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Generative AI in Science Education: A Learning Revolution or a Threat to Academic Integrity? A Bibliometric Analysis

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Abstract

The integration of generative artificial intelligence (AI) in Science, Technology, Engineering, and Mathematics (STEM) education presents transformative opportunities alongside significant challenges. This study investigates the dual impact of generative AI on STEM learning outcomes and academic integrity through a comprehensive bibliometric analysis employing co-citation, keyword analysis, and trend mapping. The results reveal that AI tools such as ChatGPT have revolutionized personalized learning by offering tailored feedback, enhancing critical thinking, and improving student engagement. However, these advancements are tempered by concerns over academic misconduct, particularly plagiarism, and the erosion of essential cognitive skills due to overreliance on AI-generated content. Ethical considerations remain critical, necessitating the development of robust policies and ethical frameworks to safeguard academic integrity. Beyond educational settings, the findings suggest broader applicability to professional training and skills development, as the benefits and challenges of AI extend beyond coursework. This research provides valuable insights for educators, policymakers, and researchers, advocating for a balanced approach to AI integration that maximizes its potential while preserving educational standards.

Keywords: Generative AI; STEM education; academic integrity; personalized learning; ChatGPT

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INTRODUCTION

The integration of generative artificial intelligence (AI) into education, particularly in Science, Technology, Engineering, and Mathematics (STEM), is rapidly emerging as a powerful force for change. Generative AI technologies, such as natural language processing (NLP) and machine learning, are offering unprecedented opportunities to revolutionize education by providing personalized, adaptive learning experiences. Tools like ChatGPT and other AI models can meet diverse student needs, facilitating the exploration of complex concepts and enhancing critical thinking, which is essential in STEM education. This growing body of research highlights both the transformative potential and the challenges these technologies pose to traditional educational practices (Boscardin et al., 2024; Xu & Ouyang, 2022).

As AI becomes increasingly integrated into educational systems, a deeper examination of its benefits and challenges is necessary.

Emerging studies, such as Tülübaş et al. (2023), which investigated the relationship between digital addiction and academic achievement, have underscored the complexity of student engagement with AI technologies. Similarly, Aravantinos et al. (2024) conducted a systematic review of AI applications in primary education, identifying how AI enhances cognitive and affective learning outcomes. Lavidas et al. (2024) examined AI usage among Humanities and Social Sciences students, revealing important factors influencing AI adoption across diverse disciplines. Together, these studies indicate that AI has the potential to reshape educational practices across different age groups and academic fields, prompting the need for a balanced approach that both leverages AI's benefits and addresses its challenges.

Generative AI has the ability to significantly improve STEM education by offering customized learning experiences that adapt in real-time to each student's progress. These tools provide immediate feedback, assist in problem-solving, and empower students to take charge of their learning. By catering to individual learning paces, AI ensures students fully grasp complex concepts before advancing to more difficult material. Moreover, the interactive nature of AI promotes greater student engagement, making the learning environment more dynamic. This represents a fundamental shift in the delivery and experience of education (AlAli & Wardat, 2024; Pedersen, 2023). However, the same characteristics that make AI transformative also pose significant challenges, particularly regarding academic integrity.

A growing concern is the reliance on AI-generated content, which has led to debates about the authenticity and credibility of student work. AI's ability to generate text, solve problems, and even assist in exams has raised issues about plagiarism and overdependence on AI tools, potentially undermining the development of essential cognitive skills. These concerns are particularly acute in STEM fields, where the accuracy and originality of student work are critical. Educators must ensure that AI's use does not compromise academic integrity. Boscardin et al. (2024) and Simms (2024) emphasize that strict guidelines and ethical frameworks must be developed to govern AI usage in educational settings, ensuring that its benefits are harnessed responsibly without sacrificing the integrity of the academic process.

The broader implications of AI integration also extend to concerns about data privacy, algorithmic bias, and the evolving role of educators. AI systems require large datasets to function effectively, which raises critical questions about how student data is collected, stored, and used. AI could exacerbate privacy risks and ethical concerns without appropriate safeguards. The biases inherent in AI algorithms could also perpetuate inequalities in the educational system, as AI decisions might unfairly favor certain groups or disadvantage others. The potential for AI to reinforce existing societal biases has been a topic of significant debate, as outlined by Kadaruddin (2023) and X. Zhou et al. (2020). Addressing these issues requires proactive measures to ensure that AI is used equitably and transparently, with appropriate regulations to protect both students and educators.

Moreover, the integration of AI in education necessitates a reevaluation of the role of teachers. As AI systems become more integrated into classrooms, educators must adapt to new pedagogical models that incorporate these technologies. This shift requires significant investment in teacher training and ongoing professional

development to ensure that teachers are equipped to use AI tools effectively. In many cases, teachers will transition from being the primary sources of knowledge to becoming facilitators who guide students through AI-enhanced learning environments. This evolving role offers both opportunities and challenges, as educators must balance the benefits of AI with the need to maintain their pedagogical authority (Uygun, 2024; J. Zhou, 2024).

Despite the challenges, the integration of AI into education presents significant opportunities to enhance learning outcomes. AI can help bridge learning gaps, especially in STEM education, by providing personalized assistance that addresses individual student needs. However, as emphasized by Alasadi and Baiz (2023), it is essential to address the ethical considerations that accompany AI's growing influence in education. This includes ensuring that AI tools are used in ways that promote fairness and equity, rather than exacerbating existing disparities. Rane (2024) also points out that AI's impact on education will largely depend on the frameworks and policies developed to regulate its use. Data protection, ethical guidelines, and strategies for addressing algorithmic bias will be critical in shaping the future of AI in education.

The literature on generative AI in education emphasizes its dual role as both a revolutionary tool and a potential challenge to academic integrity. While AI offers many advantages for improving learning outcomes, especially in STEM fields, it also raises significant ethical and practical concerns (Boscardin et al., 2024). Research must continue to explore how AI impacts learning, how educators can adapt to its growing role, and how society can address the broader implications of AI in education (Lavidas et al., 2024; X. Zhou et al., 2020). The future of STEM education in the AI era will depend on the ability of educators, policymakers, and researchers to navigate these complex issues effectively, ensuring that AI integration is both beneficial and ethically sound (Cooper, 2023).

This study seeks to contribute to this ongoing discourse by examining the dual impact of generative AI on STEM learning outcomes and academic integrity through a comprehensive bibliometric analysis. By mapping the global research landscape, this study aims to identify key trends, geographical patterns, and the most influential studies and researchers in the field. This analysis is critical for understanding how AI is shaping the future of STEM education, particularly with regard to its potential to enhance learning outcomes while preserving academic integrity.

In addition to assessing learning outcomes, this study investigates the ethical challenges posed by AI integration, including issues related to plagiarism and the authenticity of student work. By examining these challenges, the study seeks to offer strategies for ensuring that AI is used responsibly in educational settings. Furthermore, the study synthesizes insights from existing case studies and comparative analyses to provide a nuanced understanding of how generative AI is influencing educational practices across different contexts. The objective is to identify best practices and offer practical, evidence-based recommendations for the responsible and effective implementation of AI in STEM education.

The study is structured around four key research questions, which are designed to explore the dual role of generative AI in STEM education. These questions focus on AI's potential to enhance learning, the challenges it poses to academic integrity, and the insights that can be drawn from existing literature. Through this exploration, the

study aims to provide valuable recommendations for the responsible and impactful integration of AI in education:

1. What are the global research trends in generative AI for STEM education?
2. How does generative AI impact STEM learning outcomes?
3. What challenges does generative AI present to academic integrity in STEM education?
4. What insights can be drawn from case studies and comparative research on AI integration in education?

This study's significance lies in its potential to offer a comprehensive understanding of how generative AI can be integrated into STEM education while upholding academic integrity. As AI technologies continue to evolve, they will play an increasingly central role in shaping the future of education. This study provides critical insights for educators, policymakers, and researchers, offering evidence-based strategies for leveraging AI's benefits while addressing its ethical and practical challenges.

LITERATURE REVIEW

Generative AI in Education

Generative Artificial Intelligence (AI) is revolutionizing Science, Technology, Engineering, and Mathematics (STEM) education by providing innovative tools that significantly enhance learning outcomes while introducing new challenges, particularly regarding academic integrity. Technologies such as OpenAI's ChatGPT and other models have demonstrated the potential of AI to deliver personalized, adaptive learning experiences that surpass the capabilities of traditional educational tools. By leveraging Natural Language Processing (NLP) and machine learning, these AI systems can analyze extensive datasets and deliver tailored content that meets individual student needs, fostering a deeper understanding of complex STEM concepts (Tassoti, 2024; Woodruff et al., 2023).

