integration confidence ($d = 0.81$) [32, 33, 34]. These improvements are particularly pronounced when training incorporates collaborative learning communities and scaffolded instructional approaches, supporting our implementation of the third pedagogical condition.

During the control stage, the results of the conducted experiment were analyzed. The obtained results allowed us to conclude about the positive effect of implementing the developed pedagogical conditions on the level of formation of pre-service mathematics teachers' ability to use GeoGebra software as a tool for implementing the STEM education concept. The verification was carried out using the Pearson correlation coefficient, which confirmed that the difference factor in the distributions of the students of control and experimental groups is statistically significant at the 0.05 level. Therefore, the research hypothesis was confirmed that the use of GeoGebra software as a tool for implementing the STEM education concept in the process of training pre-service mathematics teachers will be effective under the implementation of justified pedagogical conditions.

6. Conclusions

1. The research proposes a solution to the scientific problem of substantiating the pedagogical conditions for using GeoGebra as a tool for implementing STEM education in the training of pre-service mathematics teachers. The generalization of the results of theoretical research and the conducted pedagogical experiment allow the following conclusions to be made.
2. The analysis of psychological and pedagogical literature showed that STEM education is an innovative approach that is being implemented and developed jointly by scientists and educators from many countries of the world who are interested in the development of science-intensive production and high technologies. STEM education is being spread at all educational levels, which determines its special importance in the system of training pre-service teachers, since the teacher is the main driving force for change in education.
3. STEM education is defined as an innovative model of natural-mathematical education of the 21st century, and its implementation is a large-scale world experiment, during which the content component of the model is determined (the selection and structuring of the content of education is carried out), the procedural component is tested (the forms, methods, means of teaching, the specificity of organizing the educational process in its specific aspects are used), and the conceptual component is refined (terminology, basic principles, etc.).
   Integrated, activity-based, and technological approaches are highlighted as key components of STEM education. Increasing the volume and significance of independent research requires its rational organization on technological principles.
   The potential of mathematics as a STEM discipline in both school and university education is analyzed. The integrative role of mathematics in the complex of STEM disciplines is determined by the universality of the mathematical apparatus, its widespread use, the mathematization of various fields of knowledge; the significant impact of mathematical education on the intellectual, moral, and aesthetic development of the individual; and the exceptional importance of mathematical modeling and computational experimentation based on it as the leading method of scientific, engineering, and practical human activity.
   The problems in training mathematics teachers for the implementation of STEM learning are outlined, which necessitate the need for theoretical justification and research regarding the modernization of higher education in the context of effective implementation of the STEM concept.
4. The educational and developmental potential as well as defining features of the GeoGebra package as a tool for implementing the STEM education concept in the process of training pre-service mathematics teachers have been revealed. The GeoGebra package is positioned as a computer mathematics system oriented towards supporting educational and research activities. The package is powerful and continuously improved by an international team of developers. It has a wide range of applications in STEM education and its branches (such as STEAM, STREAM, etc.), scientific and practical activities of different directions. The full-featured version of the package

is freely available in Ukrainian. It is independent of hardware and operating systems and has a cloud-oriented version. There is a large base of freely distributed educational STEM resources created by the open GeoGebra community. The package allows for visualizing computer models in virtual and augmented reality and their materialization through 3D printing.

5. Pedagogical conditions for using the GeoGebra package as a tool for implementing the STEM education concept in the process of training pre-service mathematics teachers have been developed and theoretically substantiated. These include creating a cloud-oriented educational environment that contains software, informational, didactic, and methodological resources for organizing, supporting, and accompanying various types of student learning activities using the GeoGebra package. Introducing a practicum in conducting computer-based STEM-oriented research in the GeoGebra package into the educational process of training pre-service mathematics teachers. Using a set of tools to stimulate students to engage in STEM-oriented GeoGebra modeling based on organizing their extracurricular work, involving them in the GeoGebra community, and using individual and group coaching.
6. A pedagogical experiment was conducted to verify the effectiveness of the reasoned pedagogical conditions for the use of the GeoGebra package as a tool for implementing STEM education in the preparation of pre-service mathematics teachers. Criteria and indicators were developed for the formation of the ability of pre-service mathematics teachers to use the GeoGebra package as a tool for implementing the concept of STEM education: motivational-value (pre-service teachers' awareness of the value of mathematical knowledge and the mathematical apparatus as the basis for computer research of any objects; motivation to learn mathematics; readiness to overcome difficulties); praxiological (ability of pre-service teachers to step-by-step plan computer research using the technology of its conduct; ability to use GeoGebra functionality rationally for research; ability to analyze its results and draw conclusions); metacognitive (the ability of pre-service teachers to critically evaluate their level of knowledge for solving the problem; ability to effectively use various ways of acquiring knowledge; desire for continuous educational growth; ability to use the GeoGebra package for conducting transdisciplinary research). The reproductive, partially exploratory, and creative levels of formation were characterized for each criterion, scales were developed for their measurement, and diagnostic tools were determined and selected. The experimental data were processed using mathematical statistics methods. The results obtained confirmed the effectiveness of the reasoned pedagogical conditions for the use of the GeoGebra package as a tool for implementing the concept of STEM education in the preparation of pre-service mathematics teachers.
7. The findings of this research contribute to the growing body of evidence supporting technology integration in mathematics teacher education. Our results align with international trends showing that successful GeoGebra implementation requires a multifaceted approach combining technological, pedagogical, and content knowledge development [35, 36]. The identified challenges and solutions provide a roadmap for institutions seeking to enhance their pre-service teacher training programs through dynamic mathematics software integration.

7. Future work

The research conducted does not exhaust all aspects of the analyzed problem. We consider the development of a model of professional training of pre-service mathematics teachers on the basis of an integrative approach and methodological principles for implementing STEM education in the training of pre-service physics, computer science, and technology teachers as promising directions for further scientific research.

Based on comprehensive analysis of current research trends and identified gaps, several critical areas warrant future investigation:

1. Tracking pre-service teachers' technology integration practices from initial training through their first five years of teaching to assess sustained pedagogical change and identify factors supporting

long-term GeoGebra adoption [37].

2. Developing and evaluating strategies for GeoGebra implementation across all mathematical domains, extending beyond the current concentration in geometry and calculus to include statistics, discrete mathematics, and mathematical modeling [38].
3. Creating targeted professional development programs specifically addressing the persistent challenge of low digital instructional material design skills, incorporating principles of Universal Design for Learning and accessibility [39, 40].
4. Investigating and addressing gender disparities in technology adoption among pre-service mathematics teachers, with particular attention to cultural and institutional factors affecting equitable access and engagement [41].
5. Exploring the potential of augmented reality (AR) and virtual reality (VR) integration with GeoGebra to create immersive mathematics learning environments, building on current 3D visualization capabilities [42, 43, 44, 45, 46, 47, 48, 49, 50, 51].

These future directions reflect the evolving landscape of educational technology and the ongoing need for evidence-based approaches to teacher preparation in the digital age.

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Declaration on Generative AI

The authors have not employed any generative AI tools.

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