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Review Article

Artificial intelligence in science education: A systematic review of applications, impacts, and challenges

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ABSTRACT

This systematic review investigates the incorporation of artificial intelligence (AI) into science education by analyzing 17 studies published from 2020 to 2024. The paper examines the utilization of AI in different scientific fields and educational settings and assesses its influence on the methods of teaching and learning. The findings demonstrate a diverse range of AI applications, including chatbots, intelligent tutoring systems, and AI-enhanced textbooks. These apps serve many functions, from being educational tools to assisting in assessments. The investigation demonstrates the favorable impact of AI on student performance, motivation, and engagement in science education, particularly in the areas of personalized learning and the development of self-regulated learning skills. Additionally, issues related to technological infrastructure, obstacles to the sensitivity and reliability of AI systems, and ethical issues were also examined. The study emphasizes the importance of teacher preparation in achieving the successful integration of AI and expresses the necessity of comprehensive professional development. Potential areas for future research encompass investigating the enduring consequences of AI utilization, exploring its applicability in diverse educational settings, and fostering the growth of AI literacy. The study's findings indicate that while AI has the potential to greatly improve science education, its successful application necessitates thoughtful evaluation of technological, pedagogical, ethical, and social elements to ensure fair and efficient integration across all educational levels.

Keywords: artificial intelligence, science education, AI-enhanced teaching, educational chatbots

INTRODUCTION

From many angles–personal, social, financial–science education is vital. From an economic standpoint, it is especially vital in satisfying the needs of the workforce in sectors including engineering and technology, which are absolutely vital for national and global development and economic advancement (Osborne & Allchin, 2024; Rotatori et al., 2021). Scientific literacy is essential for informed citizenship in a democratic society at the society level since it helps people to make reasonable decisions about socio-scientific issues, such those resulting from developments in genetics and genomics, with significant consequences for both public and personal health (Kruit et al., 2024; Ottander & Simon, 2021). Personal level science education is distinguished by the development of critical thinking and problem-solving abilities required to understand and assess ethical dilemmas and scientific claims (Greenfield et al., 2024; Sun et al., 2022; Yaki, 2022). Moreover, keeping indigenous knowledge and advancing cultural diversity depend on science education (Zidny et al., 2020). Science teachers should thus be well-informed and armed with successful teaching strategies to actively involve students and foster their scientific literacy. They should thus make sure they are ready to negotiate and help to shape a world growingly complicated and driven by science.

Artificial intelligence (AI) is the replication of human intelligence in robots that are intended to mimic human thinking and learning. AI is being more and more incorporated into several areas of education, including governance and teaching methods (Gulson & Witzenberger, 2022). This covers local government (Sarrab et al., 2020) and corporate intelligence systems and real-time online assessments in an educational environment (Seo et al., 2021). Designed to enable autonomous learning, AI systems let students specify particular study goals and have been developed to assist Korean students in English learning using the learner-created context framework, therefore enabling self-directed (Lee et al., 2023a). AI-powered solutions, such as chatbots, have demonstrated effectiveness in mitigating the negative effects of summer meltdown and enhancing college enrollment rates by offering tailored assistance to students, particularly those who are the first in their family to attend college. It helps pupils negotiate difficult operations, so improving their whole educational experience (Dai & Ke, 2022; Nurshatayeva et al., 2021). AI consists of a wide range of technologies and applications meant to replicate and improve human cognitive capacities in many spheres, including education by means of other domains.

The integration of AI into science education is important because of its transformative potential to enhance various educational dimensions and prepare students for a rapidly evolving technological environment. AI-supported tools can significantly improve teaching practices, assessment strategies, and administrative processes. This can thus produce a more interesting and efficient classroom (Almasri, 2024; Heeg & Avraamidou, 2023). The capacity of AI to create hypotheses, devise tests, and analyze data exposes students to cutting-edge scientific methods, hence enhancing the relevance and fitness of science education with present scientific approaches (Cooper & Tang, 2024; Erduran & Levrini, 2024). Moreover, AI technologies such as ChatGPT show promise in promoting self-regulated learning (SRL) by providing personalized guidance and feedback that improves students' scientific knowledge, motivation, and sustainable learning habits (Ng et al., 2024). The use of AI in education also requires a rethinking of how learning artefacts are created and assessed, pushing the field to rethink traditional educational paradigms (Sadler et al., 2024). Including AI in science classes also helps students establish links between AI and scientific ideas, therefore promoting better knowledge and respect for both disciplines (Nja et al., 2023; Park et al., 2023). Notwithstanding obstacles including content expertise and teacher support of curriculum adaptation, the advantages of AI in generating tailored, adaptive learning experiences and preparing students for a future dominated by AI technologies make integration of AI into science education not only beneficial but also required.

Research Problem

Integration of AI into science education offers both possibilities and difficulties that should be methodically investigated and comprehended. Although AI technologies show promise in enhancing learning outcomes, raising student involvement, and offering tailored learning experiences, their application raises serious ethical questions as well as issues of effectiveness. Given their rapid development, we do not entirely know how AI tools such as ChatGPT and other creative AI systems impact science teaching. Our understanding of how rapidly AI technologies such as ChatGPT, Claude and other generative AI systems influence scientific

education lags behind their explosive growth. It becomes absolutely vital to look at how these technologies could be effectively introduced into the science curriculum, how they influence student learning and motivation, and what challenges teachers have in employing AI-enabled teaching strategies. Moreover, under serious inspection should be the potential of AI to exacerbate educational inequalities and raise ethical issues about academic integrity.

Research Focus

This study centers on the utilization and consequences of AI technology in the field of science teaching across several educational tiers, ranging from elementary school to tertiary education. Specifically, it analyzes the utilization of AI tools by educators and learners for instructional objectives, generating content, and customizing learning encounters in scientific disciplines including biology, chemistry, and physics. The study aims to comprehend the utilization of AI technologies, including chatbots, intelligent tutoring systems (ITS), and AI-enhanced textbooks, in science classrooms, laboratories, and for assessment reasons. Additionally, it examines the impact of these AI applications on student learning outcomes, motivation, cognitive load, and self-regulated learning skills. The research additionally seeks to pinpoint obstacles and hindrances to the successful integration of AI in science education, encompassing technological, pedagogical, and ethical factors.

Research Aim and Research Questions

This study aims to evaluate the present level of AI integration in science education, evaluate its effects on teaching and learning strategies, and pinpoint areas of best practices and difficulties in its use. The following research questions are suggested to help reach this goal:

1. In science education at various levels and scientific disciplines, how are AI technologies applied by teachers and students?
2. What are the effects of AI-supported learning environments on students' science achievement, motivation, and self-regulated learning skills?
3. What are the main challenges and barriers faced by educators and students in applying and using AI technologies in science education?
4. How can AI tools be effectively designed and implemented to enhance science education while addressing ethical concerns and ensuring equitable access?
5. How can these technologies be sustainably included in educational practices, and what are the long-term effects of AI integration in science education?

By tackling these issues, this study seeks to give a thorough knowledge of the function of AI in science education and guide future advancements in this fast changing sector.

