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University of Aveiro, Portugal

REVIEWED BY
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Comenius University, Slovakia
Ozan Filiz,
Sinop University, Türkiye

*CORRESPONDENCE
Christiana Karousiou
✉ karousiou.c@unic.ac.cy
Maria Evagorou
✉ evagorou.m@unic.ac.cy

RECEIVED 03 November 2025
REVISED 10 March 2026
ACCEPTED 10 March 2026
PUBLISHED 08 April 2026

CITATION
Karousiou C and Evagorou M (2026)
Perspectives of teachers on integrating
AI tools in science education.
Front. Educ. 11:1738401.
doi: 10.3389/educ.2026.1738401

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Perspectives of teachers on integrating AI tools in science education

Christiana Karousiou* and Maria Evagorou*

InSSTER: Department of Education, School of Education, University of Nicosia, Nicosia, Cyprus

Introduction: This study shows how science and STEM teachers perceive the use of generative AI tools in their teaching, and the challenges and the concerns they have, before and after an online professional development programme.

Methods: As part of the study, pre-questionnaires, reflective diaries and activity designs from 43 STEM teachers were analysed.

Results: The research highlights teachers' enthusiasm for AI's potential to enhance personalised learning and student engagement. However, it also identifies significant challenges, including ethical and technical issues, data privacy concerns, and the need for further training with an emphasis on the pedagogical use of generative AI tools. The findings highlight the importance of institutional support and continuous professional development to facilitate the effective adoption of AI in education.

Discussion: While AI offers promising opportunities to transform educational practices, a balanced approach addressing both ethical and practical concerns is essential. This study contributes to the ongoing discourse on AI in education, providing valuable insights for future research and practice.

KEYWORDS

AI integration, artificial intelligence (AI), GenAI tools, science education, teacher education, teacher perspectives

1 Introduction

The field of STEM education is being rapidly reshaped by technological advancements, particularly the widespread integration of generative AI (GenAI) technologies such as OpenAI's ChatGPT, Google's Gemini, and Microsoft Copilot (Nguyen, 2025). As these technologies evolve, AI presents an innovative approach that revolutionises the educational landscape by making teaching and learning processes more personalised, adaptable, inclusive, and engaging (Chapagai and Adhikari, 2024; Kotsis, 2024). Its incorporation into STEM education has the potential to transform traditional didactic approaches by optimising pedagogical processes and addressing the constraints of conventional educational models (Nykonenko, 2023).

Research highlights AI's potential to enhance learning process, streamline administrative procedures, and improve resource allocation (Hoelscher et al., 2024). The incorporation of AI tools and resources into teaching allows for tailored instruction that meets individual student needs, promoting inclusivity and maximising learning potential. This personalised approach supports diverse learning styles and fosters critical thinking and problem-solving skills essential for success in the 21st century (Kotsis, 2024). As educators integrate these emerging technologies, they cultivate more engaging and effective learning environments, enhancing student outcomes and preparing learners for a rapidly evolving world (Sadiku et al., 2021).

Teachers play a pivotal role in pioneering educational innovations and shaping new pathways. Their attitudes towards AI significantly influence the effectiveness and acceptance of its integration into educational processes, which is vital for creating enriching learning environments and enhancing student experiences (Li and Noori, 2024; Wang et al., 2021). Therefore, understanding teachers' perceptions and challenges of integrating AI tools into traditional classrooms is crucial for their successful implementation and adoption (Mustofa et al., 2025). Despite the growing interest in AI's potential to enhance educational outcomes, existing research often overlooks teachers' perspectives on AI use, focusing more on student outcomes and technological capabilities, with less emphasis on the challenges and concerns faced by educators (Abou Karroum et al., 2024; Ajuwon et al., 2024). As the role of GenAI continues to grow in educational settings, there is an urgent need to acknowledge the importance of teachers' perceptions. This is especially important in science education and STEM education because of the special nature of the subjects and the interdisciplinarity of the topics.

Researchers in STEM and science education have highlighted the implications of generative AI for teaching practices in STEM education and also for the nature of science (Cheung et al., 2025). Erduran (2023), for example, stated that generative AI is transforming how knowledge is generated, analysed, and validated, and that science and STEM education must reflect on these changes and prepare first teachers and then students to engage critically with AI knowledge production. This paper argues that generative AI tools challenge the traditional view of science as a solely human pursuit, and that students need to understand both the role and the limitations of generative AI in scientific inquiry. A recent study by Cheung et al. (2025) also highlights that generative AI tools such as ChatGPT have already been integrated into science education to support the inquiry-based process (explanation, modelling, data interpretation), but concerns remain about uncritical engagement with scientific reasoning. Therefore, researchers highlight the importance of engaging teachers and students in critically evaluating AI-generated outputs (Avraamidou, 2024). Furthermore, according to Erduran (2023), AI is reshaping the epistemology and methodology of science and STEM itself; therefore, introducing generative AI tools into STEM education can further support inquiry-based learning, modelling, and conceptual understanding. The introduction of generative AI tools in STEM education needs to be based on pedagogical approaches that explicitly address the nature of scientific knowledge and the critical evaluation of AI. Despite the discussion of how the use of AI can interfere with the nature of scientific practices (Erduran and Levrini, 2024), recent systematic reviews in the field of STEM education have highlighted that most of the studies on generative AI and science and STEM education have focused on student outcomes and development of tools and fewer studies on teachers' experiences (Almasri, 2024; Lee et al., 2025). Some other studies such as by Park et al. (2023) have found that science and STEM teachers encounter notable challenges with pedagogical integration and ethical issues, which remain largely unexamined.

The current study focuses on addressing the gap in the literature related to the views, challenges, and ideas of STEM

teachers on the use of AI in the classroom. Therefore, this study explores how science and STEM teachers understand, explain, and design AI experiences in science and STEM teaching. The research is guided by three primary questions:

- R.Q.1: How do science and STEM teachers perceive the use of generative AI tools in STEM and science education before and after participating in an online training course?
- R.Q.2: What challenges do science and STEM teachers identify as part of the process of learning and integrating generative AI tools in their practices? How do they address these challenges?
- R.Q.3: What concerns do science and STEM teachers share regarding the use of generative AI tools in their teaching practices?

This study contributes directly to the themes of this Research Topic by providing valuable insights into the practical aspects of AI integration in science education, uncovering the real-world challenges and benefits that educators face. We examine how Cypriot science teachers navigate the complexities of integrating AI tools, highlighting the critical role of professional development in fostering adaptable and innovative teaching practices in a rapidly evolving digital landscape.

