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REVIEW ARTICLE

Evolution and Current Trends in STEM Education: A Retrospective and Bibliometric Analysis

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ABSTRACT

This study explores the evolution of STEM education, tracing its historical origins through contemporary trends and challenges. The research aims to address the need for a comprehensive understanding of current trends and directions in STEM education to align educational practices with societal demands and the evolving 21st-century labor market. The study employed a two-stage methodology: 1) a retrospective analysis of scientific literature to identify key concepts and historical milestones shaping STEM education, and 2) a bibliometric analysis of publications from the past three years (2021–2024) indexed in the OpenAlex database. The bibliometric analysis revealed emerging research clusters and themes, emphasizing trends such as interdisciplinary and transdisciplinary learning and the integration of advanced pedagogical technologies, including digital tools and AI-driven platforms. Key findings highlight the critical role of interdisciplinary approaches in fostering critical thinking, bridging disciplinary divides, and preparing students to solve complex real-world problems. The study identifies promising trajectories for STEM education's future development, including enhanced integration of STEM disciplines, adoption of innovative pedagogical strategies (e.g., project-based learning), and collaborative frameworks involving educators, policymakers, and industry stakeholders. These insights provide a foundation for advancing STEM education in ways that respond to societal challenges and the dynamic needs of the global workforce.

KEYWORDS

STEM education; transdisciplinary learning; bibliometric analysis; educational practices; discipline integration; educational adaptation

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1. INTRODUCTION

The 21st century is characterized not only by the emergence, implementation, and advancement of digital technologies, neural networks, and robotics but also by the introduction of entirely new, unconventional, and unique perspectives on human development and the world around us. Novel The 21st century is characterized not only by the emergence, implementation, and advancement of digital technologies, neural networks, and robotics but also by the introduction of entirely new, unconventional, and unique perspectives on human development and the world around us. Novel approaches to building effective and socially responsible businesses are emerging as humanity expands the boundaries of accumulated knowledge and reflects on valuable lessons from the past [1]. The rapid transformation of the global landscape demands an equally adaptive and precise approach to its study. Education serves as the cornerstone for developing the skills necessary to construct a modern society that prioritizes efficiency, rationality, and awareness [2]. Education, which forms the foundation of human thought, must also evolve. Modern education strives to cultivate innovative thinking, enabling individuals to remain effective in an ever-changing environment [3]. Among the emerging trends is the concept of STEM education, which is grounded in the application of contemporary methodologies [4]. STEM represents an integrated framework of disciplines encompassing science, technology, engineering, and mathematics [5].

In the context of shifting educational paradigms and the growing importance of STEM education as a critical tool for preparing professionals for the digital economy, the rapid increase in publication activity on this topic has made the analysis of accumulated scientific knowledge particularly relevant. Bibliometric studies, which aim to systematize and analyze publication activity, not only uncover key trends and developmental stages in STEM education but also highlight gaps in existing research that may impede further progress in this field.

Previous bibliometric studies have significantly contributed to understanding the structure, trends, and challenges of STEM education. For example, Assefa and Rorissa [6] conducted a co-word analysis of titles, keywords, and abstracts in scientific publications to explore the structure of STEM education. Their work identified key knowledge domains, including science education, technology education, engineering education, and mathematics education, while underscoring the importance of integrating these disciplines into educational programs.

Similarly, Zhan et al. [7] performed a global analysis of 1,718 documents from the Web of Science database, covering the period from 2004 to 2021. Their study revealed four primary themes addressed by the scientific community: educational equity, pedagogical practices, empirical effects, and career development. The authors observed that developed countries tend to focus on the integration of disciplines and educational equity, while developing countries prioritize pedagogical practices.

In a related study, Khalil et al. [8] conducted a bibliometric analysis of 2,645 articles from the Web of Science Core Collection, spanning the years 2019 to 2023. Their research expanded on key themes identified by earlier studies, such as the integration of STEM disciplines, the application of artificial intelligence and project-based learning, and gender disparities in STEM education.

Additionally, the study by Le Thi Thu et al. [9], which examined publications on STEM education in secondary schools from 2000 to 2020, demonstrated a significant increase in scientific activity in this field over the past five years. However, the study also revealed that the majority of publications originate from the United States, while international collaboration remains relatively limited.

Despite the valuable contributions of these and other studies to understanding global trends and identifying key aspects of STEM education development, several limitations underscore the need for further research. First, many studies focus predominantly on a limited number of countries, particularly developed nations such as the United States. This narrow geographic focus results in insufficient coverage of other regions, hindering the formation of a comprehensive global perspective on the topic's development. Second, data for analysis are frequently drawn from major databases such as Scopus and

Web of Science. While these databases are authoritative, they do not always provide equitable representation of publications from all countries, particularly those in the developing world [10], [11]. Third, existing studies often fail to adequately explore the historical development of STEM education, which limits our understanding of its historical context and evolutionary trajectory. Finally, the forecasting of future trends in STEM education remains an underdeveloped area of research. This gap is particularly critical given the rapid pace of technological and social change. Regular analysis and updating of findings are essential for the effective planning of educational strategies and the adaptation to emerging challenges.