LITERATURE REVIEW

Science Teacher Usage Artificial Intelligence in Science Education

In order to enhance many facets of science education, science teachers are including AI more and more in their courses. Quests, evaluations of student work, and academic performance prediction are produced using AI-powered systems. This helps to enhance the learning environment and increase its interactivity and personalizing power (Almasri, 2024). Crucially for scientific uses, hypotheses, design experiments, and data interpretation are generated by AI; so, science education is better in line with actual scientific research (Erduran & Levrini, 2024). Teachers employ generative AI systems like ChatGPT to create science units, rubrics and quizzes, but there are ethical questions regarding the necessity of critical review of AI-generated content (Cooper, 2023). However, the use of AI also brings challenges including the perpetuation of preconceptions and the reinforcement of prejudices, which demands teachers' constant awareness and critical evaluation (Cooper & Tang, 2024). Although information flow varies, interactions with AI and professionals in professional development programs help teachers to acquire epistemological awareness and change their teaching approaches (Dai, 2023).

AI-enabled informal formative evaluations let teachers compile student learning data and create explanations to help to clarify scientific ideas (Román et al., 2019). Another area where AI is significantly influencing and deepening students' knowledge of scientific ideas is the inclusion of computational thinking into K-12 science courses (Peters-Burton et al., 2022). Although digital technology enabled by AI is also extensively utilized in scientific classrooms to inspire students, individualize learning and enable assessments, it presents difficulties in aiding low-achieving students and properly implementing inquiry-based teaching (Walan, 2020). Last but not least, AI techniques help to support scientific debate–a difficult activity that motivates students to create and criticize arguments grounded on data and observations, therefore enabling high-quality science education (Mikeska & Lottero-Perdue, 2022). Although including AI into science education has transforming possibilities overall, its advantages must be maximized by thorough evaluation of ethical, pedagogical, and practical consequences.

The Effect of Artificial Intelligence on Science Achievement

AI has shown considerable potential in many various fields of study and education in increasing scientific productivity. AI enabled systems such as smart science stations and artificial intelligence educational robots (AIERs) have been successful in increasing student involvement and learning outcomes in educational environments. For example, the gamified AIER system run under the GAFCC model enhanced students' learning performance in relation to traditional methods for laboratory safety training (Yang et al., 2023). Similarly, smart science stations integrating guided discoveries with hands-on production have been demonstrated to produce more powerful learning outcomes in science education by letting children better grasp scientific ideas and practical skills (Yannier et al., 2020). Studies show adding AI in physics courses could help to increase student interest and learning results (Patero, 2023). Among students, AI systems can lessen cognitive burden, enhance conceptual understanding, and solve problems with less effort (Selvam, 2024). According to Heeg and Avraamidou (2023), AI has positive effect of students' achievements in science learning. Liao et al. (2024) found that higher learning performance and self-regulated learning resulting from AI-supported visual reporting emerged over time. Improved learning opportunities, data analysis, and creative research methods help AI to be applied in both educational and research settings to considerably increase scientific output.

Integration of AI in science education has clearly shown great benefits for student involvement, curiosity, and inspiration. Effective in improving students' learning experiences were AI technologies including generative AI chatbots and AI-supported educational robots. For instance, by offering customized recommendations and therefore lowering learning anxiety, the implementation of SRLbot, a generative AI-based chatbot, in a science learning environment greatly raised students' science knowledge, behavioral engagement and motivation (Ng et al., 2024). Similarly, AI-powered tools have been found to improve the learning environment by creating quizzes, assessing students' work and predicting academic performance, which collectively contribute to better learning outcomes and increased student engagement (Almasri, 2024). Research has reported a positive impact on students' scientific discussion skills, engagement, enjoyment and motivation (Heeg & Avraamidou, 2023). Furthermore, underlining its potential to make science education more relevant and interesting for students, so promoting a greater interest in scientific investigation, is the part of AI in scientific applications including developing ideas and performing experiments (Erduran & Levrini, 2024). Moreover, several AI applications–including adaptive learning systems and ITS–have been employed to enhance knowledge building and skill development in disciplines including earth sciences and physics, so enhancing learning achievements and argumentative capacity (Heeg & Avraamidou, 2023). These results taken together imply that AI not only helps to acquire scientific information but also significantly encourages student involvement, interest, and motivation in science education by means of which it sustains and increases.

Challenges in Artificial Intelligence-Assisted Science Education

Science education supplemented by AI offers many difficulties in technical, ethical, and pedagogical spheres. Integration of AI into current courses is one of the main difficulties since teachers sometimes lack confidence in their understanding of AI content and struggle to recognize its relevance when taught as a stand-alone topic (Al Darayseh, 2023; Garofalo & Farenga, 2024). This requires extensive AI resources and

support for teachers to effectively incorporate AI into discipline-based lessons (Park et al., 2023). In addition, the reliability, explainability and bias of AI systems pose significant barriers. These issues can endanger the validity of AI-supported assessments, thus affecting trust in educational systems and requiring changes to quality assurance mechanisms (Aloisi, 2023; Cooper, 2023; Lee & Zhai, 2024). Using AI is more challenging because it can reinforce biases and stereotypes. For example, AI tools such as DALL-E 3 and ChatGPT can generate stereotypical images, which can undermine efforts to promote diversity and fairness in science education (Cooper & Tang, 2024). Moreover, ethical concerns surrounding AI, such as data privacy, potential plagiarism, and socioeconomic inequalities resulting from unequal access to technology, emphasize the need for robust ethical frameworks and policies (Cooper, 2023; Nykonenko, 2023). Also, Ezquerra et al. (2022) indicate that the use of AI to monitor students' emotions and behaviors raises ethical questions about privacy and consent. Ensuring that data is collected and used responsibly is crucial.

Using different AI techniques in STEM teaching can be hard because they are technically complicated. To really meet the needs of your kids, you need to know a lot about both school and technology (Xu & Ouyang, 2022). Teachers should discuss ethical issues such copyright infringement, the impact of AI on the environment, and content moderation concerns with their pupils so that they may be guided to use AI responsibly and to have critical thinking (Alshorman, 2024; Garofalo & Farenga, 2024). Finally, AI can transform the way science is taught; yet this has to be constantly investigated and improved so that outdated approaches of instruction do not become worthless and students are prepared for a fast-changing scientific research environment (Erduran & Levrini, 2024). The demand for flexible, customized learning environments and the growth of online learning complicate AI applications even more. To create adaptive learning environments that fit well, you must be quite knowledgeable about psychometric views and sophisticated knowledge assessment approaches (Minn, 2022). Using AI in science courses depends on everyone involved–teachers, professionals, and legislators–working together; so, overall, solving these several issues is quite crucial.

Artificial Intelligence-Based Pedagogy for Teaching Science

AI is altering teaching and learning process. It presents fresh approaches to increase the effectiveness and appeal of learning (Su et al., 2022). The ITS is a significant AI tool for scientific education. These systems give every learner tailored assistance by means of AI (Adelana et al., 2024). One can modify them depending on the speed of learning of a student. They also provide rapid comments when a student attempts to solve a difficulty. Every student thus receives the correct degree of assistance at the appropriate moment (Alshorman, 2024). For challenging topics like cell biology or physics, for example, ITS can simplify multiple approaches until the student understands them (Gunawan et al., 2021; Naya-Forcano et al., 2024).