One of the primary benefits of generative AI in STEM education is its ability to create adaptive learning environments that adjust to each student's pace and learning style, enhancing both comprehension and retention. AI-powered tools such as chatbots and intelligent tutoring systems provide real-time feedback, which aids students in mastering challenging topics and improving their overall educational experience (Pack & Maloney, 2024; Vasconcelos & Dos Santos, 2023). These tools also play a critical role in fostering creativity and critical thinking by engaging students in problem-solving tasks and simulations—key skills necessary for STEM careers (Cohen et al., 2024).

Generative AI also has the potential to address issues related to equity and diversity in STEM education. By accommodating diverse learning styles and providing personalized support, AI can help reduce biases and create a more inclusive learning environment. This is especially important in ensuring that underrepresented groups in STEM fields receive equal opportunities to succeed (Adiguzel et al., 2023; Yao & Chung, 2024). By offering targeted assistance and eliminating barriers related to traditional educational models, AI can foster greater participation and success among these groups.

However, the integration of AI in education introduces significant challenges, particularly concerning academic integrity. As AI-generated content becomes more

sophisticated, the risks of academic misconduct, such as plagiarism and cheating, increase. These challenges highlight the need for educators to implement safeguards to ensure that AI is used ethically and responsibly, maintaining the integrity of the educational process (Hasnain, 2023). The literature emphasizes the dual role of generative AI in both advancing education and challenging traditional academic norms, signaling a clear need for more focused research on its specific impact on STEM learning outcomes and academic integrity (Abbas et al., 2023; Nagaraj et al., 2023). While generative AI offers powerful tools for revolutionizing STEM education, its integration requires careful consideration of ethical concerns. Addressing these challenges through focused research and thoughtful implementation will be critical for harnessing AI's full potential in enhancing STEM education while upholding academic standards.

Impact of Generative AI on STEM Learning

The integration of generative AI in STEM education has significant implications for learning outcomes, particularly in areas such as problem-solving, critical thinking, and student engagement. AI-driven tools enhance problem-solving skills by creating dynamic, interactive learning environments in which students can engage with complex problems in a personalized manner. These platforms, which often incorporate gamification strategies, have been shown to significantly improve students' ability to apply theoretical knowledge to practical challenges, fostering a deeper understanding of STEM concepts (Alenezi, 2023).

Moreover, generative AI plays a crucial role in developing critical thinking skills. AI-integrated learning environments encourage students to engage in higher-order thinking by presenting scenarios that require evaluation, synthesis, and application of knowledge. Tools such as intelligent tutoring systems are particularly effective in challenging students appropriately, pushing them to think more deeply about the subject matter (Susanto et al., 2023). Furthermore, AI significantly enhances student engagement, a key factor in learning that correlates directly with motivation and persistence in challenging subjects. AI-driven tools such as chatbots and virtual tutors provide personalized, interactive learning experiences that resonate with students' individual interests, helping to maintain their focus and motivation in STEM disciplines (H. Wu & Yu, 2023).

While the benefits of AI in enhancing STEM learning outcomes are clear, important ethical considerations remain, particularly regarding academic integrity. The ease with which AI can generate content raises concerns about potential misuse, such as plagiarism, underscoring the need for responsible AI use in educational settings. Continued research is necessary to fully understand the nuances of AI's impact on STEM education and to develop strategies that harness its benefits while mitigating its risks. Generative AI has a transformative impact on STEM learning by enhancing problem-solving, fostering critical thinking, and increasing engagement. However, addressing the ethical challenges it presents is crucial to ensuring that AI contributes positively to STEM education.

Academic Integrity Challenges in STEM Education

The rise of generative AI in STEM education presents significant challenges to academic integrity, which are becoming increasingly complex as AI technologies evolve and become more accessible. The ability of AI to generate high-quality, human-

like content has heightened the risk of academic misconduct, such as plagiarism and cheating, raising serious concerns among educators and academic institutions (Z. Chen et al., 2024; Uddin & Abu, 2024).

To address these challenges, it is essential to develop ethical frameworks and prevention strategies that integrate AI-related issues into existing academic integrity policies. This includes implementing AI detection tools and enhancing monitoring mechanisms to identify and address unethical behaviors effectively. Additionally, educating students on the ethical use of AI and the consequences of academic misconduct is crucial to fostering a culture of integrity within academic institutions (Birks & Clare, 2023).

The literature further emphasizes the need for clear guidelines and policies that define acceptable uses of AI in academic work, ensuring that students understand the ethical implications of their actions. As AI becomes more integrated into educational practices, ongoing dialogue between educators, policymakers, and technologists is necessary to navigate the ethical complexities associated with AI in education (Vallespir Adillón et al., 2024). The challenges posed by generative AI to academic integrity in STEM education are multifaceted and require a comprehensive approach (Bozkurt, 2024). By fostering a culture of integrity and establishing clear policies, educational institutions can mitigate the risks associated with AI-driven academic misconduct, ensuring that AI enhances rather than undermines the educational process.

Comparative Studies and Case Studies in Existing Literature

The adoption of generative AI in STEM education has been the subject of various comparative analyses and case studies, which provide valuable insights into its impact across different educational contexts. Comparative studies reveal significant differences in AI adoption and its effects on student outcomes, influenced by factors such as AI resources, digital literacy, and institutional support (Abbas et al., 2023; Ullah, 2024). For instance, research shows that AI tools can significantly improve educational performance by making learning more engaging and personalized, particularly in higher education settings where complex STEM concepts require innovative teaching approaches (Wang et al., 2023).

Case studies further illustrate the practical applications of AI, such as its role in teacher education and professional development, highlighting its potential to enhance teaching strategies and prepare students for the demands of modern STEM careers (Köprülü et al., 2023; S. Wu, 2024). These studies offer evidence of AI's ability to improve instructional methods and support lifelong learning for both teachers and students.

However, the integration of AI into education is not without its challenges. Studies emphasize the need for a comprehensive understanding of AI's impact across various educational contexts to avoid potential pitfalls, such as over-reliance on technology and the erosion of traditional teaching methods (K. H. D. Tang, 2024). Ethical considerations, including data privacy, algorithmic bias, and the evolving role of educators, must also be addressed to ensure that AI is used responsibly and equitably (Kadaruddin, 2023). The growing body of research on generative AI in education underscores its transformative potential but also highlights the importance of managing its impact on academic integrity and ethical practices. Comparative

studies and case studies offer valuable evidence on how AI can enhance learning outcomes, foster creativity, and support personalized education, while also pointing to the challenges that need careful navigation.

METHOD

Research Design

This study employs a bibliometric analysis to evaluate the impact of generative AI on STEM education, focusing on both learning outcomes and challenges related to academic integrity. To provide a comprehensive overview, advanced bibliometric tools—VOSviewer, Bibliometrix, and CiteSpace—were utilized to systematically map research trends, analyze existing literature, and identify key themes related to the integration of AI in education. This approach was chosen to address the study's research questions and provide insights into global research trends.

The bibliometric analysis included publications from 2010 to 2024, retrieved from the Scopus database, using a carefully constructed Boolean search string designed to capture relevant studies:

ALL (("generative AI" OR "generative artificial intelligence" OR "ChatGPT" OR "large language model" OR "LLM") AND ("science education" OR "STEM education" OR "scientific learning" OR "science teaching") AND ("ethical implications" OR "practical implications" OR "academic integrity" OR "bias" OR "equity" OR "teaching effectiveness" OR "workload" OR "critical thinking")) AND PUBYEAR > 2009 AND PUBYEAR < 2025.

The selection of this time frame was based on the rapid development of generative AI technologies post-2010, marking significant advances in AI-driven education tools. The inclusion and exclusion criteria were crucial for ensuring the relevance and quality of the studies. Publications were included if they (1) specifically addressed generative AI or large language models in the context of STEM education, (2) focused on learning outcomes or academic integrity, and (3) were published in peer-reviewed journals between 2010 and 2024. Studies were excluded if they (1) addressed general AI without a focus on education, (2) lacked empirical data or case studies, or (3) were duplicates or not published in English. These criteria ensured that only relevant and high-quality studies were included for analysis.

Three bibliometric tools were used to conduct a thorough analysis of the research landscape:

1. VOSviewer was employed to generate and visualize bibliometric maps, offering insights into co-citation, co-occurrence networks, and keyword clustering. This helped to identify the relationships between key themes, contributors, and journals in the field of AI in STEM education (Perianes-Rodriguez et al., 2016).
2. Bibliometrix (via its R-based interface, Biblioshiny) facilitated robust quantitative analysis and visualization of keyword trends and thematic developments. The tool's ability to handle large datasets was particularly useful in analyzing the global trends surrounding AI's application in STEM education (Aria & Cuccurullo, 2017).
3. CiteSpace provided critical insights into collaborative networks, frequently cited publications, and emerging research themes by mapping knowledge domains and visualizing changes in research focus. This tool played an essential role in

identifying ethical considerations, particularly concerning AI's implications for academic integrity (C. Chen, 2017).