In this context, the present study seeks to address these gaps by conducting a comprehensive bibliometric analysis, exploring the historical development of STEM education in greater depth, and forecasting future trends. The research team considers it essential to systematize the chronology of this scientific field's evolution, with particular emphasis on the thematic diversity of publications related to STEM education. This analytical endeavor aims not only to provide a holistic understanding of the field's development but also to identify the most pertinent research directions. Additionally, a key objective of this study is to project future trajectories of growth within this domain, which will help delineate prospective opportunities for advancement and innovation.

2. Methods

This study is structured into two sequential stages, each designed to contribute to the achievement of the research objectives, which focus on examining the dynamics and trends within STEM education. The first stage involved a retrospective analysis of existing scientific literature on STEM education, aimed at understanding the field's evolution and identifying the primary vectors of its development. The literature review also facilitated the identification of key approaches, models, and practices that underpin modern STEM education, including interdisciplinary and transdisciplinary approaches, as well as diverse forms of discipline integration.

The second stage of the research entailed a bibliometric analysis, selected as the primary method for investigating current trends and directions in the field. Bibliometric analysis is a quantitative research method that enables the identification of the structure and dynamics of scientific publications, the determination of key thematic clusters, and the assessment of the impact and relevance of specific research areas. This method was chosen for its capacity to systematize and analyze large volumes of scientific data, a feature particularly valuable given the rapid growth in publication activity within STEM education.

Bibliometric analysis allows for the identification of thematic trends that shape the contemporary research landscape. Its application provides an opportunity for an objective assessment of current scientific priorities and the forecasting of promising directions for future development. Within the context of this study, bibliometric analysis was employed to identify key terms, thematic clusters, and interrelationships among various aspects of STEM education.

Consequently, the second stage of the research involved the collection and analysis of recent scientific publications on STEM education from the past three years (2021–2024). A search query, "(STEM education) OR (STEM learning)," was executed in the OpenAlex database, yielding a collection of over 3,500 publications, including articles and books. These publications were subsequently processed using specialized software, VOSviewer, which enabled the identification of key terms and thematic clusters. The analysis of these publications provided insights into current trends in STEM education and helped to identify the most significant directions and challenges currently faced by the educational community. The detailed structure of the research methodology is presented in Figure 1.