Virtual reality (VR) and augmented reality are one such fantastic application of AI in scientific education. These technologies provide students' study with 3D surrounds. Could you "walk" within a plant cell or "fly" all across the solar system? This makes learning more fun and enables kids to understand difficult concepts (Kaviyaraj & Uma, 2021; Matovu et al., 2023). In chemistry class, for example, students could see and interact with VR-based molecular models. This clarifies for learner how molecules act in a way that is impossible to demonstrate in a book dependent solely on images (Brown et al., 2021).

Furthermore, improving students' scientific communication requires AI. Natural language processing (NLP) is its technology of choice. Students' science writing might get better as a result. It can verify, for instance, if students are using scientific jargon accurately (Allen et al., 2022). It can also point out areas where their justifications need some clarity. Students learning to produce lab reports or explain scientific concepts will find this quite helpful. Students' scientific writing abilities can be greatly improved by AI-assisted writing tools (Nguyen et al., 2024; Song & Song, 2023).

In science, data is absolutely crucial. AI technologies let students examine experimentally produced data (Wang et al., 2023). These tools allow students to identify trends in data that might be challenging for them to see on their own. This guides students toward thinking like actual scientists. These instruments allow one to test their hypotheses and derive results from their experiments (Ramkorun, 2024). Using AI technologies for data analysis helps students improve their scientific reasoning abilities (AlQuraishi & Sorger, 2021; Baum et al., 2021).

At last, AI is changing our perspective on student knowledge evaluation (Krenn et al., 2022). Everyone answers conventional examinations exactly. AI, however, might create tests that change based on a student's performance (González-Calatayud et al., 2021). Should the student's answer to the first question be accurate, the second one could be more difficult. Should they miss it, the next one might be easier. This precisely clarifies for teachers what every child requires assistance with and what they know (Ercikan & McCaffrey, 2022). The adaptive tests might show a more reasonable perspective on student understanding (Wulandari & Hadi, 2021).

Though all of these AI technologies are interesting, it's important to remember that they are not replacing human teachers (Felix, 2020). Instead, they help educators fulfill their duties more successfully (Ahmad et al., 2022; Chen et al., 2023; Chiu et al., 2023). Effective teaching of science most certainly requires both traditional methods and AI tools. To sum up, AI research presents various fresh approaches of instruction and learning. It can make learning more individualized, more participatory, and more like actual scientific work. Learning science can thus be more fascinating and simpler for pupils. Future teaching and learning of science should show even more fascinating shifts as AI develops.

RESEARCH METHODOLOGY

General Background

This systematic review aims to investigate the use of AI in science education. In detail, it focuses on its implementation by teachers for instructional purposes, content creation and personalization of learning experiences. In order to provide a comprehensive and unbiased review of the existing literature, a rigorous methodology was employed, following the guidelines outlined in the preferred reporting items for systematic reviews and meta-analyses (PRISMA) statement (Moher et al., 2009).

The methodology section will detail the systematic approach used to identify, screen and select relevant studies for inclusion in this review. The process began with the development of a comprehensive search strategy, which was then applied to the Scopus and Web of Science (WoS) electronic databases to gather a wide range of potentially relevant articles. After screening the search results against preset inclusion and exclusion criteria, only studies relevant to the study question were included.

This review uses a systematic and well-documented methodology to provide a reliable and comprehensive overview of AI applications in science education research and contribute to evidence-based decision-making and future research directions.

Data Collection Process

The data collection process began with the development of following search query: ("artificial intelligence" OR "AI") AND ("science education" OR "science teaching" OR "science learning" OR "biology education" OR "biology teaching" OR "biology learning" OR "physics education" OR "physics teaching" OR "physics learning" OR "chem* education" OR "chem* teaching" OR "chem* learning").

Using two main databases, Scopus and WoS, this search turned up relevant papers from 2015 onwards. Only English-language articles were used to enhance the results. The search in Scopus revealed 210 articles; from WoS, 686 articles. Additionally, 112 duplicate articles that appeared in both WoS and Scopus were removed. The titles and abstracts of the remaining articles were then screened based on predefined selection criteria.

The inclusion criteria consisted of studies focusing on:

- AI and science education,
- the use of AI for instructional purposes in science education,
- teachers' use of AI for educational content creation or personalization of education in science, and
- the assessment of science teachers' AI usage levels and knowledge.

The exclusion criteria are:

- studies examining teachers' or pre-service teachers' general attitudes and opinions,

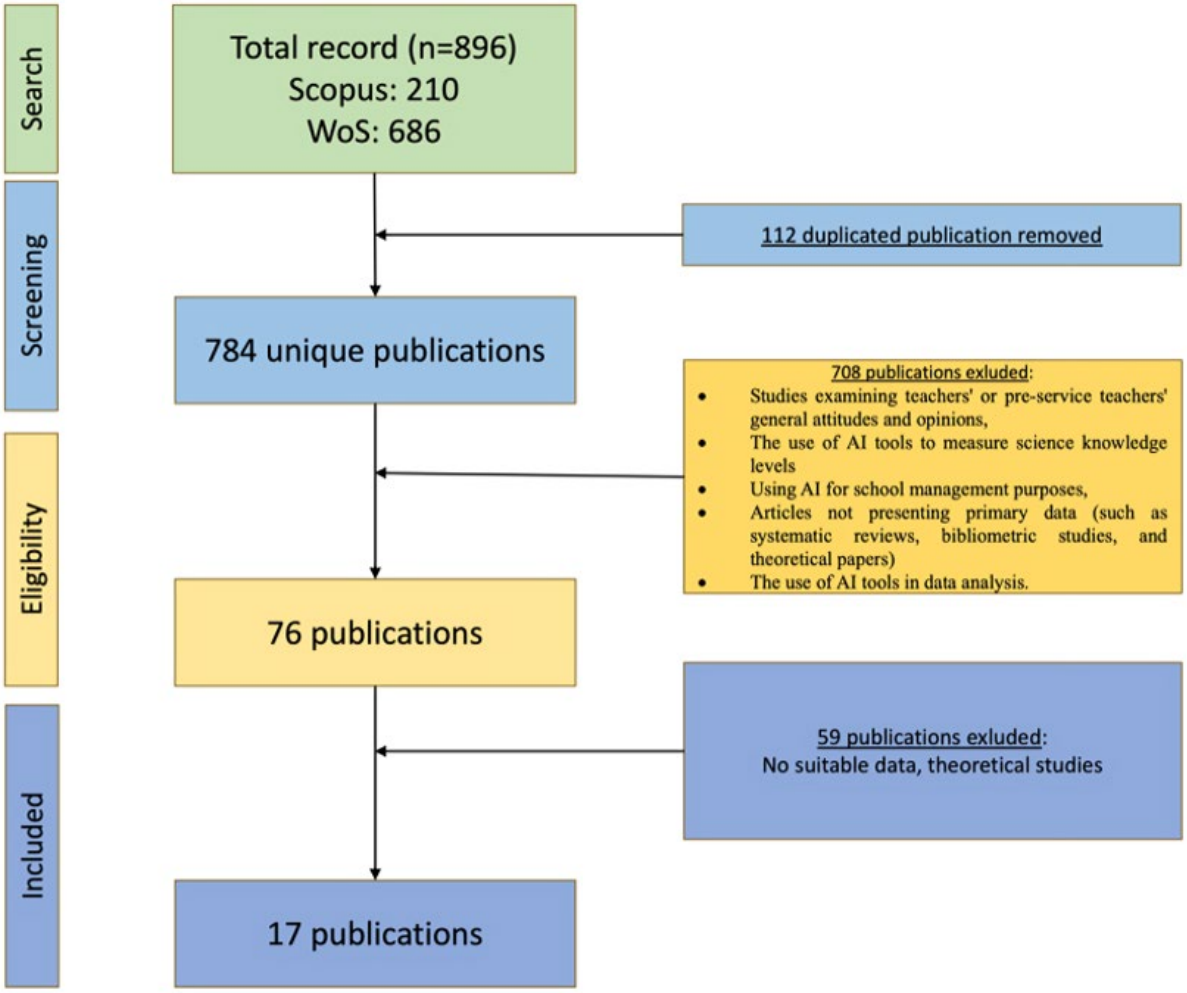

Figure 1. Data collection process (Figure created by the authors)

- the use of AI tools to measure science knowledge levels,
- using AI for school management purposes,
- articles not presenting primary data (such as systematic reviews, bibliometric studies, and theoretical papers), and
- The use of AI tools in data analysis.