Understanding these practical aspects is crucial for developing effective strategies that can support teachers in integrating AI technologies. This study not only addresses the theoretical implications of AI in education but also provides a grounded, empirical perspective on how these tools can be effectively utilised to enhance science education. By capturing the lived experiences and views of teachers, this research can potentially inform the development of targeted professional development programmes, policy initiatives, and classroom best practices. All aforementioned are essential for ensuring that AI is integrated in a way that maximises its benefits, while addressing the valid concerns of educators.

2 Literature review

The 21st century has witnessed a rapid evolution in STEM educational practices, largely driven by technological advancements, including AI. Recent progress and proliferation in machine learning have facilitated the development of increasingly sophisticated digital content generation technologies such as GenAI (Lim et al., 2023). GenAI is defined as a category of artificial intelligence systems that create new content based on input data. These systems utilise advanced machine learning models, particularly deep learning, to generate text, images, code, and other types of content that emulate human creative capabilities (Baidoo and Ansah, 2023; Bucchiarone et al., 2024). Unlike traditional AI that functions based on predefined rules, GenAI employs extensive datasets to discern underlying patterns and subsequently generate new outputs. The ability of these tools to augment both creative and technical processes is driving significant transformations across diverse sectors, notably education and software development (Harrington, 2024).

2.1 AI's potential to innovate STEM pedagogy

The integration of generative AI tools in education has markedly improved educational experience by facilitating complex activities, providing immediate feedback, and reducing the administrative burden on teachers (Gökçearsan et al., 2024; Nguyen, 2025). These tools enhance both educational and administrative processes, enriching learning by analysing cognitive behaviours to support personalised instruction and improving students' thinking skills and reading abilities (Fu et al., 2025). Furthermore, AI optimises enrolment processes and resource management, including the enhancement of online training programmes (Lukianets and Lukianets, 2023; Nguyen, 2025).

Research consistently shows that AI can significantly support educational experience and can support learning and STEM pedagogies by changing how students engage with scientific knowledge, practices, and inquiry processes. Erduran and Levrini (2024) and Lee et al. (2025) reported that generative AI tools support student growth in STEM skills like data analysis, modelling, hypothesis creation, and explanation. In this way, according to the same scholars, students will be able to participate actively in scientific practices. Generative AI tools can function as a cognitive scaffold by providing real-time feedback, generating explanations, and supporting modelling (Almasri, 2024; Kotsis, 2024). In addition, AI technologies can provide personalised learning pathways that can support students in exploring scientific concepts at their own pace (Chapagai and Adhikari, 2024; Park et al., 2023). Consequently, the use of AI tools in the ways reported previously can potentially enable new forms of pedagogical innovation (Erduran and Levrini, 2024; Fu et al., 2025).

Engagement is further enhanced when AI is used in creating interactive and immersive learning environments. AI-powered educational games and simulations can make learning more enjoyable and engaging, which can lead to better retention of information and a deeper understanding of complex concepts (Ajuwon et al., 2024). These tools can also foster critical thinking and problem-solving skills by presenting students with real-world scenarios and challenges (Hwang et al., 2020).

2.2 The pivotal role of teacher perceptions in AI adoption

AI could be a valuable educational resource with the ability to autonomously observe, understand, predict, and act, offering transformative potential for learning environments (Lu et al., 2024), but its successful integration in STEM education depends heavily on educators' attitudes (Kim and Kim, 2022). Teachers who acknowledge AI benefits are more likely to adopt AI technologies (Lu et al., 2024; Yao and Huang, 2024). This mirrors previous studies showing that the success of integrating technology in education largely depends on teachers' beliefs and attitudes towards such tools. Their perceptions are essential in determining the effectiveness of integrating information and communication technology in classrooms. Furthermore, a teacher's readiness to embrace new technologies is a decisive

factor in their effective integration into classroom instruction (Akram et al., 2022; Sung et al., 2024).

Teachers' attitudes and perceptions towards the integration of AI tools in the classroom are multifaceted, reflecting a blend of optimism, scepticism, and practical concerns. The literature reveals a spectrum of views that highlight both the potential benefits and the challenges associated with AI in education. Studies by Abou Karroum et al. (2024) and Alshehri (2023) indicate that teachers recognise AI's potential to enhance learning outcomes and pedagogical practices. These educators appreciate AI's ability to personalise learning, automate administrative tasks, and provide real-time feedback, which can lead to more efficient and effective teaching. Similarly, Akram et al. (2022) found that teachers see AI as a valuable tool for supporting differentiated instruction and engaging students in more interactive and meaningful ways.

Alshorman (2024) found that while science teachers are generally positive about AI, their readiness to adopt it varies based on factors like gender, educational background, and data privacy concerns. Age-related differences also seem to affect AI tool usage, with younger teachers being more supportive and older teachers being more sceptical because of the complexity of learning new technologies and philosophical concerns (Mnguni, 2025).

Choi et al. (2023) noted that perceived usefulness, ease of use, and trust influence teachers' decisions to use AI. Personal curiosity, a desire for student engagement, and a commitment to enhancing educational fulfilment motivate them to proceed with AI integration and digital transformation in general (Karousiou, 2025; Son, 2023). These findings align with those of Nja et al. (2023), showing positive attitudes and behavioural intentions towards AI among science teachers due to ease of use, self-esteem, and expected benefits.

2.3 Key challenges and ethical concerns for STEM educators

This optimism is, however, tempered by several concerns leading to a complex interplay of emotions among teachers regarding AI in STEM education. One of the primary concerns is the ethical implications of AI in education. Akgun and Greenhow (2022) highlighted the ethical challenges that arise in K-12 settings, such as data privacy, algorithmic bias, and the potential for AI to reinforce existing inequalities. These concerns were echoed by Choi et al. (2023), who found that teachers' acceptance of AI tools is significantly influenced by their trust in the technology and their beliefs about its ethical use. In addition, a cross-sectional survey by Daskalaki et al. (2024) revealed educators' optimism about AI's potential but expressed significant concerns about its impact on critical thinking and ethical issues related to potential misuse. Mutanga et al. (2024) highlighted that lecturers in higher education have also mixed feelings about AI, with some embracing the technology and others resisting it because of ethical considerations and the need for adaptation in teaching methods. Last, Farahani and Ghasemi (2024) pointed out that anxiety about AI amplifies existing inequalities in education, particularly if access to technology is not guaranteed for all.