These tools worked in tandem to ensure a comprehensive analysis of the selected literature. The data collection and analysis process, as illustrated in Figure 1, was designed to highlight influential works and emerging trends. This methodological rigor ensures the replicability and transparency of the research, offering a structured approach for future studies.

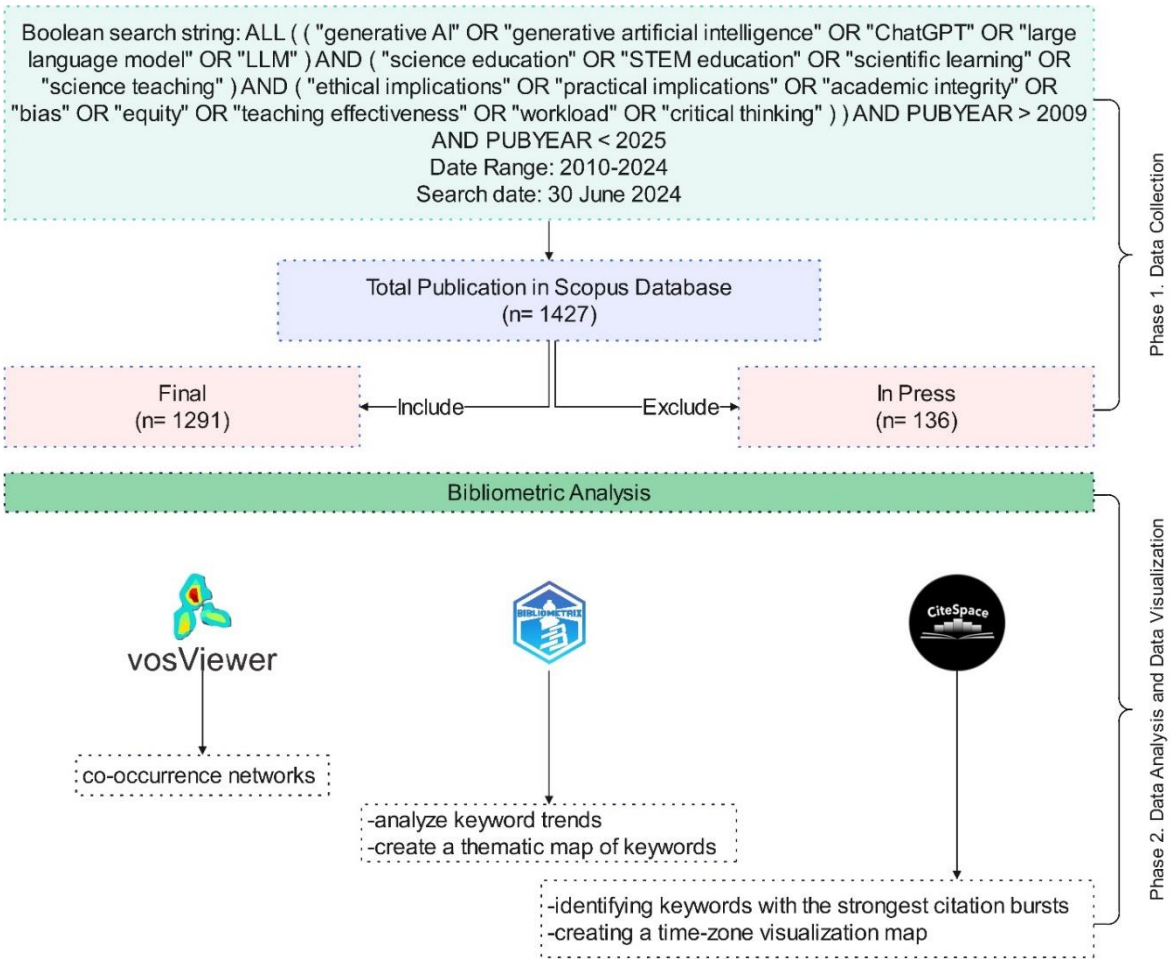

Figure 1. Flow of data collection, analysis, and visualization

Inclusion and Exclusion Criteria

To ensure transparency and replicability, the inclusion and exclusion criteria were carefully defined. Studies were included if they (1) directly examined generative AI in STEM education, (2) were peer-reviewed, and (3) focused on learning outcomes or ethical considerations, such as academic integrity. Excluded studies were those (1) outside the scope of STEM education, (2) lacking empirical data, (3) general AI discussions without a focus on education, or (4) not published in English. This rigorous selection process, covering 2010 to 2024, ensured the inclusion of studies that specifically addressed the research questions and contributed meaningful insights.

Review of Case Studies and Comparative Studies

In addition to the bibliometric analysis, a detailed review of case studies and comparative analyses was conducted to provide context-specific insights into how generative AI influences STEM education. The reviewed studies were selected based

on strict inclusion criteria: they had to explicitly address the use of AI in STEM education and provide empirical evidence of its impact on learning outcomes or ethical concerns, particularly academic integrity. Studies that focused on AI implementation in other fields, or that did not include specific outcomes related to STEM learning or integrity, were excluded.

The case studies reviewed offered rich, detailed examples of AI's practical applications in educational settings. These studies highlighted how AI tools, such as intelligent tutoring systems and AI-driven simulations, influence students' problem-solving abilities, critical thinking, and creativity. For example, some case studies documented how AI systems helped students engage more effectively with complex STEM concepts by providing personalized feedback and adaptive learning environments (Cohen et al., 2024). However, other studies raised concerns about AI's role in facilitating academic misconduct, particularly when students used AI tools to complete assignments without independent critical thinking (Hasnain, 2023).

Comparative studies played a critical role in understanding how AI impacts education across different cultural and institutional contexts. These studies compared AI's effectiveness in diverse educational systems, showing that factors such as access to AI resources, digital literacy, and institutional support can significantly affect outcomes. For instance, studies revealed that countries with advanced digital infrastructure saw greater benefits from AI integration in education, while others faced challenges related to technology access and teacher preparedness (Wang et al., 2023). Such comparative analyses also explored variations in how AI influences academic integrity, with some educational systems implementing stricter policies to prevent misuse than others (Z. Chen et al., 2024).

Data Analysis

The case and comparative studies were analyzed using thematic synthesis, categorizing the findings based on their relevance to the study's research questions. Studies were grouped according to their impact on learning outcomes (e.g., problem-solving, critical thinking, and engagement) and their implications for academic integrity (e.g., plagiarism and cheating). This thematic analysis allowed for a nuanced understanding of how AI affects different aspects of education.

The synthesis highlighted both the benefits and challenges associated with generative AI in STEM education. Studies showing improved student engagement and problem-solving capabilities were contrasted with those raising ethical concerns about AI's potential to diminish independent learning skills or facilitate academic misconduct. By examining these case studies in the context of the broader bibliometric analysis, the research provided a comprehensive understanding of the current landscape and identified gaps in knowledge that future studies should address.

RESULTS AND DISCUSSION

Research Question 1: Global Research Trends in Generative AI for STEM Education

Overview of Global Research Trends in Generative AI for STEM Education

The integration of generative AI into Science, Technology, Engineering, and Mathematics (STEM) education has rapidly expanded, transforming traditional pedagogical approaches and enabling more personalized learning experiences.

Between 2010 and 2024, a total of 1,291 documents were published on generative AI in STEM education, marking a significant annual growth rate of 61.94%. This rapid growth reflects the increasing global interest in applying AI technologies—particularly ChatGPT, large language models (LLMs), and machine learning (ML)—to enhance STEM education outcomes. AI has gained traction for its ability to provide adaptive learning, personalized feedback, and real-time problem-solving capabilities, making it an integral part of modern educational systems. Table 1 provides a summary of key metrics derived from the bibliometric analysis, highlighting the growing relevance and impact of AI in education. The data suggests that this field is still relatively young, with an average document age of 0.442 years, indicating that the bulk of research has emerged only recently. Moreover, the high level of international collaboration (24.86%) and the involvement of over 4,100 authors from 636 different sources emphasize the global and interdisciplinary nature of AI research in education.