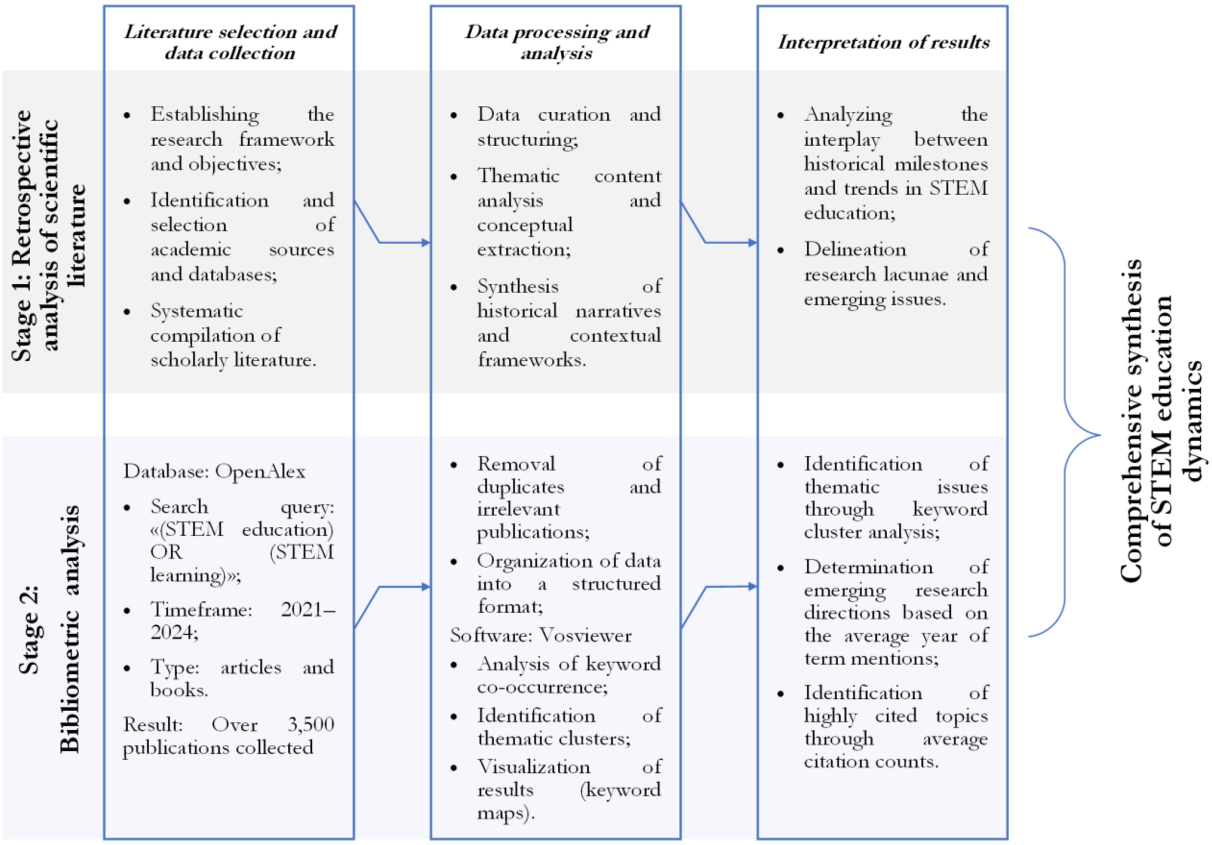

Figure 1. Comprehensive structural framework for a two-stage analysis of STEM education.

For the purposes of this study, the OpenAlex scientific database was selected, as the research team regards it as the most relevant international source, surpassing more established peer-reviewed scientific databases in several key aspects [12], [13]. This choice is justified by the primary objective of the current research, which is to analyze the dissemination of STEM education in academic publications without being constrained by conventional measures of quality. Additionally, ensuring maximum geopolitical diversity is a critical consideration, as databases such as Scopus and Web of Science often inadequately represent publications from developing countries and regions. By utilizing OpenAlex, the study aims to mitigate these limitations and achieve a more comprehensive and balanced representation of global trends in STEM education.

3. Results

3.1. The Results of The Research of Scientific Literature in Retrospect

The emergence of STEM education is often attributed to the technological race between the United States and the USSR. Following World War II, the significance of technological advancement and the promotion of innovative inventions became evident, prompting leading nations to enhance their technical potential. As a result, engineer-inventors with a technical mindset became highly sought after [14]. The need for creating, designing, and building advanced weaponry shifted the focus of education, leading to the in-depth study of these disciplines and their subsequent integration [15].

Although the term STEM was introduced in the 1990s in the United States, the acronym gained popularity due to the interest shown by the National Science Foundation [16]. In its reports, the National Science Foundation emphasizes that STEM education aims primarily at developing critical thinking, problem-solving skills in various domains, and the ability to conduct independent research through analysis, problem identification, and solution development. Such skills are intended to help students succeed in mastering multiple disciplines, building careers, and achieving success in life. It is believed that these four disciplines cannot be taught in isolation, as the application of knowledge from any one of these disciplines requires mastery of the other three. Studying all four disciplines concurrently yields the best results for cultivating comprehensive thinking based on the foundational skills needed for an informed and fulfilling life [17].

Two primary systematic approaches to understanding STEM education have been identified [18]. The first approach views education as an interconnected complex of four disciplines, allowing students to form a holistic understanding of the world. The so-called interdisciplinary approach treats the four disciplines as an indivisible whole, combining the study of theoretical foundations with practice-oriented activities. For example, Brown et al. [19] define STEM education as a comprehensive discipline encompassing science, technology, engineering, and mathematics, which are seen as parts of a unified system. The second approach (transdisciplinary) is based on the importance of studying disciplines of diverse focus to advance technological and digital progress. The transdisciplinary approach to STEM education involves a broader study of disciplines: Back et al. [20] suggest that incorporating the humanities, social sciences, and non-academic disciplines into STEM will facilitate a more informed approach to problem-solving and yield more effective outcomes. The transdisciplinary approach emphasizes the merging of different fields of study to enhance the effectiveness of problem-solving.

Furthermore, there are several concepts related to the implementation of integrated education. In addition to STEM, there is STEAM (Science, Technology, Engineering, Arts, and Mathematics)—a concept that involves integrating science, technology, engineering, and mathematics with the arts, thereby fostering a fuller understanding of the laws of nature [21]. A similar approach is STREAM (Science, Technology, Reading + Writing, Engineering, Arts, and Mathematics)—an idea based on integrating science, technology, engineering, mathematics, and arts through reading and writing, which also aims to provide students with a holistic understanding of the world and the laws of nature [22]. STEM PhBL (Science, Technology, Engineering, Mathematics through Phenomenon-Based Learning) differs from traditional STEM education due to its practice-oriented nature. This approach involves teaching students to integrate science, technology, engineering, and mathematics through direct exploration of phenomena [23]. Another variant of a practice-oriented approach is STEM PBL (Science, Technology, Engineering, Mathematics through Problem-Based Learning)—a concept where students learn by solving problems through integrating knowledge from science, technology, engineering, and mathematics. In PBL, students study concepts by addressing open-ended problems, requiring data from various disciplines and allowing for multiple solutions, which leads to a deeper understanding [24]. Moreover, this concept promotes teamwork in problem-solving, which involves sharing knowledge, addressing issues collaboratively, and modeling behaviors [25].