The impact of AI on the teacher–student relationship is a point of contention. While AI can facilitate personalised learning and provide valuable insights into student performance, it can also alter the dynamics of the classroom. This tension between the benefits of AI and the preservation of the human touch in education is a recurring theme in the literature. Teachers like those in the study by [Kim and Kim \(2022\)](#) express concerns about the potential for AI to diminish the human element of teaching, reducing opportunities for meaningful interactions and relationship-building with students. Furthermore, teachers express concerns about AI's impact on pedagogy and its integration into existing curricula ([Mnguni, 2025](#)), as well as potential shifts in power dynamics, which could diminish their authority and influence in the classroom ([Popenici and Kerr, 2017](#)).

2.4 Bridging the gap: the critical need for professional development

Positive attitudes towards AI correlate with teachers' intentions to use AI, influenced by the level of professional development and institutional support that they receive along with resource availability ([Li and Noori, 2024](#); [Ofosu-Ampong, 2024](#)). Teachers' readiness to integrate AI into their teaching practices is closely linked to the availability of adequate training and resources ([Alshorman, 2024](#); [Brandhofer and Tengler, 2024](#)). Conversely, a lack of training can lead to resistance and apprehension, as teachers may feel unprepared to navigate the complexities of AI technology. Similarly, studies by [Ajuwon et al. \(2024\)](#) and [Fu et al. \(2025\)](#) reveal that teachers often face logistical and infrastructural barriers such as inadequate technological infrastructure, limited access to AI tools, and insufficient technical support. These challenges can hinder the effective implementation of AI and contribute to a sense of frustration and scepticism among educators. On similar lines, [Nugroho et al. \(2024\)](#) stated that while some teachers in vocational high schools see the potential of AI to enhance student engagement and learning outcomes, various obstacles such as lack of training and technological infrastructure hinder optimal implementation. This body of research highlights a critical gap: while AI tools are proliferating, dedicated, practical training for in-service STEM teachers to effectively and ethically integrate them remains a significant hurdle. This study seeks to address this gap by examining teachers' perspectives *during* such a professional development experience.

3 Methodology

This study employed a multi-method research design that combined quantitative and qualitative data sources. [Halverson \(2017\)](#) defined multimethod “as combining various data types and approaches.” In the present study, data were collected through (1) a Likert-scale questionnaire that was analysed using descriptive statistics, (2) reflective diaries that were analysed using open coding, and (3) activities designed by the participants that were open-coded. Each data source addressed complementary aspects of the research questions. The different

quantitative and qualitative datasets were analysed independently, and the findings were interpreted in relation to one another at the level of discussion rather than through data integration.

3.1 Research context and participants

Forty-three in-service STEM teachers (33 women and 10 men) participated in a 12-week online course on New Technologies in Science and STEM Teaching. The participants had an average of 6.5 years of teaching experience in different educational levels. The overall aim of the course was to introduce pedagogies and technological tools that can potentially support science teaching and learning. The course included tools like virtual labs, simulations, augmented reality, virtual reality, and generative AI tools. The course activities aimed to engage participants with online presentations, readings, discussion forums, synchronous presentations, application of technologies in classroom settings, and reflection. The part of the course that focused on generative AI tools had a duration of 2 weeks and included the presentation and application of different types of tools that teachers can use either for their own preparation or to support student learning in science. In addition, teachers were introduced to the basic principles and capabilities of generative AI, with a special emphasis on science education and STEM, to familiarise them with generative AI tools that can be used for personalised teaching, automated assessment and provision of feedback, and to gain practical skills in using generative AI tools. The discussions that took place during the 2 weeks also focused on the pedagogical and ethical perspectives of the inclusion of generative AI tools, specifically in science education and STEM education. Teachers were asked to choose at least one generative AI tool from the ones presented in the course, use it as part of their teaching, and reflect on it in an asynchronous discussion forum.

3.2 Data collection

Three different data collection tools were used in order to: (a) collect data in relation to teachers' initial and final perceptions on the use of generative AI tools (R.Q.1); (b) their challenges in applying generative AI tools in their designs and their practices (R.Q.2); and (c) their concerns in relation to introducing generative AI tools in teaching science and STEM education (R.Q.3). Specifically, the following data collection tools were used:

- (a) Questionnaire at the beginning of the course to capture participants' overall skills in using different technological tools as part of their STEM teaching. The questionnaire included questions about the demographics of the participants, their views on the use of technology as part of their teaching in STEM education, the frequency of use of different categories of technological tools, how familiar they are with different categories of technological tools, and the difficulties they have in including technological tools in their teaching.

- (b) Activity designs that introduce the use of generative AI tools: As part of the course, the participants were asked to design in groups a STEM-related activity that would use a generative AI tool and test the activity in their class. Based on the instructions provided, the description of the activity should be short, focus on a STEM-related issue, and introduce a generative AI tool with pedagogical benefits for the students.
- (c) Reflective diaries: Teachers were asked to maintain reflective diaries focusing on their interactions with generative AI tools and their reflections on the benefits and challenges of using these tools in their teaching practices. The prompts included questions such as
- Describe your initial experiences with the AI tools. What were your first impressions?
 - What challenges did you encounter while using the AI tools? How did you address these challenges?
 - What do you perceive as the main benefits of using AI tools in your teaching? Provide specific examples.
 - What concerns do you have about the use of AI tools in education? How do you think these concerns can be addressed?
 - How do you think AI tools can be integrated into your teaching practices to enhance student learning?

The participants used the reflective diaries to record their thoughts, experiences, and reflections over a period of 2 weeks, thereby capturing the dynamic and evolving nature of teachers' perceptions and practices (Yi, 2008). This method, in combination with the results from the initial questionnaire and the activity design by the participants, not only provided a detailed understanding of teachers' experiences, capturing the complexities and subtleties of their professional practices, but also encouraged them to critically examine their teaching, fostering self-awareness and professional development. However, we acknowledge that the reflective nature of diary writing may be influenced by participants' prior experiences and schooling backgrounds, as noted by Abednia et al. (2013). Hence, to address these challenges, we provided clear guidelines and support to the participants, ensuring that they understood the purpose and goals of reflective diary writing.