Table 1. Main information of the metadata analyzed

Description	Results	Subject area	Doc.	(%)
Timespan	2010-2024	Social Sciences	817	35
Sources (Journals, Books, etc)	636	Computer Science	620	26
Documents	1291	Engineering	159	7
Annual Growth Rate %	61.94	Business	116	5
Document Average Age	0.442	Psychology	85	4
Average citations per doc	5.96	Mathematics	70	3
References	85700	Arts and Humanities	68	3
Authors	4113	Medicine	68	3
Authors of single-authored docs	212	Decision Sciences	49	2
Single-authored docs	219	Economics	40	2
Co-Authors per Doc	3.69			
International co-authorships %	24.86			

The interdisciplinary nature of generative AI research in education is a notable trend. AI is not limited to technical domains such as computer science and engineering; rather, it is increasingly applied to address broader educational and social challenges. For instance, research has expanded into fields such as psychology, medicine, and decision sciences (Table 1), reflecting the recognition that AI has the potential to enhance critical thinking, decision-making, and personalized education across disciplines. In medical education, for instance, AI-driven tools are used to simulate real-life clinical scenarios, providing students with hands-on experience in a controlled, virtual environment (Boscardin et al., 2024). Similarly, in psychology and education studies, AI models are being deployed to analyze student behavior, engagement, and cognitive development, thereby offering educators deeper insights into the learning process.

This interdisciplinary application of AI in STEM education also suggests a growing collaboration between technical experts and education specialists. As AI technologies become more sophisticated, educators are increasingly partnering with computer scientists and engineers to design AI-driven learning environments that are tailored to the specific needs of STEM students. This collaboration is essential for ensuring that AI tools are both pedagogically sound and technologically advanced.

Annual Scientific Productions and Document Types

As depicted in Figure 2a**,** the annual scientific production on generative AI in STEM education has seen a dramatic increase, particularly since 2022. Publications jumped from 15 in 2022 to 395 in 2023, and then to 853 in 2024. This exponential growth is aligned with the release of advanced AI tools such as ChatGPT, which have enabled more widespread and impactful applications of AI in educational settings. Additionally, Figure 2b shows the distribution of document types. Journal articles make up 55% of the total publications, reflecting the rigorous peer-reviewed nature of the research in this area. Conference papers (23%) suggest that a significant amount of research is presented in academic forums, which are vital for the rapid dissemination of new findings. Other document types, such as book chapters and reviews (7% each), indicate that the field is maturing, with more comprehensive treatments of AI's educational applications being developed. The remaining 8% comprises editorials, short surveys, and conference reviews, further underscoring the diversity of research outputs in this domain.

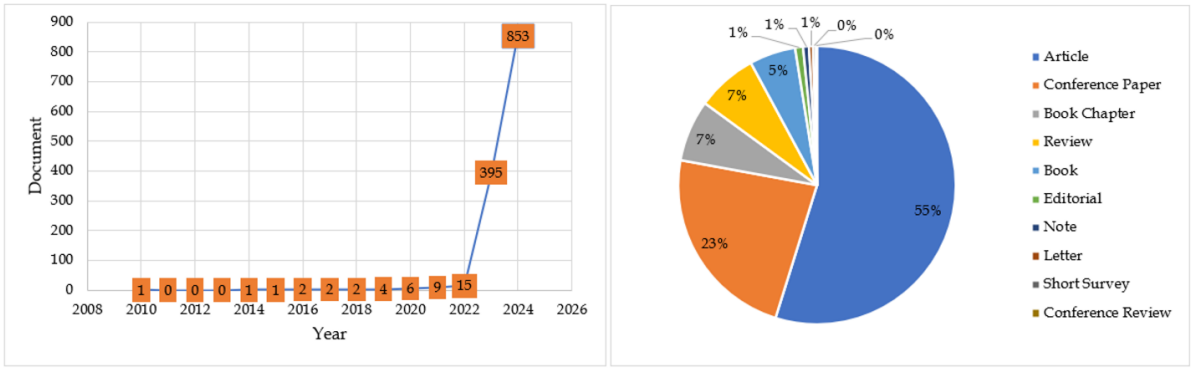

Figure 2. (a) Generative AI Publication Trend; (b) Document types published regarding to Generative AI

The prominence of journal articles underscores the ongoing scholarly effort to produce peer-reviewed, rigorous studies that investigate the implementation and effectiveness of AI in education. Conference papers, on the other hand, reflect the importance of disseminating cutting-edge AI research at academic and professional forums, allowing for the rapid exchange of ideas and developments in the field.

The dominance of journal articles and conference papers suggests that research on AI in education is still in a developmental phase, with scholars actively exploring new avenues for AI application and assessing its impact on STEM learning outcomes. The increasing number of review articles highlights the growing need to synthesize findings from diverse studies, reflecting the maturing state of the research field. These reviews often provide comprehensive overviews of the benefits and challenges of AI in education, such as its ability to enhance problem-solving skills while raising concerns about academic integrity and overreliance on AI-generated content.

Thematic Clusters and Emerging Keywords

Keyword co-occurrence analysis was conducted to better understand the thematic focus areas within the field. Table 2 lists the most influential keywords, ranked by the number of documents they are associated with and their total link strength, which indicates their interconnectedness within the research network.

"Artificial intelligence" appears in 367 documents with a total link strength of 2,086, making it the most central keyword. "ChatGPT" follows closely, appearing in 346 documents with a link strength of 1,912, demonstrating the significant academic focus on this specific AI tool.

Table 2. Keywords with the strongest links

Rank	Cluster	Keywords	Documents	Total Link Strength
1	3	Artificial intelligence	367	2086
2	3	Chatgpt	346	1912
3	3	Students	239	1855
4	1	Education computing	135	1203
5	1	Language model	123	1044
6	1	Large language model	99	915
7	2	Human	87	746
8	2	Education	109	707
9	5	Engineering education	89	682
10	5	Generative ai	106	647

The prominence of "ChatGPT" and "large language models" points to the growing academic interest in these technologies' role in transforming educational practices. These tools have revolutionized how educators approach teaching by providing instant feedback, generating personalized content, and automating administrative tasks. As a result, teachers can focus more on interactive and critical aspects of education, such as fostering creativity and problem-solving skills (Singh et al., 2024).

Beyond the technical applications of AI, keywords like "students," "critical thinking," and "learning outcomes" suggest that researchers are also exploring how AI enhances cognitive skills and learning efficacy. This research direction underscores the central question in AI's educational integration: Can AI tools meaningfully improve learning outcomes in STEM disciplines? Preliminary findings suggest that AI can indeed support self-regulated learning by providing adaptive learning pathways that align with each student's unique pace and understanding level (Nguyen Thanh et al., 2023). However, further empirical studies are necessary to establish AI's long-term effectiveness in diverse educational settings.

Figure 3 visualizes the keyword co-occurrence network, illustrating the relationships between various key terms. The blue cluster, centered around "artificial intelligence," also includes concepts such as "students," "critical thinking," and "learning," reflecting the widespread application of AI in educational settings. This cluster emphasizes the role of AI in enhancing learning outcomes by fostering critical thinking and integrating AI into higher education curricula.

The red cluster, dominated by "large language model," highlights the technical aspects of AI research, focusing on the development and application of advanced AI models. Terms like "machine learning" and "language processing" indicate that this cluster is more concerned with the computational underpinnings of AI. These tools are particularly relevant for STEM education, where AI is increasingly being used to facilitate interactive and problem-based learning.

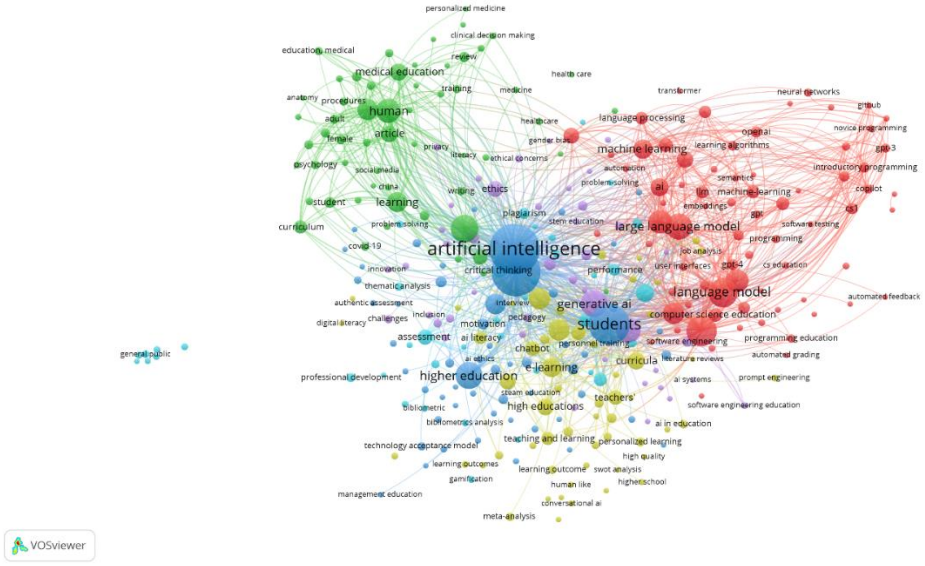

Figure 3. Keywords co-occurrence network

The green cluster focuses on the ethical and human-centered applications of AI, with keywords like "human," "ethics," and "medical education" suggesting an emphasis on how AI can support human decision-making and educational equity. AI's integration into medical education, for instance, provides students with virtual simulations of clinical scenarios, enhancing practical learning without the need for physical resources (Boscardin et al., 2024).