There are several reasons for the disagreements regarding the definition and implementation of STEM education. Firstly, science and mathematics occupy a dominant position among the four disciplines and are considered the most well-established and universally accepted [26]. Secondly, educators may struggle to find connections between their disciplines and others. Thirdly, engineering often remains unclear and inaccessible to educators from other fields. Additionally, technology is frequently associated solely with computers, which may limit educators' perspectives. Many educators may lack the necessary qualifications to implement STEM education. Finally, those interested in adopting this approach may not collaborate with colleagues in research work [27]. All these factors complicate the process of reforming education within the framework of STEM education [28].

With the recognition of the need for educational system transformation, the topic of integrated education has gained notable popularity among researchers worldwide. Interdisciplinary education has been extensively studied from both theoretical and practical perspectives. Theoretical research suggests several advantages of STEM education, including improving a country's economic climate, enhancing students' academic performance and literacy [29], developing critical thinking skills, and fostering greater independence in problem-solving [30]. The practice-oriented nature of the curriculum enhances students' interest in learning the discipline [31], contributing to the nation's economic competitiveness and social welfare. Experimental studies on this topic are of particular interest, as they highlight the tangible benefits of STEM education. For example, Greene [32], in his study on the use of integrated education methods for California schoolchildren, noted significant success in implementing such a program. Over four years of observation, there was an improvement in the quality and speed of learning, as well as increased student engagement. Beane's research [33] also found improvements in student achievement among those learning through integrated education. Hartzler [34] analyzed 30 quantitative studies on integrated curriculum programs and their impact on student achievement. The findings indicated that students in integrated education programs performed better on standardized tests, national standardized assessments, statewide testing programs, and other assessments developed by curricula compared to students in traditional programs.

STEM education has its challenges, which hinder its development: educators unprepared for new programs, instructional materials, program manuals, and parents who support traditional education methods and fixed study periods [35]. A significant advantage of STEM education is the increase in students' creativity and independence in decision-making [36]. Learning through this method develops students' real-world problem-solving skills and contributes to their personal and social development [37]. This approach encourages active and integrated learning, as problem-solving often requires knowledge from multiple fields. In STEM education, students integrate concepts from various disciplines to address practical challenges. Experiments and data processing are conducted using technology and mathematical methods, allowing students to better understand scientific concepts and acquire practical skills. Research on the impact of STEM education on teachers and students is important, as it helps determine the effectiveness of this approach and its potential impact on the education system as a whole [38]. Moreover, research on STEM informatization has shown that synchronous discussion sessions in small groups positively impact mathematics learning outcomes online, while self-reflection supports mathematics learning and improves performance, particularly among middle school students. Virtual laboratories can also benefit students, especially in foundational courses, by providing access to learning at any time and allowing them to work at their own pace. The findings indicate that students who benefit most from virtual lab-based learning often have greater educational needs [39].

Despite the advantages, STEM education has critics who argue that its implementation should proceed cautiously. This caution stems from the surge in popularity during the global financial crisis. The idea of implementing STEM education was seen as a means to increase a workforce capable of addressing modern business and industrial challenges while driving advances in engineering and science. However, this goal led to resistance among educators, who are primarily interested in enhancing students' academic performance, literacy, and critical thinking skills, rather than contributing to the national economy [40].

Although this approach offers undeniable benefits, it is mistakenly perceived as something fundamentally new and unexplored. In reality, STEM education does not always imply a radical departure from traditional methods; rather, it represents their evolutionary development [41]. At the core of STEM education lies the integration of multiple disciplines, allowing learners to deeply and comprehensively examine complex real-world problems. This interdisciplinary approach enables collective efforts to find effective solutions to global challenges faced by contemporary society [42].

When considering STEM education at the international level, it is crucial to note that many governments support this initiative by creating legislative policies for education. STEM education is often a subject of federal debates on science, education, workforce, national security, and immigration policies, indicating the interest of policymakers [43]. Many countries pursue national education policies to boost labor market supply, enhance the nation's competitiveness, and improve its scientific and technical potential [44]. The push for STEM education was driven by declining performance in science and mathematics and the imbalance between supply and demand in the labor market. Coordinated actions at the national level in education reform indicate countries' efforts to engage youth in science, raise professionalism, and accelerate scientific and technological progress [45]. However, the anticipated economic growth resulting from STEM education, aimed at aligning labor market needs, is feasible only if efforts are made to establish STEM education systems and nurture new generations of specialists over several years [46].