There were 76 papers left over from the title and abstract screening. 17 papers were selected for in-depth research after thoroughly reading the whole texts of these works (**Figure 1**). Emphasizing the use of AI by teachers for instructional, content development, and personalizing purposes, this methodical and rigorous data collecting technique guaranteed that the most relevant papers were found for inclusion in the review.

Data Analysis

Using a systematic approach, the information gathered from the 17 chosen papers was examined to solve the study objectives and provide a complete knowledge of the use of AI in science education. Starting with a descriptive study of the papers included using the strategy advised by Petticrew and Roberts (2008), the analysis approach moved toward systematic reviews. The process entailed documenting the essential attributes of each study, such as the authors, publication year, title, scientific discipline, research methodologies, participants or data sources, and citation count. The data was organized into a table to give a concise summary of the present status of research in this field, using the standards suggested by Moher et al. (2015) in the PRISMA declaration.

Following Braun and Clarke (2006)'s recommendations, a thematic analysis was conducted to identify recurrent themes and patterns in the studies following the descriptive analysis. This process involved careful

reading and close inspection of the whole texts of the selected papers, organizing related information and grouping like concepts into more general subjects. The main themes found in this research were the purposes of AI in science education, the people using AI tools, the several contexts in which AI is used, the consequences of AI on science education, and the challenges related with applying AI.

A content analysis was undertaken, adhering to the guidelines outlined by Krippendorff (2018), in order to comprehend the application of AI in science education. This involved examining the specific AI tools and applications described in each study, their purpose and the context in which they were used. The results of this analysis are summarized in a table that provides details about the purpose of each study, the role of AI, who used the AI tool and where it was used in the teaching process.

Using the method advised by Gough et al. (2012) for synthesizing research in systematic reviews, the stated outcomes of every study were examined and synthesized to evaluate the effects of AI in science education. This study concentrated on both negative consequences (like possible over-reliance on AI technologies) and good ones (such better learning outcomes and more motivation). Following Kim et al. (2016) advice for efficient visual presentation of quantitative data, the analysis's findings were graphically shown in some capacity. Using the continual comparative approach stated across the research, the issues reported were examined to find common obstacles to the implementation of AI in scientific education. These difficulties were arranged and summarized; the outcomes were shown graphically.

Furthermore, following the prospective approach advocated by Webster and Watson (2002) in their literature review, suggestions for future research in the reviewed studies were analyzed in order to identify key areas for further research. Throughout the analysis process, comparisons were made across studies to identify similarities and differences in findings, methodologies and contexts, as suggested by Booth et al. (2016) to increase the rigor of systematic reviews. This comparative approach helped to highlight consistency in the literature as well as areas of difference that may require further research. The findings from these analyses were critically interpreted in the light of the existing literature on AI in education, as presented in the introduction and literature review sections, following the integrative review methodology described by Torraco (2005). This multifaceted approach of analysis allowed for a comprehensive examination of the current status, impacts, challenges and future directions of the use of AI in science education. By combining quantitative descriptive data with qualitative thematic analysis, this study provides a nuanced understanding of the complex landscape of AI integration in science education.

RESEARCH RESULTS

According to **Table 1**, the fact that the majority of the studies examined were published in 2023 and 2024 (for example, Chen & Chang, 2024; Kurniawan et al., 2024; Ng et al., 2024) clearly reveals the topicality and dynamic nature of this field. This situation can be considered as a reflection of the rapid developments in educational technologies and the increasing awareness of the potential of AI in the field of education.

When the fields of science covered by the research are analyzed, a wide spectrum is observed. It is seen that AI applications have been investigated in different disciplines such as general science (Chen & Chang, 2024; Ng et al., 2024), chemistry (Tassoti, 2024; Young et al., 2024), physics (Kurniawan et al., 2024; Ramkorun, 2024)) and biology (Koć-Januchta et al., 2020; Lin & Ye, 2023). This diversity shows the applicability and potential impact of AI technologies in different areas of science education.

A rich diversity is observed in terms of research methods. Experimental designs (Chen & Chang, 2024; Chen & Liu, 2024), mixed methods (Ng et al., 2024; Taani & Alabidi, 2024), design and development research (Kurniawan et al., 2024; Lee et al., 2024), surveys (Rojas, 2024; Tassoti, 2024), qualitative research (Ramkorun, 2024) and case studies (Chang et al., 2023). This methodological diversity shows that the effects of AI in science education are examined in a multidimensional way and evaluated from different perspectives.

When the target audiences of the studies are examined, it is seen that the higher education level is predominant (e.g., Kurniawan et al., 2024; Su, 2022; Taani & Alabidi, 2024), but there are also studies covering K-12 education. Studies conducted at middle school (Chen & Chang, 2024; Chen & Liu, 2024), primary school (Lee et al., 2023c) and high school (Lin & Ye, 2023) levels explore the potential of AI at different educational

Table 1. Descriptive information on studies

Authors	Title	Domain	Methods	Data source	Citations
Chang et al. (2023)	Using an artificial intelligence chatbot in scientific inquiry: Focusing on a guided-inquiry activity using inquirybot	Science	Single case study	Lower-secondary school	8
Chen and Chang (2024)	Effectiveness of AI-assisted game-based learning on science learning outcomes, intrinsic motivation, cognitive load, and learning behavior	Science	Experimental design	Lower-secondary school	2
Chen and Liu (2024)	Impact of ai robot image recognition technology on improving students' conceptual understanding of cell division and science learning motivation	Science	Experimental design	Lower-secondary school	0
Deveci Topal et al. (2021)	Chatbot application in a 5th grade science course	Science	Experimental design	Lower-secondary school	97
Koć-Januchta et al. (2020)	Engaging with biology by asking questions: Investigating students' interaction and learning with an artificial intelligence-enriched textbook	Biology	Experimental design	Higher education	35
Kurniawan et al. (2024)	A hybrid automatic scoring system: Artificial intelligence-based evaluation of physics concept comprehension essay test	Physics	Research and development	Higher education	0
Lee et al. (2024)	Collaborative learning with artificial intelligence speakers: Pre-service elementary science teachers' responses to the prototype	Science	D&D research	Higher education	2
Lee et al. (2023b)	Development of the hands-free AI speaker system supporting hands-on science laboratory class: A rapid prototyping	Chemistry	Design and development	Higher education	5
Lee et al. (2023c)	Improving science conceptual understanding and attitudes in elementary science classes through the development and application of a rule-based AI chatbot	Science	Experimental design	Elementary school	1
Lin and Ye (2023)	Development of an educational chatbot system for enhancing students' biology learning performance	Biology	Experimental design	High school	6
Ng et al. (2024)	Empowering student self-regulated learning and science education through ChatGPT: A pioneering pilot study	Science	Mixed	Secondary school	13
Ramkorun (2024)	Graph plotting of 1-D motion in introductory physics education using scripts generated by ChatGPT 3.5	Physics	Qualitative	Higher education	2
Rojas (2024)	An investigation into ChatGPT's application for a scientific writing assignment	Chemistry	Survey	Higher education	4
Su (2022)	Implementation of innovative artificial intelligence cognitions with problem-based learning guided tasks to enhance students' performance in science	Science	Mixed	Higher education	12
Taani and Alabidi (2024)	ChatGPT in education: Benefits and challenges of ChatGPT for mathematics and science teaching practices	Science	Mixed	Higher education	2
Tassoti (2024)	Assessment of students use of generative artificial intelligence: Prompting strategies and prompt engineering in chemistry education	Chemistry	Survey	Higher education	3
Young et al. (2024)	Chemistry students' artificial intelligence literacy through their critical reflections of chatbot responses	Chemistry	Mixed	Higher education	1