Emerging Keywords and Citation Bursts

Table 3 presents the top 10 keywords that have experienced significant citation bursts, indicating rising academic interest. The term "codes (symbols)" shows the strongest burst (4.03), beginning in 2022, likely due to advancements in AI applications for coding and symbol recognition. Other notable terms include "professional development" (burst strength of 3.26) and "academic libraries" (2.69), suggesting a growing focus on how AI tools are being incorporated into professional and academic contexts.

Table 4. Top 10 Keywords with the Strongest Citation Bursts

Keywords	Year	Strength	Begin	End	2010 - 2024
codes (symbols)	2022	4.03	**2022**	2024	
professional development	2017	3.26	**2017**	2024	
academic libraries	2019	2.69	**2019**	2024	
copilot	2022	2.52	**2022**	2024	
gpt 3	2022	2.5	**2022**	2024	
novice programming	2022	2.48	**2022**	2024	
github	2022	2.13	**2022**	2024	
codex	2022	2.13	**2022**	2024	
information literacy	2020	1.96	**2020**	2024	
natural language processing systems	2010	1.95	**2010**	2024	

The emergence of "GPT-3" and "codex" in 2022, both with strong citation bursts (2.5 and 2.13, respectively), highlights the increasing relevance of these large language models in educational research. These tools are revolutionizing how students and

educators interact with content, providing real-time, AI-generated insights that personalize learning experiences.

Most Influential Publications

Table 4 lists the most influential publications in the field, ranked by total citations and citation rates per year. The top-ranked article, "What Is the Impact of ChatGPT on Education? A Rapid Review of the Literature" by Lo (2023), has garnered 392 citations, reflecting its central role in shaping discussions around AI's transformative potential in education. Other influential works, such as Aggarwal's "Neural Networks and Deep Learning: A Textbook" and Cooper's "Examining Science Education in ChatGPT," further highlight the pivotal role of large language models in reshaping STEM education.

Table 4. Most influential publication

Rank	Title	Year	TC	TC/Year	Normalized TC
1	What Is the Impact of ChatGPT on Education? A Rapid Review of the Literature (Lo, 2023)	2023	392	195.00	30.49
2	Neural Networks and Deep Learning: A Textbook (Aggarwal, 2023)	2023	358	178.00	27.83
3	Examining Science Education in ChatGPT: An Exploratory Study of Generative Artificial Intelligence (Cooper, 2023)	2023	270	134.50	21.03
4	AI for next generation computing: Emerging trends and future directions (Gill et al., 2022)	2022	268	89.00	5.01
5	War of the chatbots: Bard, Bing Chat, ChatGPT, Ernie and beyond. The new AI gold rush and its impact on higher education (Rudolph et al., 2023)	2023	235	116.50	18.21
6	ChatGPT for Education and Research: Opportunities, Threats, and Strategies (Rahman & Watanobe, 2023)	2023	197	98.50	15.40
7	The robots are coming: Exploring the implications of OpenAI codex on introductory programming (Finnie-Ansley et al., 2022)	2022	186	12.27	1.00
8	Data-intensive text processing with MapReduce (Lin & Dyer, 2010)	2010	184	61.00	3.43
9	Automatic Generation of Programming Exercises and Code Explanations Using Large Language Models (Sarsa et al., 2022)	2022	171	55.33	3.11
10	Revolutionizing education with AI: Exploring the transformative potential of ChatGPT (Adiguzel et al., 2023)	2023	155	77.00	12.04
11	Shaping the Future of Education: Exploring the Potential and Consequences of AI and ChatGPT in Educational Settings (Grassini, 2023)	2023	153	74.50	11.65
12	Generative AI and ChatGPT: Applications, challenges, and AI-human collaboration (Fui-Hoon Nah et al., 2023)	2023	150	71.50	11.18
13	The rise of ChatGPT: Exploring its potential in medical education (Lee, 2024)	2024	139	138.00	83.25
14	To use or not to use ChatGPT in higher education? A study of students' acceptance and use of technology (Strzelecki, 2023)	2023	138	68.50	10.71

Rank	Title	Year	TC	TC/Year	Normalized TC
15	Unlocking the opportunities through ChatGPT Tool towards ameliorating the education system (Javaid et al., 2023)	2023	105	52.50	8.21
16	Programming Is Hard - or at Least It Used to Be: Educational Opportunities and Challenges of AI Code Generation (Becker et al., 2023)	2023	101	49.50	7.74
17	Transformative effects of ChatGPT on modern education: Emerging Era of AI Chatbots (Gill et al., 2024)	2024	100	97.00	58.52
18	What ChatGPT means for universities: Perceptions of scholars and students (Firat, 2023)	2023	98	47.50	7.43
19	Large Language Models in Medical Education: Opportunities, Challenges, and Future Directions (Abd-alrazaq et al., 2023)	2023	78	38.50	6.02
20	Collaborating with ChatGPT in argumentative writing classrooms (Su et al., 2023)	2023	78	38.00	5.94

Thematic Mapping and Future Research Directions

The thematic map of the research landscape (Figure 4a) reveals four quadrants that categorize themes based on their centrality and density within the research ecosystem. Themes such as "artificial intelligence" and "ChatGPT" occupy the Basic Themes quadrant, indicating that while they are central to the discourse, they are still in the developmental phase. These themes are foundational to the ongoing research, as AI tools like ChatGPT continue to be refined for educational applications (Capinding, 2024).

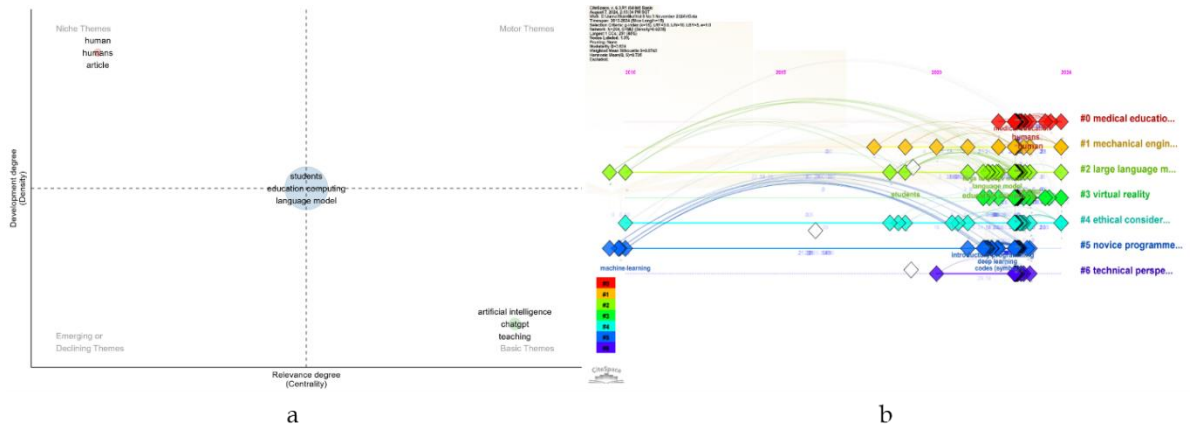

Figure 5. (a) Keywords thematic map; and (b) Keywords of the time zone visualization map

In contrast, themes like "ethics" and "human" are situated in the Niche Themes quadrant, suggesting that they are well-developed but less connected to the broader AI discourse. This points to a need for more integration between ethical considerations and the technical development of AI tools, particularly as AI becomes more embedded in educational systems. The lack of motor themes (highly developed and central themes) indicates that the field is still evolving, with no single research area dominating the landscape. The time zone visualization in Figure 4b illustrates the evolution of research themes over time, with recent years (2022–2024) witnessing a surge in interest in topics such as "medical education" and "ethical considerations."

These emerging themes reflect the growing complexity of AI applications, where technical advancements must be balanced with ethical considerations to ensure equitable and responsible use of AI technologies in education.