3.3 Data analysis

The initial questionnaire included Likert-scale questions, yes/no questions, and open-ended questions. For the Likert-scale and yes/no questions, the average score and descriptive statistics were presented, whilst the data from the open-ended questions were analysed using thematic analysis. The activity designs and the data from the reflective diaries were also analysed using thematic analysis. Thematic analysis is a method that involves identifying, analysing, and reporting patterns (themes) within the data (Braun and Clarke, 2021). The thematic analysis for both the activity designs and the reflective diaries was examined separately and followed a six-phase process. The first phase, which consisted of familiarisation with the data, involved reading and re-reading the reflective diaries to become deeply familiar with the content. This step was crucial for gaining an initial understanding of the data and identifying preliminary insights. The second phase, which involved the generation of initial codes, entailed a systematic

coding of interesting features of the data across the entire dataset. This process helped in organising the data into meaningful groups and facilitated the identification of patterns. In the third phase, the initial codes were collated into potential themes, and all data relevant to each potential theme were gathered. This phase involved a more focused analysis, where the aim was to identify broader patterns of meaning within the data. The fourth phase involved checking whether the themes worked in relation to the coded extracts and the entire dataset. This step ensured that the themes accurately represented the data and were coherent and consistent. A thematic map of the analysis was generated during this phase to visualise the relationships between themes. The fifth phase required refining the specifics of each theme and generating clear definitions and names for each theme. This phase was essential for ensuring that each theme was distinct and captured the essence of the data it represented. Finally, the sixth phase involved selecting vivid and compelling extract examples, conducting a final analysis of the selected extracts, and relating the analysis back to the research questions and literature. This comprehensive approach ensured that the findings were well supported by the data and provided a thorough understanding of the teachers' experiences and perspectives on the use of AI tools in science education.

To enhance the credibility and transferability of the study, we employed strategies such as searching for counter-examples and alternative explanations. This approach, as suggested by Morse (2015), involves actively seeking out data that may contradict or challenge the emerging themes and interpretations. By exploring alternative explanations, we were able to demonstrate that the identified themes were robust and applicable across different contexts, thereby enhancing the transferability of the study. Furthermore, rich, thick descriptions were provided to offer detailed accounts of the research context, participants, and findings. These descriptions allow readers to gain a comprehensive understanding of the setting of a study and the experiences of the participants (Guba and Lincoln, 1985). By offering such detailed narratives, the study enabled readers to determine the transferability of the findings to other contexts.

3.4 Ethical considerations

The study adhered to ethical guidelines, ensuring confidentiality and anonymity. All the participants were informed about the study, and consent to use their data was obtained. The identities of the participants were kept anonymous in the study, as we used abbreviations for their names: T for teacher attached with a number, e.g., T1,...,T43. Data were securely stored and accessible only to the research team. The Cyprus National Bioethics Committee (CNBC) granted approval for the study (Ref. EEBK EII 2024.01.133).

4 Results

4.1 Results of pre-questionnaire

Table 1 presents teachers' responses on three 5-scale Likert-scale questions related to teachers' beliefs.

TABLE 1 Frequency and percentage distribution of teachers' perceptions of technology use in STEM before the beginning of the course (N = 43).

Statement	Very important/ very satisfied [N (%)]	Somewhat important/ somewhat satisfied [N (%)]	Important/ satisfied [N (%)]	Not important/not satisfied [N (%)]	Not sure [N (%)]
Technology can improve learning outcomes	30 (69.8)	13 (30.2)	0 (0)	0 (0)	0 (0)
Inclusion of technological tools is important	23 (53.5)	18 (41.9)	2 (4.7)	0 (0)	0 (0)
Satisfaction with technology use	16 (37.2)	13 (30.2)	12 (27.9)	2 (4.7)	0 (0)

TABLE 2 Technological tools that science and STEM teachers use in their teaching.

Which technological tools do you use?	N (43)	%
Teleconference platforms (i.e., zoom)	35	81.4
Simulations (i.e., Phet)	7	16.3
Applets (i.e., GeoGebra)	8	18.6
Interactive whiteboard	15	34.9
Internet-based apps (i.e., Desmos, Kahoot, Canvas, Quizlet)	13	30.2

As presented in Table 1, the teachers have strong positive beliefs about the role of technology in improving science and STEM learning outcomes. Almost 70% of the participants believe that technology is very important in improving learning outcomes, and 30.2% believe that technology is important. Most of the teachers (53.5%) consider the inclusion of technological tools in science and STEM as very important, and 41.9% consider it as important. What is also evident here is that the teachers are satisfied with the results of using technology with their students, with 37.2% being very satisfied and 30.2% being somewhat satisfied.

Eighty-six per cent of teachers reported using technological tools in their teaching, as listed in Table 2.

As given in Table 2, most of the teachers (81.4%) had used teleconference platforms with their students at one point of time, and as they explained in their responses, they had to use such platforms during the COVID-19 pandemic. A smaller percentage of teachers use tools like simulations (16.3%), applets (18.6%), and internet-based apps (30.2%) in their teaching. Also, more than one-third of the teachers (34.9) use the interactive whiteboard in their class.

The teachers were also asked about the frequency of using the technological tools in their classroom, and their responses are presented in Table 3.

As given in Table 3, 67.4% of the teachers use technologies with their students at least once per week, while only 1 of the 43 teachers reported that they never use technologies in their teaching. When asked about the reasons that affect the use of technology in the classroom, most of the teachers (81.4%) reported the lack of teacher training in skills and pedagogical knowledge as the main reason, while 27.9% of the teachers reported limited technological recourses in schools as an additional reason; 11.6% of them cited student discipline issues

TABLE 3 Frequency of use of technologies.

How often do you use technologies with your students?	N (43)	%
Never	1	2.3
Not very often (1–2 times per month)	13	30.2
Sometimes (1–2 times per week)	16	37.2
Often (in every lesson)	13	30.2

as a reason that makes the use of technology in the classroom difficult.

The teachers were also asked about their confidence in using different tools and to rate it on a 3-point Likert scale with 3 as the top. The results of their responses are presented in Table 4.

As given in Table 4, more than 88% of teachers feel confident in using distance learning platforms with their students, more than 60% feel confident in using interactive whiteboards in their class, but most of the teachers do not feel very confident in using simulations, applets, virtual reality, and AI tools.

Furthermore, teachers were asked about the main challenges in implementing generative AI tools in their science and STEM teaching, and their responses are presented in Table 5.

As given in Table 5, most of the teachers report the lack of knowledge of pedagogical implementation of the available tools and concerns related to reducing students' critical thinking skills as the main hurdles in implementing generative AI tools in their teaching of science and STEM topics. Furthermore, more than 58% of teachers report the disagreement of school leadership on the use of generative AI tools as an additional challenge, and less than 50% report the lack of knowledge of available tools and disagreement from parents.