Research on international policies governing STEM education has shown that technological progress has led to changes in perspectives on the future of work and the role of disciplinary knowledge in preparing for it [47]. The level of participation in broadly defined STEM disciplines, such as engineering, science, information technology, healthcare, and agriculture, varies by region and country. Between 2011 and 2015, the highest level of participation was observed in Western Europe (Finland, Germany, Sweden, United Kingdom) and East Asia (South Korea, China), as well as Singapore. In comparison, the United States and Australia showed lower levels of participation [48].

Large-scale systemic changes in infrastructure, schools, and programs are long-term goals and are not required for immediate implementation of reforms. Gradual changes facilitate the advancement of reformed education, while a renewed focus on the role of the teacher in improving their ability to teach effectively is a key starting point [49]. The quality of teaching is prioritized in the reformed education system. Change strategies aimed at enhancing teaching methods offer the greatest potential for improving students' educational outcomes [50]. We must continue to explore and implement more advanced methods, use more effective recruitment strategies, and develop more effective systems for evaluating talented students to ensure our country's success in STEM development. It is also crucial to continue supporting and inspiring our students [51]. To gain a deeper understanding of the state of higher STEM education, data on various indicators such as the number of applicants, current student population, time for degree completion, and financial levels should be regularly collected and updated [52]. Furthermore, in the world of information technology, STEM education must be integrated to prepare qualified specialists with 21st-century skills [53].

3.2. The Results of The Bibliometric Analysis of Actual Scientific Publications

In a rapidly evolving scientific community and in the context of swiftly changing educational demands, it has become increasingly important to conduct research that reflects current trends and indicates the directions of development in STEM education. Publications in this field highlight both achievements and problem areas that require further investigation. Therefore, the research team found it necessary to conduct a bibliometric analysis to gain a deeper understanding of the current priorities and challenges of STEM education and to determine which approaches and strategies are proving most successful in contemporary settings.

Based on a keyword analysis that allowed for the identification of thematic clusters present in scientific publications on STEM education, several significant trends and themes were highlighted, which shape the modern landscape of this academic field. STEM education is evolving as an interdisciplinary platform that combines various approaches and methods, making it not only relevant but also a promising direction for pedagogical and educational research. The clusters identified from the keywords are illustrated in Figure 2 and encompass a wide range of topics, from engineering and critical thinking to instructional approaches and pedagogical technologies.

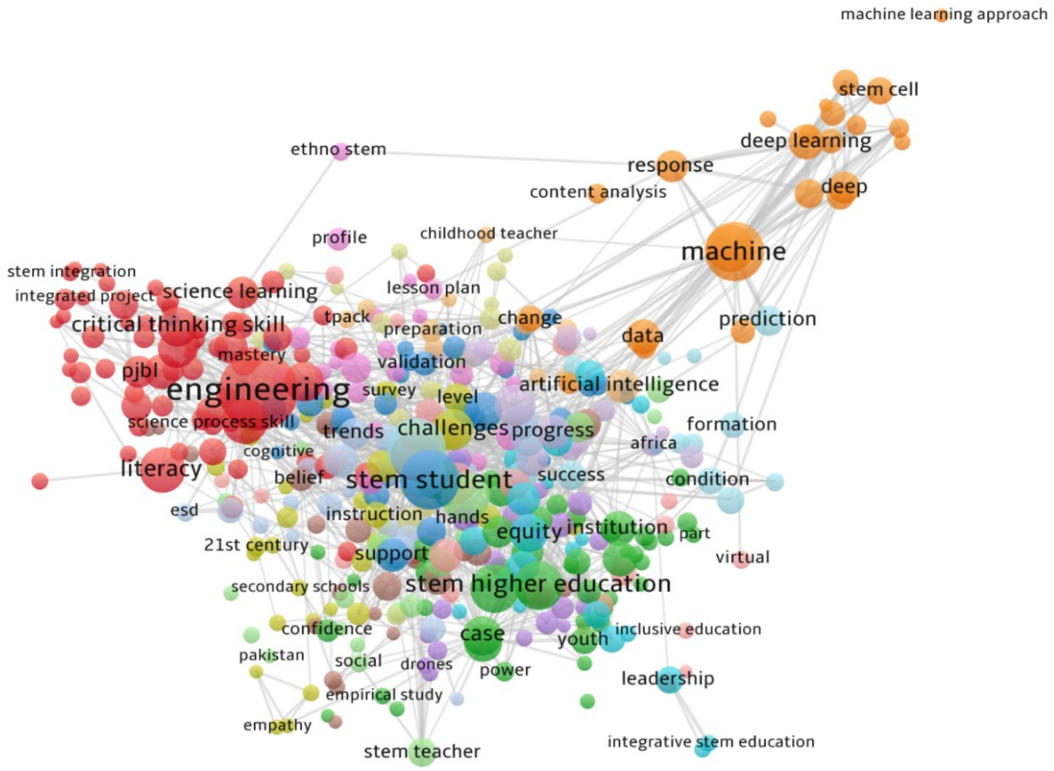

Figure 2. A network of keywords and terms from scientific articles on STEM education, with color-coded thematic clusters.