levels. This distribution shows that AI applications are more widely studied in higher education but are also receiving increasing attention in K-12 education.

A great diversity is observed in terms of the number of citations. The fact that the most cited study is research published in 2021 with 97 citations (Deveci Topal et al., 2021) shows that some studies in this field can make an impact quickly. On the other hand, the fact that many recently published studies have not yet

been cited indicates the dynamic nature of the field and that the impact of new research can be measured over time.

As a result, this descriptive analysis reveals that the use of AI in science education is a rapidly developing, multidisciplinary research area that covers various educational levels. The timeliness of the studies, the variety of methods used, and the application of different AI technologies demonstrate the dynamic nature and potential of this field. However, it is also understood that more research is needed in K-12 education and the long-term effects of AI in science education need to be examined more comprehensively. These findings provide important clues for the future of the use of AI in science education and may be instructive in shaping future research directions.

According to **Table 2**, the users and uses of these tools provide important information for understanding the potential and impact of AI in science education. From the perspective of users of AI tools, it appears that both teachers and students benefit from these technologies. By using AI as an assistant (Kurniawan et al., 2024; Taani & Alabidi, 2024), teachers receive support in lesson planning, evaluation, and feedback processes. For example, automatic essay evaluation systems in the field of physics (Kurniawan et al. (2024) reduce the workload of teachers and at the same time provide fast and consistent feedback to students. On the other hand, students use AI tools directly as a learning resource. For example, AI-powered e-books (Koć-Januchta et

Table 2. Using AI in science education

Authors	Aim of study	Role	Who use tool		Where it is used		
			T	S	PT	IT	AT
Chang et al. (2023)	Exploring how to use an AI chatbot pedagogically in scientific inquiry by developing a guided-inquiry activity using an AI chatbot and applying it.	Teaching tool		OK		OK	
Chen and Chang (2024)	Examining the impact of integrating ChatGPT into digital game-based learning on students' science education	Teaching tool		OK		OK	
Chen and Liu (2024)	The usage of AI robot image recognition technology systems to engage students in a role-reversal scenario.	Teaching tool		OK		OK	
Deveci Topal et al. (2021)	Investigating the effect of chatbots that work with artificial intelligence on the success of students and their opinions about chatbots in the 'matter and the changing state of matter' unit in the 5th grade science course.	Teaching tool		OK		OK	
Koć-Januchta et al. (2020)	Investigating students' interaction and learning with an AI book.	Teaching tool		OK		OK	
Kurniawan et al. (2024)	Developing and implementing an artificial intelligence-based essay scoring system called a hybrid automatic scoring system.	Teacher assistant	OK				
Lee et al. (2024)	demonstrating that AI can function not only as a tool for learning, but also as an intelligent agent with which humans can engage in collaborative learning in science classrooms.	Teaching tool		OK		OK	
Lee et al. (2023b)	The design and development research approach for the hands-free AI speaker system supporting a hands-on science laboratory class.	Teaching tool		OK		OK	
Lee et al. (2023c)	Developing a specialized rule-based AI chatbot tailored for a sixth-grade optics unit.	Teaching tool		OK		OK	
Lin and Ye (2023)	Investigating biology learning chatbot systems to support traditional biology education.	Assistant for students		OK			OK
Ng et al. (2024)	determining differences between the SRLbot and Nemobot platform that influence students' SRL, motivation and science knowledge.	Teaching tool		OK		OK	
Ramkorun (2024)	Exploring three introductory physics examples related to 1-D motion and employs ChatGPT 3.5 to generate scripts that will produce graphs from raw data.	Teaching assistant	OK	OK	OK	OK	

Table 2 (Continued).

Authors	Aim of study	Role	Who use tool		Where it is used		
			T	S	PT	IT	AT
Rojas (2024)	The integration of ChatGPT in a chemistry classroom writing assignment.	Assistant for students		OK			OK
Su (2022)	Evaluating students' science learning effectiveness and completing the teaching site focus of issues.	Teaching tool		OK		OK	
Taani and Alabidi (2024)	identifying AI usage in diverse science subjects.	Teacher assistant	OK	OK	OK	OK	OK
Tassoti (2024)	Investigating the use of text-generative AI by undergraduate students in a chemistry context.	Teaching tool		OK		OK	
Young et al. (2024)	Thematically describe how students critically reflect on AI.	Teaching tool		OK		OK	

Note. T: teacher; S: Student; PT: Pre-teaching; IT: In-teaching; AT: After teaching

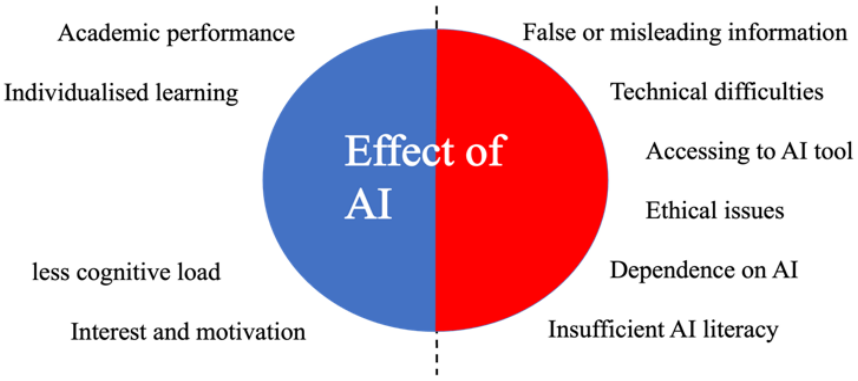

Figure 2. The effect of AI on science education (Figure created by the authors)

al., 2020) are used to learn biology, or chatbots (Tassoti, 2024) to solve chemistry problems. This shows that AI supports both teacher- and student-centered approaches.