4.2 Results of activity designs

Table 6 presents a summary of the analysis of the 13 group activity designs that the teachers submitted as part of the course they were attending.

As presented in Table 6, the activity designs show a diverse use of generative AI tools with five categories of tools being used: conversational AI tools (i.e., chatGPT); data analysis tools (i.e., Google Colab); content creation tools (i.e., Canva); simulation

TABLE 4 Frequency and percentage distribution of teachers' self-reported ability to use technology tools (N = 43).

Statement	Well [N (%)]	Somehow well [N (%)]	Moderate [N (%)]	Not well enough [N (%)]
How well can you use interactive whiteboards in the class	11 (25.6)	16 (37.2)	8 (18.6)	8 (18.6)
How well can you use simulations in your class	4 (9.3)	12 (27.9)	10 (23.3)	17 (39.5)
How well can you use distance learning platforms?	13 (30.2)	25 (58.1)	3 (7.0)	2 (4.7)
How well can you use virtual learning tools?	1 (2.3)	6 (14.0)	18 (41.9)	18 (41.9)
How well can you use applets in your teaching?	5 (11.6)	6 (14.0)	16 (37.2)	16 (37.2)
How well can you use AI tools in your teaching?	3 (7.0)	12 (27.9)	16 (37.2)	12 (27.9)

TABLE 5 Main challenges in implementing generative AI tools in science and STEM teaching.

Statement	N (43)	%
Lack of knowledge of pedagogical implementation of available tools	36	83.7
Concerns related to reducing students' critical thinking skills	32	74.4
Disagreement on school leadership level on the use of generative AI tools	25	58.1
Lack of knowledge of available tools	22	51.2
Disagreement from parents on the use of generative AI tools	12	27.9

and visualisation tools (i.e., Gemini AI); and gamified tools (i.e., AI-generated quiz tools). Furthermore, as given in the table, the teachers use the AI tools in three primary pedagogical roles: as a learning assistant, as a scientific or analytical tool, and as a creative and presentation tool. Furthermore, the teachers seem to incorporate pedagogical strategies such as inquiry-based learning and collaborative learning, and the role of the teacher in the activities is that of facilitators.

4.3 Analysis of reflective diaries

The thematic analysis of the 43 in-service science teachers' reflective diaries revealed four major themes regarding their perceptions of integrating AI tools in science education. These themes, which directly address the study's research questions, are: (1) perceived benefits of AI tools, (2) challenges in learning and integration, (3) ethical and pedagogical concerns, and (4) strategies to address challenges.

4.3.1 Perceived benefits: personalisation, efficiency, and engagement

The integration of AI tools in education has been widely recognised by the majority of participants for its potential to revolutionise teaching and learning processes. AI tools have been praised for their ability to tailor educational content to individual student needs, thereby enhancing personalised learning experiences. T24 explained, "AI tools like Smart Sparrow can adapt exercises to address specific areas where students need more practice. This keeps students engaged and

allows them to progress at their own pace." Another teacher highlighted the benefits of personalised feedback: "Using AI tools, I can provide immediate and personalised feedback to my students, which helps them understand their mistakes and improve more quickly" (T33). The ability of AI tools to customise learning experiences based on individual student performance was seen as a significant advantage. This personalised approach helps students to better understand complex concepts and stay motivated. T5 noted, "Learning with AI can be personalised according to the needs of the students." Another added, "AI can adapt the educational process to the needs of each student by analysing performance data and adjusting the content and pace of learning accordingly" (T6).

Teachers highlighted the efficiency gains from using AI tools, particularly in automating repetitive tasks such as grading and providing feedback. This allowed them to focus more on interactive and creative aspects of teaching. As T37 noted, "AI tools have significantly reduced the time I spend on administrative tasks. For example, using AI for grading has freed up more time for me to engage with students and develop interactive lessons." Another teacher shared a similar experience: "The automation of routine tasks like grading and attendance tracking has been a game-changer. It allows me to dedicate more time to lesson planning and student interaction" (T11). The automation of administrative tasks was also seen as a major benefit, allowing teachers to allocate more time to direct student engagement and lesson development. T7 mentioned, "AI offers significant benefits in education by adapting learning to the needs of each student, providing personalised support and feedback" (T7). Another added, "The main benefits of AI initially include the time saved by the user, whether they are a teacher or a student" (T8).

The interactive nature of AI tools was seen as a major benefit in increasing student engagement. Teachers reported that tools like chatbots and virtual labs made learning more interactive and enjoyable for students. T42 shared, "Using AI tools like virtual labs has made my lessons more engaging. Students are more involved and excited to participate in simulations and experiments." T19 added, "AI tools have made it easier to create interactive and visually appealing content, which captures students' attention and makes learning more fun." The ability of AI tools to create engaging and interactive learning experiences was highly valued by teachers. These tools helped to capture students' attention and make learning more dynamic and enjoyable. T1 noted, "AI can positively influence learning and

TABLE 6 Overview of activity designs by teachers after the implementation of the course.

Topic of activity	Type of AI tool	Pedagogical use of AI	Pedagogical strategy	Quote
Geometry with QuiverVision	AR-based visualisation tool	Student interaction with visual models; conceptual visualisation	Experiential learning; constructivist visualisation	“Students will be able to see the shapes “come to life” in 3D and rotate them in real time.”
Climate Change activity	ChatGPT, Ideogram, Gamma, Google Earth Engine, Go-Lab	Research, analysis, report writing, and presentation	Inquiry-based learning; collaborative learning; project-based learning	“Students will use text generation tools such as ChatGPT to compose a short report explaining the results of their analyses.”
Chemistry learning with ChatGPT	Conversational AI (ChatGPT)	Student inquiry and critical evaluation	Inquiry-based learning; metacognitive learning	“Students will attempt to formulate their own questions... and evaluate the responses.”
NotebookLM activity	AI summarisation and conversational analysis tool	Content summarisation, guided questioning, and discussion	Scaffolded learning; guided constructivism	“Simple notes can be generated... including a study guide, glossary of concepts, and terminology.”
Simple Harmonic Motion	Conversational AI (ChatGPT)	Student interaction with AI tutor; conceptual clarification	Inquiry-based learning; collaborative learning; dialogic learning	“Students will pose their questions to the AI digital assistant (ChatGPT).”
Genetics activity	ChatGPT and Canva	Information retrieval and presentation creation	Collaborative learning	“Students will use the AI tool ChatGPT... to search for additional information.”
Pressure simulation activity	Gemini AI	Simulation creation, data analysis, and visualisation	Inquiry-based learning	“Students create objects with the help of Gemini AI... and compare the results.”
Mechanics and AI analysis	Google Colab and Python AI tools	Data analysis, modelling, and prediction	Inquiry-based learning	“They use artificial intelligence techniques to calculate the relationship between velocity and acceleration.”
Chemical kinetics analysis	ChatGPT and Google Colab	Data analysis	Inquiry learning	“We use ChatGPT as a guide... to analyse the data.”
Maths labyrinth game	AI-based adaptive learning system	Adaptive assessment and feedback	Gamification; personalised learning	“AI technology recognises the user”s correct answers.”
Weather prediction activity	Machine learning tools	Data analysis and prediction	Inquiry-based learning; authentic scientific practice	“They will create a simple weather prediction model.”
Newton’s laws activity	AI-assisted quiz generation tool	Assessment preparation	Formative assessment	“The teacher can use artificial intelligence to create questions for students.”
Natural selection simulation	Simulation-based AI tool	Hypothesis testing	Inquiry-based learning	“Students formulate hypotheses... and test them by interacting with the AI tool.”