The global research trends in generative AI for STEM education indicate rapid growth in the field, with the volume of publications increasing exponentially, particularly since 2022. While the academic engagement with these topics is substantial, as reflected in an average of 5.96 citations per document (Table 1), a deeper analysis reveals that much of this research is concentrated on the technical development of AI. Studies in computer science and engineering tend to emphasize algorithmic innovations and machine learning applications, with less focus on how these technologies are practically implemented in educational settings (Xu & Ouyang, 2022). This suggests that while generative AI offers vast potential, its transformative role in everyday teaching and learning, particularly within the classroom, remains underexplored.

The prevalence of AI research in fields such as education computing and engineering education (Table 2) highlights the growing recognition of AI literacy as an essential skill in technical disciplines. However, a key gap in the current research is the lack of focus on how AI can be applied to directly enhance learning outcomes, particularly in underserved populations. AI tools have demonstrated the ability to personalize learning, providing students with the flexibility to engage with STEM concepts at their own pace (Capinding, 2024). Yet, without equitable access to these technologies, disparities in educational outcomes could widen, raising concerns about inclusivity and fairness in AI-driven educational reforms. Despite these challenges, the transformative potential of AI in STEM education remains significant. AI tools, such as ChatGPT and large language models, have already begun to revolutionize how students and educators interact with content by offering personalized feedback and adaptive learning environments. These tools can address long-standing challenges in STEM education, such as student engagement, critical thinking, and the ability to provide individualized support in large classrooms. However, the success of AI in realizing these benefits depends on a more balanced integration of AI technologies into real-world educational contexts, ensuring that the technology is accessible to a broad spectrum of learners.

Research Question 2: The Impact of Generative AI on STEM Learning Outcomes

The integration of generative AI in STEM education has had a significant dual impact, offering considerable advantages for both teaching and learning while introducing challenges that must be addressed to ensure its responsible use. Generative AI tools such as ChatGPT, large language models (LLMs), and machine learning applications are being increasingly adopted in educational settings to enhance learning outcomes, particularly by providing personalized feedback, fostering student engagement, and facilitating critical thinking.

Enhancing Learning Outcomes with AI

Generative AI has transformed STEM learning by enabling students to engage more interactively with complex content. Personalized learning environments, supported by AI-driven tools, allow educators to tailor instructional methods to meet the specific needs of individual students. By offering adaptive assessments and feedback mechanisms, AI empowers students to engage deeply with material at their

own pace, which is particularly crucial in STEM subjects, where understanding foundational concepts is essential for mastering more advanced topics (Nguyen Thanh et al., 2023). These technologies are designed to adapt to a student's learning curve, providing dynamic support that enhances problem-solving abilities and critical thinking.

For example, AI-driven tutoring systems can automatically generate tailored exercises and provide real-time feedback, creating a more responsive and interactive learning environment. This personalized support is especially beneficial for students who may struggle with conventional learning methods, offering a customized approach that promotes deeper understanding and retention of STEM concepts (Capinding, 2024). AI tools can also simulate practical STEM tasks, enabling students to experiment and learn in virtual environments that closely mimic real-world conditions.

Furthermore, AI enhances engagement by integrating gamification techniques into the learning process. Games and simulations designed with AI algorithms can motivate students to tackle challenging problems through interactive and rewarding experiences. Such approaches not only improve student motivation but also promote active learning, which is key to developing critical thinking skills in STEM disciplines (Alenezi, 2023).

In addition to enhancing learning outcomes, generative AI has the potential to significantly reduce educational inequalities by providing access to high-quality learning experiences for diverse student populations. AI tools can be designed to cater to students with different learning needs, offering personalized content that addresses various learning disabilities or language barriers (Aballa Nkechi et al., 2024). By automating routine tasks such as grading, AI also allows educators to dedicate more time to personalized instruction and mentorship, further enriching the learning experience.

Challenges to Academic Integrity and Cognitive Skills

While the benefits of AI in STEM education are clear, its integration also presents challenges, particularly regarding academic integrity and the potential erosion of essential cognitive skills. One of the most prominent concerns is the risk of overreliance on AI tools, which can undermine the development of independent critical thinking and problem-solving skills (Chan, 2023). Students may become too dependent on AI-generated solutions, diminishing their ability to engage deeply with the material and independently navigate complex problems. This is particularly relevant in STEM education, where the development of strong analytical and cognitive skills is essential for success.

Generative AI tools, such as automated writing assistants and problem-solving applications, have raised concerns about plagiarism and academic misconduct. These tools can generate human-like content with ease, making it difficult for educators to distinguish between student-generated work and AI-generated solutions (Srinivasan et al., 2024). The potential for misuse of AI technologies thus poses a significant challenge to maintaining academic standards in STEM education.

The literature also raises concerns about the ethical implications of AI in education. AI systems, which rely on large datasets for training, may perpetuate existing biases in educational content, leading to unequal learning outcomes for

students from different backgrounds (Qadhi et al., 2024). Ensuring that AI tools are used responsibly and ethically is crucial to preventing the reinforcement of existing educational inequalities.

Additionally, there is concern that the use of AI might reduce the need for students to engage in the cognitive processes that are fundamental to STEM learning, such as experimentation, hypothesis testing, and critical reflection. If students become accustomed to relying on AI-generated solutions, they may not develop the deep understanding required to excel in STEM fields, where the ability to independently analyze and solve complex problems is critical (Đan et al., 2024).

Ethical Considerations and Academic Integrity

Ethical considerations surrounding the use of AI in education are central to ongoing discussions about its role in shaping the future of STEM learning. The widespread use of generative AI tools in education presents new challenges for academic integrity, as students have increased access to automated systems capable of generating essays, solving problems, and providing answers with minimal input. While these tools offer valuable learning support, they also raise questions about originality, authorship, and the role of students in the learning process (Srinivasan et al., 2024).

To address these ethical challenges, it is essential to develop clear policies and guidelines that define the acceptable use of AI tools in educational settings. Institutions must create frameworks that encourage the responsible use of AI, ensuring that it enhances rather than undermines the learning process. Educators should also be equipped with tools to detect AI-generated content and assess student work more effectively, thus safeguarding academic integrity (Qadhi et al., 2024).

Moreover, the ethical design of AI tools is paramount to preventing biases in the educational content delivered to students. Ensuring that AI systems are trained on diverse datasets is essential to avoid perpetuating existing inequalities and ensuring that all students benefit equally from AI-enhanced education. Educators, policymakers, and AI developers must work collaboratively to create tools that are both pedagogically sound and ethically responsible, addressing the diverse needs of students in various educational contexts (Nixon et al., 2024).

The Dual Impact of Generative AI in STEM Learning

The dual impact of generative AI in STEM education reflects both its promise and its potential pitfalls. On one hand, AI offers transformative benefits by personalizing learning experiences, providing real-time feedback, and enabling more efficient and focused teaching approaches (Konyrova, 2024). These advantages are particularly valuable in STEM disciplines, where understanding complex concepts and engaging in problem-solving activities are critical to student success. AI-driven interventions have been shown to improve student engagement, motivation, and self-regulated learning, making AI a powerful tool for enhancing STEM education (Nurjanah et al., 2024).

On the other hand, the potential for AI to undermine the development of essential cognitive skills such as critical thinking, writing, and independent analysis cannot be overlooked. Overreliance on AI tools may lead students to disengage from the learning process, relying instead on automated systems to provide solutions. This issue is compounded by ethical concerns about academic integrity, as AI-generated

content becomes more difficult to distinguish from student work (Srinivasan et al., 2024).

Balancing the benefits and risks of AI in STEM education requires a nuanced approach that leverages the strengths of AI while addressing its limitations. Educational institutions must take a proactive role in developing policies that promote the ethical use of AI, ensuring that students remain active participants in the learning process. By fostering a balanced integration of AI, educators can harness its potential to enhance learning outcomes while safeguarding academic integrity.

Generative AI has undoubtedly had a profound impact on STEM learning outcomes, offering both opportunities and challenges. On the positive side, AI tools have revolutionized STEM education by providing personalized learning experiences, fostering student engagement, and enhancing critical thinking. These tools offer students more control over their learning, enabling them to engage with content at their own pace and according to their individual needs. Additionally, AI's ability to automate routine tasks has allowed educators to focus on more meaningful and interactive instruction, further enriching the educational experience.

However, the integration of AI into STEM education also presents significant challenges, particularly regarding academic integrity and the potential erosion of essential cognitive skills. Overreliance on AI tools can undermine students' ability to think critically and independently, raising concerns about the long-term effects of AI on the learning process. Moreover, ethical considerations, such as the potential for bias in AI systems and the risks of academic misconduct, must be addressed to ensure that AI is used responsibly in educational settings.