The analysis of thematic clusters revealed that the largest number of keywords and highest frequency of occurrences are concentrated in clusters related to engineering, literacy, and meta-analysis (Cluster 1, red). These topics represent the foundational elements of STEM education, aimed at developing both professional and personal competencies among students. The relatively recent average publication year (around 2022) and a significant average citation level (3.55) suggest that these areas continue to be of central interest to the research community. Engineering and literacy in the context of STEM contribute to preparing students for the demands of the modern technological world, fostering robust skills in practical problem-solving and critical analysis.

Special attention should be paid to clusters distinguished by high levels of citations, particularly Cluster 6 (blue), which includes topics related to the integration of STEM disciplines and interdisciplinary approaches to learning (with an average citation count of 6.71). The interest of the scientific community in these topics is not accidental; integrating disciplines creates conditions for a comprehensive perspective among students, which is especially crucial in a rapidly changing world where problem-solving requires knowledge from multiple disciplines. Such an approach to STEM education contributes to creating an environment where students learn not only to acquire knowledge but also to apply it practically, interacting with different aspects of science and technology.

Clusters 4 (olive), 7 (orange), and 11 (light green) also demonstrate a high level of citations and relatively high relevance, indicating the sustained demand for topics related to critical thinking, pedagogical technologies, and cognitive aspects of learning. These clusters emphasize the importance of fostering analytical skills among students, enabling them to be active participants in the educational process. The implementation of pedagogical technologies aimed at developing critical thinking opens new opportunities for students to engage actively in the learning process, making it more interactive and motivating.

Promising future research directions may include clusters characterized by a high degree of novelty, such as Cluster 14 (violet), which comprises studies related to new forms of collaboration and interaction in the educational process. The relatively recent average publication year (around 2023) and comparatively low citation rate (1.40) may indicate the early stages of research in these areas, yet their relevance and importance in the context of contemporary educational trends are clear. Developing new forms of student cooperation, using group and project-based learning methods, promises to open new horizons in STEM education, contributing not only to the formation of professional skills but also to social responsibility.

Thus, in the field of STEM education, there is sustained interest in both traditional topics, such as engineering and literacy, as well as interdisciplinary and cognitive aspects of learning. Promising directions for further research include new forms of pedagogical interaction and the introduction of innovative technologies in the learning process, which will contribute to the creation of a flexible and adaptive educational environment. The dynamics of citations and the relevance of publications indicate the research community's readiness to explore and develop new approaches aimed at effective education in a rapidly changing world, making STEM education an extremely promising and significant direction in the context of future educational reforms and transformations.

4. DISCUSSION

The findings of this study align with the conclusions of previous works dedicated to analyzing trends and challenges in STEM education; however, they expand the existing understanding by providing a more in-depth analysis of the historical context and contemporary trends. In particular, while prior research has predominantly focused on individual aspects, such as the integration of disciplines, the development of critical thinking, or the application of pedagogical technologies, the current study offers a comprehensive perspective on the evolution of STEM education. It highlights key stages of its development and current directions shaping the modern landscape of this field. This approach not only systematizes accumulated knowledge but also identifies gaps that warrant further investigation.

The significance of the obtained results lies in their potential to reshape the theoretical and practical landscape of STEM education. The findings emphasize the necessity of integrating various disciplines within the educational process to foster a deeper interaction among scientific fields. This integration aligns with the increasing demand for 21st-century skills such as critical thinking, problem-solving, creativity, and adaptability, which are highly sought after in the modern labor market. Moreover, the results highlight key research priorities, including the adoption of interdisciplinary and transdisciplinary approaches, as well as the implementation of advanced pedagogical technologies. These priorities reflect the global trend towards creating educational systems that are more holistic, inclusive, and responsive to technological advancements. For instance, the adoption of phenomenon-based and project-based learning approaches has been shown to enhance students' ability to engage in collaborative problem-solving, which is crucial for preparing them to address real-world challenges effectively.

The initial retrospective analysis of the literature revealed long-term trends that have shaped the foundation of STEM education, ranging from the technological race of the mid-20th century to contemporary interdisciplinary approaches to learning. The historical context of STEM development highlights the necessity of integrating science, technology, engineering, and mathematics to equip students with the skills needed to solve complex real-world problems, foster critical thinking, and enhance their competitiveness in the labor market. This evolution—from narrow specialization to interdisciplinary and transdisciplinary approaches—reflects the ongoing adaptation of education to address modern challenges and technological advancements.

The bibliometric analysis enabled the identification of current research directions and themes that are central to the scientific community's interests. The identified thematic clusters demonstrate a significant demand for interdisciplinary approaches, underscoring the importance of integrating diverse scientific disciplines to create a holistic educational experience. The analysis of recent publications also revealed a strong focus on the adoption of innovative pedagogical technologies designed to enhance cognitive and critical thinking skills among students, as well as the development of new forms of pedagogical interaction, such as project-based and phenomenon-based learning.