teaching. The major challenge is for both students and teachers to learn how to use these tools correctly” (T1). Another added, “The benefits include making lessons more experiential with the use of AI” (T2). A third teacher mentioned, “These tools can make lessons interactive and particularly attractive for each student” (T3).

These extracts collectively illustrate the perceived benefits of AI tools in education, including personalised learning, immediate feedback, efficiency, and enhanced engagement. These benefits support the first research question by demonstrating how AI tools can transform educational practices and improve student outcomes. The ability of AI tools to customise learning experiences based on individual student performance, automate administrative tasks, and create engaging and interactive learning environments highlights their potential to significantly enhance the teaching and learning process.

4.3.2 Challenges in learning and integrating AI tools

Despite the perceived benefits, teachers identified several practical challenges in learning and integrating AI tools. Based on the reflective diaries, teachers mentioned the lack of familiarity and the need for considerable time to understand and experiment with AI tools, especially content creation tools like chatbots and video software. Many teachers mentioned the need for additional guidance or technical support. One teacher noted, “Personally, I have not made extensive use of AI, only experimenting to see if it could theoretically meet my needs in the future if necessary” (T2). Another teacher shared, “Initially, I did not know the AI tools that contribute to educational processes. However, with study, I managed to understand and familiarise myself with some of them” (T3). To overcome this complexity, they stressed the need for additional guidance or

technical support, sought through online seminars and instructional videos. As a teacher explained, “The main technical challenge was the lack of familiarity with AI tools. It took considerable time to understand and experiment with these tools, especially content creation tools like chatbots and video software” (T8).

AI tools can be complex, requiring substantial time commitment to learn and use effectively. Teachers must balance this with their regular teaching responsibilities and overloaded curricula. As T6 explained, “AI tools rely heavily on data to ‘learn’ and produce accurate results.” Another teacher mentioned, “The software of an AI tool can have a complex way of use, making the process unfamiliar to students (at least initially)” (T7). Understanding the full range of functionalities and making the most of them is rather challenging.

Learning to use AI tools effectively requires substantial time commitment, which teachers must balance with their regular teaching responsibilities and the overloaded curricula. As T1 mentioned, “Learning to use AI tools effectively requires substantial time commitment, which teachers must balance with their regular teaching responsibilities and the overloaded curricula.” These challenges align with the research question on the challenges that teachers encounter in integrating AI tools through online platforms, providing valuable insights into the practical barriers to AI adoption in education, highlighting the need for comprehensive training, reliable infrastructure, and support systems to facilitate effective AI integration.

Ensuring a stable and fast internet connection is a significant challenge, especially in areas with unstable internet. Some AI tools require subscriptions or have limited free functionalities, creating a barrier for schools with restricted budgets. T4 mentioned, “Using AI tools requires a stable and reliable internet connection,” while T5 added, “I personally believe that AI makes lessons much more interesting and attractive for children. I think the biggest challenges are in the school’s technical equipment and the management of technology by teachers” (T5). Teachers stated that they struggle to load and use AI tools in areas with unstable internet, disrupting the learning process. One teacher noted, “Ensuring a stable and fast internet connection was a significant challenge. In areas with unstable internet, it was difficult to load and use AI tools, which disrupted the learning process” (T13).

4.3.3 Ethical and pedagogical concerns: misuse, data privacy, and bias

Beyond practical challenges, the integration of AI tools has raised several concerns among teachers, reflecting a range of issues, including the potential misuse of AI, data privacy and security issues, biases and inaccuracies, and the impact on social and emotional development. One primary concern is the potential misuse of AI, with students relying extensively on these tools for answers rather than enhancing and supporting their understanding. As they explained, this reliance could hinder the development of critical thinking and problem-solving skills, leading to superficial learning. T1 explained, “The main concern about the use of AI by students is that they do not use it correctly. Students have tools that provide them with solutions to their assignments and school obligations, and most students

think this is the main benefit, without having the maturity and patience to use these tools for deeper understanding and guidance” (T1). Another teacher added, “The main concerns about the use of AI are whether I will be able to integrate it correctly and constructively into the lesson and whether I will be able to follow the school’s curriculum” (T2).

Data privacy and security are also significant concerns among participants. Specifically, teachers worry about the collection and storage of sensitive personal data by AI tools, fearing that students’ performance data and personal information could be vulnerable to misuse or breaches. T29 expressed, “I am concerned about the data privacy issues associated with AI tools. The collection and storage of students’ performance data and personal information need to be secure to prevent misuse.” Another teacher shared a similar concern: “Data privacy is a significant issue. We need to ensure that AI tools comply with data protection regulations and that students’ personal information is safeguarded” (T6).

Another concern identified is the potential for AI tools to perpetuate biases and inaccuracies. AI systems can produce biased or incorrect outputs if trained on biased data, leading to misinformation and reinforcing stereotypes. T3 stated, “The unreliability in the production of results and bias, especially on issues of gender and ethnicity, is a concern. This can be addressed by cultivating critical thinking and a culture that does not rely on stereotypes” (T3). While T4 added, “AI can incorporate biases or make incorrect assessments, negatively affecting students and the decisions made for them.”