Research Question 3: How Generative AI in STEM Education Challenges Academic Integrity

The integration of generative AI into STEM education introduces significant challenges related to academic integrity, particularly in preventing academic misconduct. Generative AI tools, such as ChatGPT and other large language models (LLMs), can produce human-like content with little input, raising concerns about plagiarism, authorship, and the overall authenticity of academic work. As these tools become more widely accessible, it is increasingly difficult to distinguish between AI-generated content and student-generated work, creating new challenges for educators, institutions, and policymakers.

The Erosion of Traditional Academic Standards

Generative AI's ability to produce high-quality, human-like text introduces complexities in maintaining academic integrity. Students can use AI to generate essays, solve problems, and even create code, leading to potential cases of plagiarism, ghostwriting, or unauthorized collaboration (Turner et al., 2022). This ease-of-use challenges traditional definitions of authorship and originality, making it difficult for educators to determine whether a student's work is truly their own. The risk of academic dishonesty grows as more students gain access to AI tools, which can effortlessly generate content that mimics human reasoning and style.

The literature highlights these concerns, particularly in STEM fields, where original problem-solving and critical thinking are core components of the educational process (Nam & Bai, 2023). If students rely heavily on AI-generated content, they may bypass critical learning stages, diminishing their ability to develop independent

cognitive skills. This reliance on AI could lead to a situation where students complete assignments without fully engaging with the material, undermining the educational purpose of the task.

AI-Facilitated Academic Misconduct

Generative AI has made it easier for students to engage in various forms of academic misconduct, including plagiarism and ghostwriting. AI tools can quickly produce essays, research papers, or even technical problem solutions, often indistinguishable from human-authored work (Weber-Wulff et al., 2023). This raises concerns about the credibility of student submissions and the ability of educational institutions to uphold academic integrity standards.

The threat posed by AI to academic integrity is particularly acute in STEM education, where assessments often involve complex problem-solving and technical writing. Students might misuse AI tools to complete assignments without engaging in the intellectual processes required to truly master the material (Srinivasan et al., 2024). This not only undermines the learning process but also devalues the qualifications and certifications granted by educational institutions.

Institutional Responses to AI-Driven Misconduct

In response to these challenges, educational institutions must adopt new strategies to safeguard academic integrity. One of the most effective approaches is the development of clear, specific policies that address the use of AI in academic work (Perkins & Roe, 2024). Current academic integrity policies often lack the specificity needed to manage the complexities introduced by AI, leaving both educators and students unclear about the acceptable use of these technologies. Institutions need to revise and update their academic integrity guidelines, clearly defining the roles that AI tools can play in the learning process and ensuring that students understand the ethical implications of their use.

Another essential strategy is designing assessment tasks that are resistant to AI-facilitated academic misconduct. Assignments that require deep engagement, original thought, and critical thinking are less susceptible to AI-generated solutions. For example, educators can design assessments that require students to explain their reasoning process or reflect on their learning experiences, making it harder for students to rely solely on AI tools (Sabrina et al., 2022). Additionally, oral examinations and real-time problem-solving exercises can help verify a student's understanding of the material, providing a more accurate measure of their knowledge and skills.

The Role of AI Literacy and Training

Increasing AI literacy among both students and educators is critical for addressing the challenges posed by generative AI. AI literacy programs can help students understand the ethical implications of using AI tools in their academic work, fostering a culture of responsibility and integrity. By educating students on the limitations and appropriate uses of AI, institutions can encourage responsible behavior and reduce instances of academic misconduct (Farrelly & Baker, 2023).

For educators, AI literacy is equally important. Teachers must be equipped with the knowledge and tools to identify AI-generated content and assess student work more effectively. This includes training in the use of AI detection tools, as well as strategies for designing assessments that promote authentic learning (Kumar &

Mindzak, 2024). By integrating AI literacy into both student and teacher training, educational institutions can better navigate the ethical challenges posed by AI and ensure that its use supports, rather than undermines, academic integrity.

Ethical Considerations and the Need for Regulatory Frameworks

As generative AI becomes more integral to education, it is vital to establish robust regulatory frameworks that govern its use. These frameworks should ensure that AI tools are used ethically and responsibly, both by students and educators (Karadağ, 2023). Transparency is a key component of these efforts; students and scholars should be encouraged to declare when they have used AI tools in their work, allowing for greater openness and accountability in academic writing (A. Tang et al., 2024).

Institutions must also invest in AI detection tools that can help identify AI-generated content and verify the authenticity of student submissions. These tools are essential for maintaining academic integrity as AI technologies become more sophisticated and harder to detect. By implementing a combination of detection tools, clear usage policies, and ethical training programs, educational institutions can uphold academic standards even as AI continues to evolve (Weber-Wulff et al., 2023).

The Importance of Ongoing Policy Review and Adaptation

Given the rapid pace of AI development, it is essential for institutions to regularly review and update their academic integrity policies to keep pace with technological advancements (Engstrom & Scott, 2020). Policies that were effective a few years ago may no longer be sufficient to address the complexities of generative AI in today's academic environment. Continuous evaluation of AI integration practices, along with regular updates to institutional policies, will help educational institutions stay aligned with evolving academic integrity challenges.

Educational institutions should also foster a culture of integrity that encourages students to value original thought and independent work over quick, AI-generated solutions. Awareness campaigns and ongoing education are vital for promoting a culture where academic honesty is prioritized, and the ethical use of AI is understood and respected (Eshet et al., 2024). By cultivating this culture, institutions can mitigate the risks associated with AI and preserve the integrity of academic work.

The integration of generative AI into STEM education presents significant challenges to academic integrity, particularly in terms of preventing plagiarism, ghostwriting, and other forms of academic misconduct. As AI tools become more accessible and capable of generating high-quality, human-like content, the lines between original student work and AI-generated material become increasingly blurred. This complicates the enforcement of academic standards and raises concerns about the future of academic integrity in education.

Educational institutions must develop clear policies that define the acceptable use of AI in academic work and design assessments that promote deep engagement and critical thinking to address these challenges. Additionally, fostering AI literacy among both students and educators is essential for ensuring that AI is used responsibly. Ethical considerations, transparency, and the development of regulatory frameworks must also be prioritized to safeguard the credibility of academic work in the age of AI.

Research Question 4: Insights from Case Studies and Comparative Studies on Generative AI in STEM Education

The adoption of generative AI in STEM education has yielded a range of outcomes, influenced by the distinct educational, cultural, and technological contexts in which it is implemented. Comparative and case studies in the literature provide key insights into the opportunities and challenges associated with integrating AI technologies into STEM curricula, offering valuable lessons for institutions seeking to navigate the complexities of AI in education.

The Role of AI in Personalized Learning and Engagement

One of the most significant benefits of generative AI in STEM education is its ability to personalize learning experiences. Across diverse educational contexts, AI-driven tools have been shown to enhance student engagement by providing individualized feedback, customized assessments, and adaptive learning pathways. For instance, AI-based systems like intelligent tutoring and automated grading platforms allow educators to address the specific learning needs of each student, offering real-time support that helps students progress at their own pace (Baek & Wilson, 2024).

Case studies from Ukraine highlight AI's critical role in supporting distance learning during periods of conflict. In this context, generative AI tools provided personalized content and assessments that helped maintain educational continuity despite the challenges posed by external disruptions (Bakhmat et al., 2023). This demonstrates AI's potential not only in fostering engagement but also in ensuring that education remains accessible in challenging environments. The ability to offer tailored learning experiences, regardless of the circumstances, positions AI as a valuable tool for both enhancing and safeguarding STEM education in diverse settings.

Similarly, the implementation of AI-driven curricula in Pakistan has revolutionized STEM education by promoting innovative teaching practices that encourage deeper student engagement (Rathore et al., 2023). These curricula leverage AI tools to foster critical thinking, creativity, and problem-solving skills, allowing students to explore STEM concepts more interactively. The positive outcomes in these case studies suggest that generative AI has the potential to significantly improve educational outcomes when integrated effectively into teaching and learning frameworks.

Challenges in Academic Integrity and AI Literacy

While the benefits of AI in enhancing personalized learning and engagement are evident, case studies also reveal significant challenges, particularly regarding academic integrity and the need for AI literacy. The ease with which AI tools can generate human-like content has raised concerns about plagiarism, unauthorized collaboration, and the erosion of students' cognitive skills (Sarwar et al., 2024). This is especially problematic in settings where AI literacy is low, and students and educators alike may not fully understand the ethical complexities associated with AI-generated content.