Furthermore, the applications of AI tools and their times of use vary. AI is reportedly employed in pre-lesson preparation (Taani & Alabidi, 2024). This suggests that educators are leveraging AI to update the course of instruction or augment the past knowledge of their students. It is somewhat usual to apply AI in classrooms. AI can be included in the active learning process, for instance, by employing ChatGPT in game-based learning environments (Chen & Chang, 2024) or hands-free AI conversation systems in laboratory courses (Lee et al., 2023b). The post-lesson procedure also depends heavily on AI. It demonstrates that AI can be useful at all phases of the learning process, whether students use ChatGPT in their writing assignments (Rojas, 2024) or AI chatbots in their after-class work (Lin & Ye, 2023).

Furthermore, changing the conventional roles of teachers and students in science education is the application of AI. According to some research, students either study in cooperation with the AI or assume the duty of teaching the AI (Chen & Liu, 2024). This reveals that AI is beginning to be considered as an active participant in the learning process as well as a teaching tool. Teachers and students in many phases of their education, as well as in several scientific fields, use AI tools. This great spectrum of applications shows how AI could revolutionize and improve science education. To fully achieve this promise, though, we must pay close attention to problems including raising AI literacy, guaranteeing ethical use, and revamping instructional techniques to fit AI technologies.

The Effect of Artificial Intelligence on Science Education

AI applied in scientific education reveals the ability to revolutionize learning environments. Studies have shown that, in science education, AI has both good and bad consequences (**Figure 2**).

Learning strategies aided by AI have shown success in raising the academic performance of learner. Students utilizing AI-supported game-based learning for instance outperformed those using just games (Chen

& Chang, 2024). Students using AI chatbots likewise showed better learning performance than those learning using more conventional approaches (Lin & Ye, 2023). These results amply show how well AI could raise learning results.

Another important effect of AI tools is to increase students' interest and motivation in science. The use of AI chatbot significantly increased students' interest in science (Lee et al., 2023c) and made the learning process more fun (Deveci Topal et al., 2021). AI-supported laboratory systems made the lessons more enjoyable and positively affected students' attitudes (Lee et al., 2023b). These findings show the potential of AI to make science education more attractive and engaging.

In addition, the individualized learning experiences and immediate feedback provided by AI systems help students progress at their own pace and better understand difficult concepts (Chen & Chang, 2024; Taani & Alabidi, 2024). Furthermore, AI chatbots helped kids acquire self-regulating abilities. Particularly those with strong scientific background were more likely to create self-regulation plans leveraging AI tools (Ng et al., 2024).

Furthermore, lessening students' cognitive strain are AI-supported systems. Students utilizing AI-supported GBL, for instance, reported less cognitive load than those who merely played games (Chen & Chang, 2024).This demonstrates how AI could simplify the difficult scientific ideas for learners.

From the teachers' point of view, AI saves time in evaluating student performance and simplifies the evaluation process (Kurniawan et al., 2024). Moreover, AI systems perform repetitious chores, which frees teachers to concentrate on more worthwhile instruction (Lee et al., 2023b).

Still, the application of AI in scientific education presents certain difficulties. Sometimes AI systems generates false or misleading information. ChatGPT might, for instance, assume incorrectly in graph drawing, therefore causing errors in data computation (Ramkorun, 2024). Students run the danger of depending too much on AI tools and stifling their own ability to solve problems (Chen & Chang, 2024).

Technical difficulties can hinder the effective use of AI systems. Problems such as speech recognition errors and response delays can disrupt the learning process (Lee et al., 2024). Furthermore, the insufficient AI literacy of many students makes it difficult to use AI tools effectively and to evaluate accurate outputs (Tassoti, 2024).

For learners from low socioeconomic backgrounds or without access to technological infrastructure, the employment of AI technology may be a drawback (Deveci Topal et al., 2021). This could lead to more disparity in educational possibilities. Moreover, the use of AI tools in the processes of academic writing generates ethical questions (Rojas, 2024).

In conclusion, the use of AI in science education has the potential to improve learning outcomes, increase motivation and provide individualized learning experiences. However, for the effective use of these technologies, accuracy and reliability issues need to be addressed, AI literacy needs to be increased, and ethical concerns need to be addressed. Optimizing the role of AI in science education requires a careful balancing of these positive and negative impacts and the adaptation of education systems to these new technologies.

Challenges

This systematic review study on the use of AI in science education reveals various challenges encountered in the integration of AI technologies into the educational process (as shown **Figure 3**). These challenges are important for understanding the barriers to the full realization of AI's potential in science education. In the light of the findings from the reviewed studies, the following main challenges stand out:

Technological infrastructure and access problems

The papers highlight the technical infrastructure and access issues required for the efficient application of AI techniques. For instance, highlighted as major obstacles were students' restricted access to personal devices (Deveci Topal et al., 2021) and the lack of consistent internet connectivity (Taani & Alabidi, 2024). Particularly for poor socioeconomic background pupils, this condition has negative effects and increases the likelihood of widening educational inequality of opportunity.

Figure 3. Challenges about using AI in science education (Figure created by the authors)

Accuracy and reliability issues of artificial intelligence systems

The fact that AI systems sometimes produce erroneous or misleading information is a major concern in science education as in other fields of science. Especially in sensitive areas such as chemistry, mathematical errors and hallucinations (Tassoti, 2024) in AI-generated answers can lead to serious problems. Likewise, in the field of physics, the assumptions made by ChatGPT during graph drawing (Ramkorun, 2024) can lead to erroneous results. This increases the risk of students acquiring wrong information and may hinder the development of critical thinking skills.

Cost of implementation

The high initial costs of integrating AI technologies into educational institutions (Chen & Liu, 2024) pose a significant barrier, especially for resource-strapped schools.

Student motivation and interaction problems

Several research indicate that students may encounter demotivation when engaging with AI systems. Students who possess limited knowledge may eventually get disinterested in the feedback provided by AI chatbots, as stated in the document (Ng et al., 2024). This prompts the inquiry of how AI technologies might be customized to accommodate various learning methods and proficiency levels.

Cognitive load and complexity

The intricacy of AI-enhanced learning systems could cause cognitive stress for students. For instance, some interactive elements in AI-enhanced textbooks (Koć-Januchta et al., 2020) test students' ability for self-regulation. This implies that the design of AI systems should take educational ideas and user experience into consideration.

Language and communication issues

Particularly in different classroom situations, AI systems' incapacity to grasp language nuances (Taani & Alabidi, 2024) and limits in identifying unanticipated student replies (Chang et al., 2023) complicate successful communication.

Personalized learning and progress tracking

The inability of some AI applications to track student progress and produce personalized assessments (Taani & Alabidi, 2024) creates challenges in providing individualized learning experiences.