Teachers also referred to the negative impact of AI on social and emotional development. According to teachers’ accounts, excessive use of AI tools could reduce face-to-face interactions, diminishing social skills development, stressing that the human element of teaching, including empathy and personal connection, is irreplaceable for comprehensive education. T5 explained, “The excessive use of AI by students, especially if limited to interaction processes through machines, can reduce personal interactions and affect the social and emotional skills of students” (T5). Another teacher added, “My main concern is whether AI will contribute to the isolation of children, as it may limit interpersonal relationships between students and with the teacher” (T6). These concerns align with the research question on teachers’ concerns about AI use in their teaching practices, providing valuable insights into the ethical and practical issues associated with AI integration.

4.3.4 Strategies to overcome challenges and address concerns

In their reflections, teachers not only identified challenges but also proposed strategies to overcome them. The most frequently mentioned strategy was the need for comprehensive training and ongoing support. T17 explained, “To effectively use AI tools, I needed more training and support. Online seminars and instructional videos were helpful, but hands-on workshops would have been even better.” T41 highlighted the importance of ongoing professional development: “Continuous professional development is essential for staying updated with the latest AI technologies and methodologies. Institutional support is crucial for providing the necessary training and resources.” The need

for training and support was a recurring theme, with teachers expressing a desire for more hands-on workshops and continuous professional development opportunities. One teacher noted, “The first contact came during this course. It was impressive how an AI tool can offer so many possibilities. The difficulty was mainly in finding the most useful tool for me, so the search part was the most demanding” (T3).

Ensuring strong data privacy protections to safeguard students’ performance data and personal information is another critical strategy mentioned by participants. Implementing robust guidelines and policies to ensure responsible use of AI in educational contexts was one of the main suggestions. One teacher mentioned, “To safeguard students’ performance data and personal information, it is crucial to implement robust data privacy protections. This includes using encryption and secure storage solutions to prevent unauthorised access” (T18). Another teacher added, “Establishing clear guidelines and policies for the responsible use of AI in education is essential. These policies should outline the ethical considerations and ensure that AI tools are used to enhance learning without compromising students’ privacy” (T19). T40 asserted, “Regular audits and assessments of AI systems can help identify potential privacy risks and ensure compliance with data protection regulations. This proactive approach can mitigate ethical concerns and build trust among students and educators,” while T37 suggested, “Educating students and educators about data privacy and the ethical use of AI tools is vital. Providing training sessions and resources can empower them to make informed decisions and use AI responsibly.” These measures would help address data privacy concerns, ensuring that AI tools are used responsibly and effectively to enhance the learning experience, while safeguarding students’ personal information.

Maintaining human interaction and support in the classroom to balance the use of AI tools is also significant for research participants who emphasise the importance of integrating AI in a way that enhances, rather than replaces, human interaction and support. T8 explained, “The use of AI in education certainly has great potential, but there are also some areas where its application may not be as effective. AI, although evolving, cannot replace the emotional intelligence required in many educational situations.” Another teacher emphasised, “AI tools are not always effective for activities that involve emotional understanding, such as empathy in a good conversation or personal issues that we need to address with students. Additionally, excessive automation tends to kill creativity and critical thinking” (T11). A participant added, “While AI can provide valuable support in terms of personalised learning and data analysis, it is crucial to maintain the human element in education. Teachers play an irreplaceable role in fostering a supportive and empathetic learning environment” (T15). According to teachers’ testimonies, by integrating AI in a way that complements rather than replaces the human touch, educators can ensure that students receive both the technological advantages and the emotional and social support they need for holistic development.

5 Discussion

The findings of this study, derived from science and STEM teachers’ questionnaires, activity designs, and reflections during an online professional development programme, highlight a

critical tension: positive attitudes towards the use of technology in relation to student positive learning outcomes, and especially the use of generative AI tools, but this is matched by practical, pedagogical, and ethical concerns. This discussion interprets these findings in relation to the three research questions and makes the connection with studies on generative AI tools in science and STEM teaching and learning. As highlighted in the Introduction, AI in STEM education can potentially transform core scientific practices such as modelling, experimentation, data analysis, and inquiry, which are central to the epistemology and pedagogy of science, and this can impact how teachers introduce generative AI tools in their teaching.

5.1 Teachers’ perceptions of the use of generative AI tools in STEM and science education

The findings from the analysis of the questionnaires and the reflective diaries indicate that science and STEM teachers hold positive perceptions with regard to the potential of including generative AI tools in their teaching. Before the training programme, the teachers had already expressed positive beliefs about the role of technology in enhancing STEM learning outcomes but were not satisfied with their own use of technology in their classroom. This finding is in line with recent studies that have explored teachers’ attitudes towards the use of generative AI tools in the classroom (Rasool, Li and Liu, 2025; Yim and Wegerif, 2024) and found out that teachers are positive towards the use of technology. Following the training programme, in their reflective diaries, the teachers demonstrated increased awareness of the pedagogical potential of generative AI tools in STEM education. Furthermore, the teachers recognised that generative AI tools can help students with personalised learning, can provide feedback, and increase student engagement. Similar findings in relation to increased student engagement and personalised learning were also reported in Yim and Wegerif (2024), who explored teachers’ attitudes towards AI. The teachers in their study reported that the use of AI can motivate students to learn and support them in individualised learning. In the context of STEM education specifically, personalised feedback and adaptive learning can be seen as particularly important, given the conceptual complexity and abstract nature of scientific concepts. The teachers in our study reported that AI tools can potentially support students’ understanding of difficult STEM topics by providing explanations, feedback, and opportunities for iterative learning. Empirical evidence from a previous study with university students support this finding (El Fathi et al., 2025).

Furthermore, the activity designs that the teachers developed in their groups highlight that generative AI tools were understood by the teachers not only as tools to support with teaching but also as tools that can enhance authentic STEM learning practices. For example, the teachers used conversational AI tools to support student inquiry, data analysis tools to analyse experimental data, and simulation tools to support scientific modelling and experimentation in relation to climate change. These findings suggest that the teachers understand generative AI tools as pedagogical tools in supporting key STEM

competencies and practices, with a special emphasis as shown in the activity design on modelling, hypothesis testing, and interpretation of scientific data. These findings are in line with those of recent studies (El Fathi et al., 2025; Moundridou et al., 2024), which show that when trained on the use of different generative AI tools and pedagogical approaches, STEM teachers often reconceptualise these AI tools as assistants in designing inquiry-based activities for their students. Previous research indicates that STEM teachers need example activities using generative AI in inquiry-based teaching to apply this approach with students (Yim and Wegerif, 2024).