When compared to historical trends in STEM education research (summarized in Table 1), these findings illustrate a clear evolution: from an early emphasis on interdisciplinary integration and workforce development to a current focus on innovative pedagogical technologies, collaborative learning, and the cultivation of 21st-century skills. This shift highlights the dynamic nature of STEM education research and its responsiveness to both global challenges and advancements in educational practices.

Table 1. Temporal Dynamics of STEM education research trends

Time Period	Trends in STEM Education Research
1990s – Early 2000s	• Origins of STEM. Emergence of STEM education as a response to the technological race between the US and USSR, with a focus on advancing national technical potential and innovation; • Interdisciplinary Integration. Early emphasis on the interconnectedness of science, technology, engineering, and mathematics, with the goal of fostering holistic understanding and problem-solving skills; • Workforce Development. STEM education seen as a means to address labor market demands, particularly in engineering and technology sectors; • Theoretical Foundations. Introduction of interdisciplinary and transdisciplinary approaches, with debates on whether STEM should remain focused on core disciplines or expand to include humanities and social sciences (e.g., STEAM, STREAM); • Educational Goals. Focus on developing critical thinking, problem-solving, and independent research skills, with the belief that STEM disciplines cannot be taught in isolation;

Time Period	Trends in STEM Education Research
	• Early Challenges. Struggles with defining STEM, integrating engineering and technology into curricula, and overcoming educators' lack of qualifications in interdisciplinary teaching.
2020s (Recent Years)	• Engineering and Literacy: Dominant focus on engineering and literacy as foundational elements of STEM education, with a strong emphasis on preparing students for the technological demands of the modern world; • Interdisciplinary and Transdisciplinary Approaches: Growing interest in integrating STEM with other disciplines, such as humanities and social sciences, to foster a more comprehensive perspective on problem-solving; • Critical Thinking and Pedagogical Technologies: Increased research on the cognitive aspects of learning, with a focus on developing critical thinking skills through innovative pedagogical technologies; • Collaborative Learning: Emerging research on new forms of collaboration, group learning, and project-based approaches, which aim to enhance social responsibility and teamwork among students; • Virtual and Online Learning: Rapid adoption of virtual laboratories and online learning tools, particularly in foundational courses, to provide flexible and accessible learning environments; • 21st-Century Skills: Strong emphasis on preparing students with skills such as creativity, independence, and adaptability, which are essential for success in a rapidly changing global economy; • Global and Policy Perspectives: Increased focus on international policies and the role of STEM education in addressing global challenges, such as technological progress, workforce demands, and national competitiveness. • Challenges and Criticisms: Ongoing debates about the overemphasis on economic goals in STEM education, with concerns about neglecting broader educational objectives such as academic performance, literacy, and critical thinking.

Both components of the study—the retrospective analysis and the bibliometric analysis—converge on a central conclusion: the future of STEM education is intrinsically tied to its capacity to adapt to evolving social and technological conditions. The interdisciplinary and transdisciplinary approaches, identified through historical analysis and reaffirmed by current research, emerge as pivotal vectors of development. Crucially, the relevance of STEM education extends beyond the cultivation of technical skills; it also encompasses fostering students' ability to solve complex problems, collaborate effectively in teams, and apply creative approaches. These dimensions ensure the successful integration of STEM into modern educational systems, positioning it as an essential component in preparing future specialists capable of driving innovation.

The practical application of the results of this study can be multifaceted, with particular emphasis on their use in research activities. First, the identified priorities can serve as a foundation for developing new research programs aimed at studying the effectiveness of various approaches to STEM education. This is especially relevant in the context of the growing need for evidence-based research that can inform decision-making in educational policy. Second, the study's findings can be utilized to form interdisciplinary research groups that will address complex problems requiring the integration of knowledge from various fields. For example, investigating the impact of STEM education on the development of problem-solving skills could involve specialists in pedagogy, psychology, sociology, and information technology. Such an approach would not only provide a deeper understanding of the processes occurring in the educational environment but also contribute to the development of innovative methodologies that can be adapted to different contexts.

Furthermore, the results of this study may stimulate further exploration of new forms of interaction in the educational process, such as group-based and project-based learning, which have been identified as promising directions. This opens up opportunities for conducting experiments and pilot projects aimed at evaluating the effectiveness of these approaches in various educational settings. For instance, research could explore how the implementation of project-based learning influences student motivation and their ability to apply acquired knowledge in practice.

This study also reaffirms the growing importance of balancing traditional STEM disciplines with broader educational perspectives, such as incorporating humanities and social sciences. This shift towards a transdisciplinary framework enriches the learning process and promotes innovation by encouraging students to apply diverse perspectives to problem-solving. Additionally, the bibliometric analysis underscores the increasing role of virtual and online learning environments, which have become indispensable in providing accessible and flexible educational opportunities in a rapidly evolving global context.