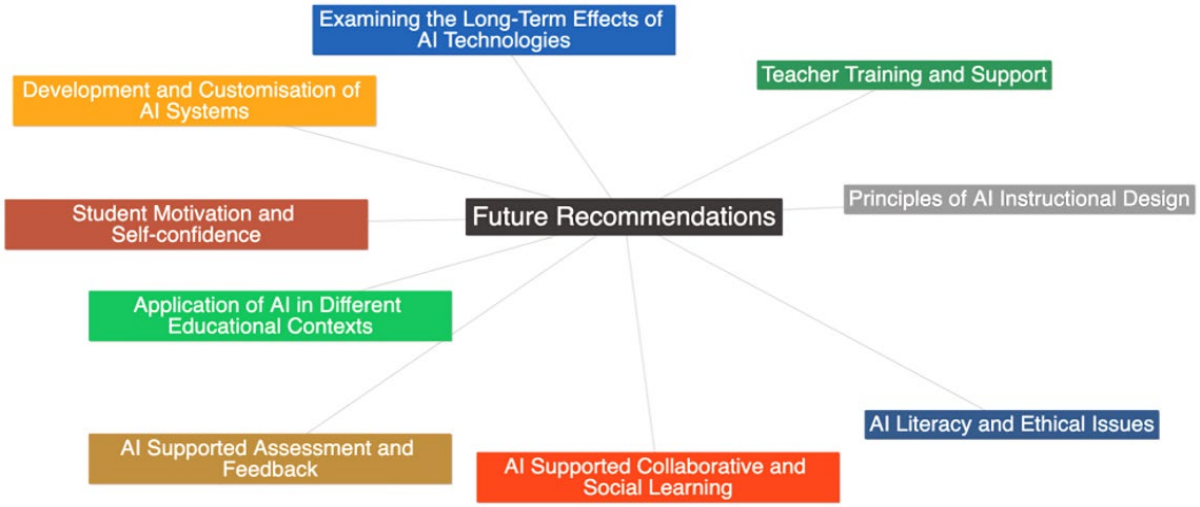

Figure 4. Future research recommendations (Figure created by the authors)

Ethical concerns and academic integrity

The use of AI in academic writing processes raises ethical concerns. Ethical concerns about students producing texts using ChatGPT (Rojas, 2024) show that the concepts of academic integrity and originality need to be re-evaluated.

Teacher training and adaptation process

Teachers must have sufficient instruction if they are to properly apply AI tools. Time-consuming and resource-intensive, this process (Chen & Liu, 2024) can be Furthermore a significant difficulty is teachers' adaptation to AI technology and including them into their teaching methods.

Stakeholder support and understanding

Ensuring the understanding and support of parents and other stakeholders for the use of AI tools in education is an important challenge (Lin & Ye, 2023). This situation shows the need for social awareness and training on the use of AI technologies in education.

In conclusion, this systematic review reveals the opportunities offered by the use of AI in science education as well as the significant challenges faced. To overcome these challenges, it is necessary to improve the technological infrastructure, increase the accuracy and reliability of AI systems, develop strategies to increase student motivation, address ethical concerns, and strengthen teacher training. Furthermore, designing AI tools in a way that is compatible with pedagogical principles and involving all stakeholders in this process is critical for the full realization of the potential of AI in science education.

Recommendations for Future Studies

When the future recommendations of the reviewed studies are analyzed, several main themes emerge (**Figure 4**).

Examining the long-term effects of artificial intelligence technologies

Many studies emphasize that the long-term effects of AI tools in science education should be examined in more detail. For example, Taani and Alabidi (2024) suggest conducting long-term studies to assess the sustained impact of ChatGPT on student learning outcomes and engagement. This is critical to understanding whether AI technologies create lasting and meaningful changes in education.

Application of artificial intelligence in different educational contexts

Researchers state that the use of AI technologies in different age groups, subjects, and cultural settings should be examined. Taani and Alabidi (2024) and Chen and Chang (2024) particularly emphasize this issue and highlight the importance of understanding the effectiveness of AI in various educational contexts.

Artificial intelligence-supported collaborative and social learning

It is suggested that future research should focus on how AI can support collaborative and social learning experiences. Chen and Chang (2024) suggest investigating how ChatGPT can support multiplayer interactions, peer feedback or team-based problem solving.

Artificial intelligence literacy and ethical issues

Improving the AI literacy of students and educators and examining the ethical dimensions of AI use stands out as an important research area. Young et al. (2024) and Rojas (2024) specifically focus on these issues and emphasize the need to develop strategies for a deep understanding of AI literacy and the protection of academic integrity.

Development and customization of artificial intelligence systems

Many studies suggest that existing AI systems should be further developed and customized according to educational needs. For instance, Lee et al. (2024) says that AI speakers should be created to enable real-time learning and better "listen" to pupils. Lin and Ye (2023) advise including technologies for NLP into chatbot systems.

Teacher training and support

Effective use of AI tools depends on teachers being taught and supported; it is highlighted. Designs and implementations of training courses for instructors on the effective application of AI technologies should be based, claims (Taani & Alabidi, 2024). Researchers urge more pragmatic and transdisciplinary applications of AI in scientific education should be looked at. Including useful application tools into AI systems will help students transition to autonomous learning, claims (Chen & Liu, 2024). Using ChatGPT in more advanced subjects including 2D motion and animation production in physics teaching is suggested in (Ramkorun, 2024).

Student motivation and self-confidence

It is suggested that future research should focus on how AI tools can increase student motivation and scientific self-confidence. Lee et al. (2023c) emphasizes that chatbot applications should be developed specifically to increase students' confidence in science.

Artificial intelligence supported assessment and feedback

It is suggested to investigate how AI can be used more effectively in student assessment and feedback processes. Deveci Topal et al. (2021) suggest the development of AI-supported alternative tools to measure students' cognitive learning.

Principles of artificial intelligence instructional design

Lee et al. (2023b) emphasize the need to develop comprehensive design principles and models for AI-supported education. This will help to design future AI educational applications more systematically and effectively.

In conclusion, these recommendations provide a rich research agenda for the future of AI use in science education. Topics such as the study of long-term effects, applications in different contexts, collaborative learning, ethical issues, system development, teacher training, and interdisciplinary approaches stand out as focal points for future research. These recommendations provide guidance for a more effective and meaningful integration of AI in science education.

DISCUSSION

Descriptive Information on Studies

The descriptive analysis of the studies included in this review reveals some notable trends and characteristics of current research on AI in science education. The majority of studies published in 2023 and 2024 underline the rapidly evolving nature of this field and reflect the growing interest and investment in AI

technologies for educational purposes. This is in line with the 2022 findings on growing AI integration into various sectors of life by Gulson and Witzenberger (2022). The numerous scientific disciplines addressed–general science, chemistry, physics, and biology–showcase the tremendous relevance of AI in many spheres, so validating the theory put up by Erduran and Levrini (2024). The noted methodological variety–experimental designs, mixed methodologies, and qualitative approaches–points to multifarious research of the influence of AI as recommended by Heeg and Avraamidou (2023). Though studies conducted at the higher education level are somewhat widespread, they also expose a likely deficiency in research at the K-12 level and reflect arguments raised by Osborne and Allchin (2024) regarding the need of complete scientific teaching at all educational levels. The differences in the citation count assist to illustrate the dynamic and changing character of this area of study. This result is consistent with remarks on the swiftly evolving field of AI in education requiring consistent observation and revision made by Cooper and Tang (2024). All things considered; this descriptive study emphasizes the areas needing more research as well as the successes already attained by means of a rigorous analysis of the present situation of AI in scientific education.

Application and Use of Artificial Intelligence in Science Education

From teacher aid tools to student-centered learning platforms, the results expose a broad spectrum of AI applications in scientific education. As Almasri (2024) and Heeg and Avraamidou (2023) underline, this broad spectrum of uses is in accordance with the transforming potential of AI in improving many educational dimensions. The widespread use of AI as a teaching tool, especially in the form of chatbots and ITS, supports Ng et al.'s (2024) claim that AI technologies such as ChatGPT show promise in promoting self-regulated learning and providing personalized guidance.