For example, case studies from Nigeria and Pakistan have highlighted concerns about academic misconduct facilitated by AI tools. In these settings, the availability of generative AI technologies without corresponding ethical guidelines or AI literacy programs has led to incidents of plagiarism and the submission of AI-generated work

as student-authored content (Ibrahim et al., 2024; Rathore et al., 2023). These challenges underscore the importance of developing comprehensive AI literacy programs that educate both students and educators on the responsible use of AI in academic work.

Additionally, the lack of clear policies on AI usage has further complicated efforts to maintain academic integrity. Comparative studies emphasize the need for institutions to establish robust policies that define acceptable AI use in educational settings, ensuring that AI serves as a tool for learning rather than a substitute for original thought (Kadaruddin, 2023). By fostering ethical AI practices and providing clear guidelines on its integration into academic work, institutions can mitigate the risks of AI-facilitated academic misconduct.

Ethical Considerations and the Importance of Oversight

Ethical concerns surrounding the use of generative AI in STEM education are a recurring theme in case studies, particularly regarding the reliability of AI-generated content and the potential for bias. In educational contexts where AI is being used to generate content for assessments or digital storytelling, the accuracy and fairness of AI outputs are critical considerations. Case studies from countries like Egypt have highlighted the need for rigorous validation processes to ensure that AI-generated content is both reliable and pedagogically sound (Temsah et al., 2024).

To address these challenges, institutions must develop oversight mechanisms that ensure the ethical use of AI tools in education. This includes the implementation of AI detection tools, as well as the development of training programs that equip educators with the skills to assess AI-generated content effectively (Nam & Bai, 2023). The importance of transparency is also emphasized, with institutions being encouraged to require students to declare the use of AI in their academic submissions to maintain integrity and accountability.

Furthermore, comparative analyses show that collaboration between educators, researchers, and policymakers is essential for the successful and ethical integration of AI in education (Ibrahim et al., 2024). In this context, international partnerships can facilitate the sharing of best practices, helping institutions worldwide to develop frameworks that address the ethical implications of AI in education while leveraging its potential to enhance learning outcomes.

Addressing Educational Inequities through AI

Generative AI also holds the potential to address educational inequities by offering personalized learning opportunities to diverse student populations. Studies from underrepresented and resource-limited regions demonstrate how AI can help close achievement gaps by providing high-quality, adaptive learning resources to students who might otherwise have limited access to such technologies. For example, AI-driven educational platforms in countries like Pakistan have improved access to STEM education by offering students in remote or underserved areas personalized content that addresses their specific learning needs (Rathore et al., 2023).

However, the success of these initiatives depends on the presence of robust infrastructure and support systems that ensure equitable access to AI tools. Comparative studies highlight the importance of aligning AI implementation with local needs and challenges, as the effectiveness of AI-driven solutions varies depending on the educational context. In settings where technological infrastructure

is weak or where students lack access to devices and reliable internet, AI's potential to improve educational outcomes may be limited (Familoni & Onyebuchi, 2024).

To maximize the benefits of AI in reducing educational inequities, institutions must invest in the necessary infrastructure, provide adequate training for educators, and ensure that AI tools are accessible to all students, regardless of their geographic or socioeconomic background. This requires a coordinated effort between governments, educational institutions, and technology providers to create inclusive, AI-enhanced learning environments that serve the needs of diverse populations.

The insights gained from case studies and comparative analyses on generative AI adoption in STEM education reveal both the transformative potential of AI and the significant challenges it presents. AI has been shown to enhance personalized learning, improve student engagement, and provide innovative teaching methods in various educational contexts. However, the integration of AI also raises critical concerns about academic integrity, the ethical use of AI-generated content, and the need for comprehensive AI literacy programs.

To successfully integrate AI into STEM education, institutions must develop clear policies and ethical guidelines, implement robust oversight mechanisms, and foster collaboration among educators, researchers, and policymakers. Furthermore, AI must be aligned with local needs and challenges, with a focus on ensuring that all students, regardless of their background, have access to the benefits of AI-enhanced learning. By addressing these challenges and adopting a balanced approach to AI integration, educational institutions can harness AI's transformative potential while safeguarding the integrity of the educational process.

Limitations of the Study

This study provides valuable insights into the dual impact of generative AI on STEM learning and academic integrity, but several limitations should be acknowledged. The selection of literature for the bibliometric analysis may have introduced biases due to the reliance on specific databases, search terms, and citation metrics, potentially overlooking relevant studies or recent research. The scope of the case studies reviewed is limited by the availability of documented examples, primarily reflecting higher education contexts, which may not fully represent other educational levels or regions.

Additionally, the generalizability of the findings is challenged by the context-dependent nature of AI's impact, which is influenced by factors such as technological infrastructure, institutional policies, and regional differences. The assessment of ethical implications is constrained by the rapidly evolving nature of AI technologies, which may lead to unforeseen challenges not fully anticipated in this study. Finally, the temporal scope of the bibliometric analysis (2010-2024) may not capture the latest developments or long-term trends in the field, potentially affecting the study's conclusions.

Ongoing research is needed to address these limitations and ensure the effective integration of AI in diverse educational contexts. Future studies should aim to expand the breadth of the analysis, include newer developments in AI, and explore its long-term effects on both learning outcomes and academic integrity in a wider range of educational settings.

CONCLUSION

This study provides a comprehensive analysis of the dual impact of generative AI on STEM education through both bibliometric analysis and literature review, highlighting its significant benefits alongside notable challenges. The findings demonstrate that generative AI technologies, such as ChatGPT, have greatly enhanced personalized learning by providing tailored feedback, creating interactive learning environments, and offering adaptive assessments. These tools have proven particularly effective in fostering self-regulated learning, improving critical thinking, and aligning educational outcomes with professional demands. They introduce innovative teaching methodologies that enhance student engagement and improve learning outcomes in STEM disciplines.

However, the study also underscores the challenges associated with the integration of AI, particularly in maintaining academic integrity. The ease with which AI can generate human-like text raises concerns regarding the authenticity of student work, potentially leading to overreliance on AI tools and undermining essential cognitive skills such as independent thinking and problem-solving. Additionally, the ethical dilemmas surrounding AI use, particularly related to plagiarism and the erosion of academic standards, highlight the need for more robust ethical frameworks and institutional policies.

This study makes critical contributions to understanding how generative AI is reshaping STEM education, particularly in addressing the demand for innovative and adaptive learning experiences. It highlights the importance of balancing AI's transformative potential with the need to preserve the integrity of the learning process. Furthermore, the study addresses an essential gap in the literature by focusing on the ethical implications of AI in education, advocating for the responsible and thoughtful integration of AI technologies. By recommending robust policies and ethical frameworks, the study provides practical guidance for educators, policymakers, and researchers to ensure that AI adoption enhances, rather than compromises, the quality and integrity of education.

RECOMMENDATION

The findings of this study emphasize the transformative potential of generative AI in STEM education, but they also highlight the need for a cautious and balanced approach to its integration. To fully harness the advantages of AI while addressing its associated risks, educational institutions must ensure that AI complements, rather than replaces, traditional educational practices. While AI tools can significantly enhance personalized learning and improve student engagement, their use should be carefully managed to preserve critical cognitive skills, such as independent thinking, problem-solving, and critical reflection. Promoting AI literacy is crucial for both educators and students. Institutions should develop programs that provide clear guidance on the responsible use of AI, ensuring that users understand both the capabilities and limitations of these technologies. Such programs will help prevent overreliance on AI tools and encourage their ethical use, fostering a deeper understanding of how these technologies can enhance learning outcomes without undermining the academic process.

In addition, educational institutions need to establish clear and robust policies on academic integrity. These policies should define acceptable uses of AI in academic

work, addressing issues such as plagiarism and the authenticity of student submissions. By providing explicit guidelines on how AI tools can be ethically incorporated into learning and assessments, institutions can help safeguard academic standards and ensure that students are engaging meaningfully with their coursework. Moreover, it is essential to invest in tools and methods designed to combat academic misconduct. As AI technologies become more advanced, so too must the systems in place to detect AI-generated content. Developing reliable detection tools will be key to maintaining the integrity of academic assessments and ensuring that AI enhances, rather than diminishes, educational standards. Finally, the ethical implications of AI in education must be continually monitored and evaluated. Institutions should implement comprehensive ethical frameworks that guide the responsible use of AI technologies, ensuring that their adoption aligns with the core values of academic integrity, equity, and fairness. Through responsible and thoughtful integration, AI has the potential to become a powerful tool in enhancing educational outcomes while upholding the foundational principles of academic excellence and integrity.

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The authors have sufficiently contributed to the study. All authors have read and agreed to the published version of the manuscript.

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