Despite significant progress in understanding the trends and challenges of STEM education, there remain areas that require further investigation, and the results of this study allow for the identification of several key directions for future research. One such area is the study of new forms of collaboration and interaction in the educational process, which may include not only group-based and project-based learning but also the use of digital platforms to facilitate collaborative work among students. Additionally, further research could focus on examining the impact of STEM education on diverse student groups, including those from different cultural, social, and academic backgrounds. This would enable the development of more inclusive educational programs that account for the diversity of student needs and capabilities, as well as identify factors that contribute to the successful integration of STEM approaches in various educational contexts.

While the study offers valuable insights, it is important to acknowledge its limitations. The analysis was primarily based on publications indexed in specific databases, which may not fully capture regional or localized research contributions. Future studies should aim to expand the scope of bibliometric analysis to include a wider range of data sources and explore the contextual adaptation of STEM education in different cultural and economic settings. Furthermore, longitudinal studies could provide deeper insights into how STEM education evolves over time and its long-term impact on workforce development and societal progress.

5. Conclusion

The retrospective analysis of the literature revealed that STEM education has undergone significant transformations over the decades, evolving from a focus on narrow specialization during the mid-20th century to contemporary interdisciplinary and transdisciplinary approaches. These changes reflect the dynamic nature of STEM education as it adapts to technological advancements and global challenges, emphasizing the necessity of integrating science, technology, engineering, and mathematics to equip students with the skills needed to solve complex real-world problems, foster critical thinking, and enhance their competitiveness in the labor market.

The bibliometric analysis further identified current research trends and priorities, such as the adoption of innovative pedagogical technologies, the emphasis on critical thinking, and the integration of diverse disciplines to enhance the educational process. These findings highlight the importance of fostering collaboration, creativity, and adaptability in students to prepare them for the demands of an increasingly complex and technology-driven world. The analysis also revealed a growing focus on new forms of pedagogical interaction, such as project-based and phenomenon-based learning, which are essential for developing students' ability to apply knowledge in practical contexts and work effectively in collaborative environments.

The comparison of historical and contemporary trends underscores the ongoing evolution of STEM education. The early emphasis on workforce development and interdisciplinary integration has shifted towards addressing global challenges, promoting collaborative learning, and equipping students with 21st-century skills. This evolution reflects the responsiveness of STEM education research to societal needs and technological progress, as well as its capacity to adapt to the changing demands of the global economy and labor market.

The findings of this study highlight the necessity of further strengthening the integration of STEM education into educational practices. Particular emphasis should be placed on interdisciplinary teaching methods, the active incorporation of advanced pedagogical technologies, and the development of innovative forms of collaboration and interaction. Such measures will contribute to the creation of a flexible, adaptive, and resilient educational environment—one that is equipped to address the challenges of the 21st century, enhance the quality of workforce training, and bolster society's innovative potential. The primary trajectory for the development of STEM education lies in reinforcing connections between diverse disciplines and fostering conditions that promote holistic and flexible thinking among learners. This will empower them to navigate and address future challenges in an increasingly dynamic and complex world.

In conclusion, the future trajectory of STEM education lies in its ability to integrate diverse disciplines, foster holistic learning approaches, and adopt advanced pedagogical technologies. By strengthening interdisciplinary teaching methods, promoting collaboration, and leveraging innovative tools, educational systems can create adaptive, resilient environments that empower learners to navigate and address the challenges of the 21st century effectively. The continued emphasis on flexibility, innovation, and inclusivity will ensure that STEM education remains vital to preparing future specialists capable of driving global progress and societal transformation.

DECLARATIONS

Author Contributions

Sokolova Elizaveta Vitalievna: Conceptualization, Methodology, Software, Data curation, Visualization. **Blaginin Victor Andreevich:** Supervision, Writing – Review & Editing. **Shatrova Alexandra Yaroslavovna:** Writing – Original Draft. All authors have read and approved the final version of this manuscript.

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Ethical Approval

This study did not involve human or animal participants; therefore, ethical approval was not required.

Competing Interests

The authors declare that they have no competing interests.

Generative AI and AI-Assisted Technologies Statement

During the preparation of this manuscript, the authors used DeepSeek and Grammarly to enhance its readability, language, and overall structure. Following the use of these tools, the authors performed a comprehensive review and editing process to ensure the accuracy, integrity, and quality of the content. The authors accept full responsibility for the content and conclusions presented in this publication.

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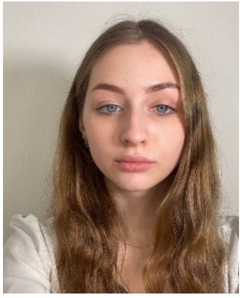

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