The fact that AI tools are applied at several phases of the teaching process–from pre-teaching preparation to post-teaching evaluation–reflects the great influence of AI on education defined by Seo et al. (2021) and Sarrab et al. (2020). As suggested by Minn (2022), this multifarious integration of AI points to a move towards more flexible and customized learning surroundings.

Effects of Artificial Intelligence on Science Education

As reported in our findings, the positive effects of AI on student performance, motivation, and engagement in science education are consistent with the expectations set forth in the literature. The observed improvements in learning outcomes and increased student interest support the claims made by Cooper and Tang (2024) and Erduran and Levrini (2024) about the potential of AI to increase the interest and appeal of science education.

Chen and Chang (2024) show a decrease in cognitive load, which supports the theory put forth by Selvam (2024) that AI systems can lower cognitive load and increase conceptual understanding. Moreover, the improvement of self-regulation skills under AI-supported learning, especially observed among students with strong scientific backgrounds (Ng et al., 2024), is in line with the potential of AI to improve critical thinking and problem-solving abilities, as advised by Greenfield et al. (2024) and Sun et al. (2022).

However, the identified challenges, such as the risk of generating misinformation and over-reliance on AI tools, underscore the concerns raised by Cooper (2023) about the need for critical scrutiny of AI-generated content and the importance of protecting the human presence in AI-supported education. Supervision in AI-supported education.

Challenges in Artificial Intelligence-Assisted Science Education

The technological infrastructure and access issues highlighted in our findings echo concerns raised by Xu and Ouyang (2022) about the technical complexities of AI implementation in STEM teaching. These challenges, which particularly affect students from low socioeconomic backgrounds, are in line with Cooper (2023) and Nykonenko (2023)'s warnings about the potential for AI to exacerbate inequalities in education.

The accuracy and reliability issues of AI systems, particularly in sensitive areas such as chemistry and physics, reinforce the cautionary notes raised by Cooper and Tang (2024) regarding the potential for AI to perpetuate biases and misconceptions. This emphasizes the importance of developing robust ethical frameworks and policies for the use of AI in education, as also advocated by Cooper (2023) and Nykonenko (2023).

The identified challenges related to student motivation, cognitive load and communication issues emphasize the need for careful design of AI systems that consider pedagogical principles and user experience, as suggested by Ezquerra et al. (2022) and Minn (2022). The ethical concerns and academic integrity issues raised in our findings, particularly in relation to the use of AI in academic writing, are in line with the broader ethical questions discussed by Cooper (2023) and emphasize the need for a reassessment of concepts of academic integrity in the age of AI.

Future Directions

The suggestions for next studies found in our study quite fit the gaps and needs emphasized in the literature. The demand to investigate the long-term effects of AI technologies reflects the attitude voiced by Osborne and Allchin (2024) and Rotatori et al. (2021) on the need of knowing the continuous influence of educational interventions on scientific literacy and workforce development. As stressed by Zidny et al. (2020), the focus on researching AI applications in many educational environments and cultural settings is in line with the need to maintain local knowledge and enhance cultural diversity in science education.

The focus on AI literacy and ethical issues in future research proposals overlaps with concerns raised by Cooper (2023) and Nykonenko (2023) about the need for robust frameworks to guide the ethical implications and use of AI in education. The call for more research on teacher training and support in the application of AI is in line with Gulson and Witzenberger (2022) claim about the increasing incorporation of AI into educational management and teaching methods, emphasizing the need for educators to be well equipped to keep pace with this technological change. Match this development in technology.

Finally, this conversation implies that the results of our systematic review significantly complement and expand the body of knowledge already in publication on AI in scientific education. Although AI has great potential, the problems found underscore the need for careful implementation and continuous study to guarantee that AI enhances rather than compromises the quality and equity of scientific education.

CONCLUSIONS AND IMPLICATIONS

This systematic review of AI applications in science education reveals a rapidly evolving landscape with significant potential to transform teaching and learning processes. The findings lead to many important conclusions and implications for researchers, educators, and policymakers.

AI technologies are being applied in a variety of scientific disciplines and educational levels, and serve many roles, from teaching tools to assessment aids. The positive effects on student performance, motivation, and engagement in science education are encouraging. Educational institutions should consider strategically incorporating AI tools into their science curricula, considering the need for careful implementation and continuous evaluation.

The capacity of AI to provide personalized learning experiences and promote self-regulated learning is an important finding. AI can play an important role in meeting individual student needs and developing independent learning skills necessary for lifelong learning in a rapidly changing scientific environment.

The identified challenges, including technological infrastructure issues, the accuracy and reliability of AI systems, and ethical concerns, highlight the complex nature of AI integration in education. These findings underline the need for a comprehensive approach to AI implementation that addresses not only technological aspects but also pedagogical, ethical, and social considerations. There is a need to develop robust guidelines and policies for the ethical use of AI in education, as well as strategies to ensure equitable access to AI technologies.

The results highlight how important teachers are to the effective integration of AI into scientific education. Comprehensive professional development initiatives are therefore desperately needed to raise teachers' AI literacy and their capacity to successfully include AI tools in their curricula.

The analysis reveals several areas that require further research, including the long-term effects of AI use, applications in various educational contexts, and the development of AI literacy. This calls for longitudinal studies, cross-cultural research, and research into the development of AI-related competences among students and educators. The complex nature of AI integration in science education requires collaboration

between educators, AI developers, ethicists, and policymakers. This means that interdisciplinary research and development efforts are needed to create AI systems that are not only technologically advanced, but also pedagogically sound and ethically responsible.

While the potential benefits of AI in science education are significant, the challenges identified require a balanced approach. This implies the need for careful, evidence-based application of AI technologies, with continuous monitoring and evaluation to ensure that they improve rather than undermine the quality and equity of education.

AI could essentially improve science education; but achieving this promise requires careful assessment of technical, pedagogical, ethical, and social elements. As we progress, we must approach the integration of AI into science education with both critical knowledge of its restrictions and possible perils as well as enthusiasm about its possibilities. Future research and projects should focus on developing AI systems in line with educational aims, addressing equity issues, enhancing teacher preparation, and so raising students's AI literacy along with their scientific knowledge and skills. By doing this, we could help to build a future in which AI is a powerful tool enabling more effective, entertaining, and readily available scientific education for every student.

The Limitations of the Study

It is important to know the limitations of this methodical research even if it provides interesting analysis of how AI is applied in scientific education. First of all, given the rapid pace of AI development, some of the most recent advancements might not be exactly reflected in the published literature included in this assessment. Second, the focus on English-language publications could have omitted relevant studies from non-English speaking countries, therefore limiting the spectrum of cultural points of view. Different quality of the studies included, some small sample size, or short intervention lengths could have affected the generalizability of the results. Moreover, even if the evaluation covers many scientific domains and educational levels, its broad breadth may have forbidden more in-depth studies of AI applications in certain environments. Dependency on published studies also increases the danger of publication bias, in which case excellent results are more likely to be stated than negative or null ones. Moreover, direct comparisons are challenging since research lacks consistent methods for evaluating how AI affects learning results. Finally, the emphasis of the review on scholarly literature could have missed important material from grey literature, practitioner reports, or current projects not yet published in scholarly journals. These restrictions should be considered while analyzing the data and guide the planning of next studies in this fast-developing sector.

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