Teachers in their questionnaires and reflective diaries also show that they consider generative AI tools as being appropriate tools to increase student engagement in science and STEM, a finding that has also been highlighted in other studies (Avci et al., 2025). In addition, in the reflective diaries, the teachers highlighted the added value associated with generative AI tools, particularly in automating repetitive tasks such as grading and providing feedback, something that has also been reported by STEM teachers in other studies in relation to how AI tools help them streamline some of their tasks and save time (Avci et al., 2025).

5.2 Challenges in learning and integrating generative AI tools in STEM teaching

Despite the positive perceptions, teachers identified challenges linked to introducing generative AI tools in their STEM teaching practices. The most significant challenge identified was the lack of pedagogical knowledge on how to integrate generative AI tools into STEM teaching. This finding is particularly important in STEM education, where effective integration of AI requires not only technical competence but also a pedagogical knowledge of how AI tools can support scientific inquiry, modelling, and experimentation. In this study, teachers were supported by the feedback provided by the instructor in designing pedagogically appropriate activities. Recent studies (Kosmas et al., 2025) have also identified the co-design approach between researchers and teachers as a step towards designing pedagogically appropriate activities. Teachers also reported low levels of confidence in using AI tools and highlighted the need for time to learn and experiment with generative AI tools as learners before introducing them in the teaching practice. Infrastructure-related challenges were also identified, including unstable internet connections and limited access to technological resources. These challenges limited teachers' ability to effectively integrate AI tools into their STEM teaching, particularly in activities involving simulations, data analysis, and modelling. Similar findings related to the lack of pedagogical knowledge on the use of generative AI tools have been reported in other studies as well, both with STEM teachers and with teachers of other topics (Avci et al., 2025; Konstantinidou et al., 2026; Yim and Wegerif, 2024).

5.3 Teachers' concerns regarding the use of generative AI tools in STEM teaching

The teachers in this study expressed ethical and pedagogical concerns regarding the use of generative AI tools in science and

STEM education. A significant concern expressed by teachers was that providing students with pre-packaged information generated from AI tools might reduce their ability to think critically and reason scientifically. This finding is in line with that of previous studies that have noted teachers' concerns that an over-reliance on AI can encourage superficial engagement with knowledge and reduce cognitive effort, thus undermining the development of critical thinking (Giannakos et al., 2025). The teachers in our study were concerned that students might rely excessively on AI-generated answers without engaging in scientific inquiry processes. They also expressed concerns regarding the accuracy and reliability of AI-generated information, highlighting the importance of ensuring epistemic reliability in STEM education. This finding that places an emphasis on ensuring epistemic reliability in STEM education has not been reported by teachers previously based on our reading of the literature. Finally, the teachers emphasised the importance of maintaining the teacher's role as a facilitator of scientific inquiry and mentioned that AI tools should be used as additional tools in a way that can support students' thinking process and scientific inquiry.

6 Conclusion

The rapid expansion of AI technology has profoundly impacted the field of education, reshaping teaching and learning practices. With the potential to revolutionise education, the growing prevalence of AI tools in educational technology has created significant interest in their ability to transform pedagogical methodologies and enhance student learning. Understanding stakeholders' perceptions of AI as a tool to support educational practice is crucial. Exploring teachers' perceptions provides valuable insights into how they interact with AI in education, and can potentially inform the development of strategies for integrating AI into educational practices, especially those linked to STEM education.

This study investigated teachers' perspectives on the use of AI tools in science and STEM education. The findings highlight both the benefits and the challenges of integrating AI in education. Specifically, teachers showed positive attitudes for AI's potential to support personalised learning, enhance efficiency, and help with student engagement. Moreover, the teachers supported the use of AI tools for their ability to customise educational content to individual student needs, automate repetitive tasks, and create interactive learning experiences for the students. At the same time, the findings reveal challenges related to teachers' pedagogical preparedness and ethical considerations for the impact of their use on students' critical thinking and inquiry-based learning skills. The teachers emphasised the need for targeted professional development, institutional support, and clear pedagogical frameworks to support the effective integration of generative AI tools in STEM education.

Overall, the study findings highlight that generative AI tools can transform science and STEM teaching by supporting inquiry-based learning, modelling, and scientific reasoning if they are integrated using appropriate pedagogical models and are based on the epistemic aspects of science and STEM education. Effective integration of AI tools in STEM and science

education requires sustained support for teachers, including professional development. What is especially important is training on pedagogical integration and support the development of teachers' activities by using a co-design approach with other teachers and researchers (Kosmas et al., 2025).

7 Implication and future directions

The successful integration of generative AI within educational settings should follow a multifaceted approach. A structured educational framework is needed to integrate generative AI tools into science and STEM teaching practices. This framework should provide teachers with clear pedagogical strategies for introducing the generative AI tools within instructional activities. Special emphasis in this framework should also be placed on the epistemic aspects of STEM and science education in relation to the AI tools (Erduran and Levrini, 2024).

While AI integration in STEM education is promising and beneficial, it comes with challenges that require careful consideration, starting with addressing technical, ethical, and pedagogical issues to ensure effective and responsible AI use in education in order to address teachers' concerns in relation to the ethical perspectives of using AI with students. Insights from this study contribute to the ongoing discourse on AI in education with a special emphasis on STEM and science education supporting the need for targeted training with a focus on the epistemic aspects of the disciplines.

Teachers' positive attitudes towards AI, with proper support and resources, can lead to successful integration (Li and Noori, 2024; Wang et al., 2021). Therefore, as evident from the findings of this study, interactive online workshops, hands-on activities, and collaborative projects that are placed within specific pedagogical approaches like inquiry-based learning and authentic learning, can potentially allow teachers to practice using generative AI tools (Akram et al., 2022). Future studies should use longitudinal methods to assess how teachers' use of AI affects student outcomes and critical thinking in STEM education. These results will clarify the long-term influence of AI tools on learning in STEM fields.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

This study involving humans were approved by The Cyprus National Bioethics Committee (CNBC) granted approval for the study (Ref. EEBK EII 2024.01.133). The studies were conducted

in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

CK: Software, Data curation, Visualization, Writing – original draft, Methodology, Resources, Conceptualization, Investigation, Project administration, Validation, Writing – review & editing, Formal analysis, Supervision. ME: Project administration, Validation, Methodology, Visualization, Data curation, Conceptualization, Writing – review & editing, Supervision, Investigation, Resources, Software.

Funding

The author(s) declared that financial support was not received for this work and/or its publication.

Acknowledgments

We are grateful to the teachers who participated in this study.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

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