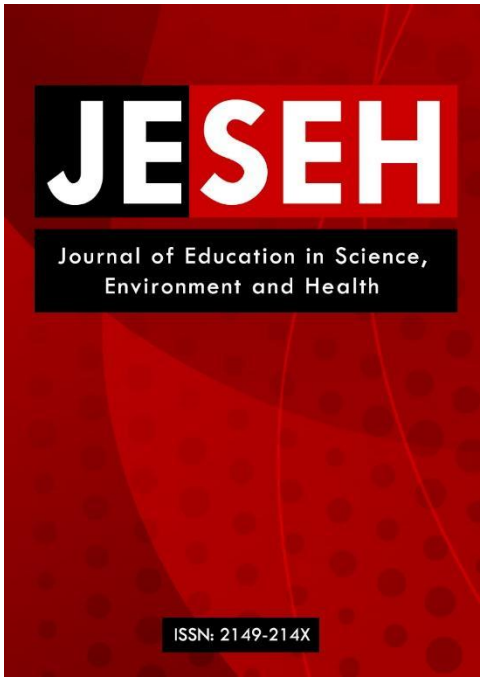

ISSN: 2149-214X

Journal of Education in Science, Environment and Health

www.jeseh.net

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To cite this article:

Gunsaldi, M.S., Guner, E.G., Uckan, M. & Bati, K. (2025). The impact of generative AI applications on student learning outcomes in science education: A systematic review. *Journal of Education in Science, Environment and Health (JESEH), 11*(3), 196-208. https://doi.org/10.55549/jeseh.840

JESEH
Journal of Education in Science, Environment and Health
Volume 11, Issue 3, 2025
https://doi.org/10.55549/jeseh.840

The Impact of Generative AI Applications on Student Learning Outcomes in Science Education: A Systematic Review

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Article Info

Article History

Published:
01 July 2025

Received:
02 April 2025

Accepted:
25 June 2025

Keywords

GenAI,
Artificial intelligence,
Science education

Abstract

This systematic literature review examines the impact of generative artificial intelligence (AI) applications on student learning outcomes in middle school science education. Twelve studies that met the inclusion and exclusion criteria were included in the study. The studies were accessed from the WOS, SCOPUS, ERIC, and TrDizin indexes and databases. The PRISMA protocol was used in the selection of studies. The analysis reveals that generative AI tools significantly contribute to academic achievement, conceptual understanding, scientific and digital literacy, personalized learning opportunities, and students' motivational and emotional outcomes. The systematic review further emphasizes the importance of integrating AI tools into science education in a pedagogically and ethically sound manner. Recommendations include increasing AI literacy among teachers, incorporating ethical awareness into instruction, and developing culturally sensitive and interdisciplinary educational practices. Generative AI stands out as a transformative technology for improving the quality, accessibility, and inclusivity of science education.

Introduction

Science education is one of the basic disciplines aiming to develop students' critical thinking, problem-solving, and analytical thinking skills. In recent years, with the increasing role of technology in education, it is observed that especially technologies such as generative artificial intelligence tools have started to transform learning processes. When the literature is examined, different approaches and studies in which productive artificial intelligence applications are employed to improve students' learning outcomes stand out (Arslan, 2020; Erkoç & Çolak, 2024; Zengin et al., 2023). Generative Artificial Intelligence (GAI) technologies are increasingly used in the field of education in general and science education in particular and offer the opportunity to apply innovative approaches in educational processes. AI technologies are considered to have significant and great potential in education, especially for increasing the accessibility of learning opportunities, scaling individually customized learning experiences, and optimizing methods and strategies for targeted learning outcomes (Zengin et al., 2023).

Arslan (2020), in his study in which various tools and examples of GAI and the use of artificial intelligence in education are tried to be given as a whole, states that any explanation or any information about artificial intelligence in education will be incomplete. New educational applications based on artificial intelligence will appear tomorrow as they do today with new techniques (Arslan, 2020). Artificial intelligence applications enable students to learn according to their abilities and learning speed is considered the most positive effect of these applications (Vieriu & Petrea, 2025).

In addition to the advantages of using artificial intelligence in education, it is also possible to come across studies that mention its disadvantages. In particular, when the justifications of teachers who do not find the use of artificial intelligence in lessons useful are examined, it is seen that the opinions expressed by them that it reduces creativity is not sufficient, and is unnecessary come to the fore. In addition, it is reported that many teachers today believe that technological applications can reduce students' manual dexterity and creativity (Zawacki-Richter et al., 2019). This belief weakens teachers' tendency to use productive artificial intelligence tools in their lessons (Erkoç & Çolak, 2024).

This study aims to systematically examine the impact of generative artificial intelligence applications on student learning outcomes in science education and to reveal the potential of these technologies in education. It is believed that the results of the study will provide concrete evidence to educators, researchers, and policymakers in the integration of GAI tools into science education.

Theoretical Framework

In the developing technological world, innovations in the field of technology are increasing day by day. This situation also closely concerns and affects education. Artificial intelligence is a very effective field that has been used quite actively recently. It is known that the concept of artificial intelligence was first mentioned in a proposal for the 'A Proposal for the Dartmouth Summer Research Project on Artificial Intelligence' in 1955 (McCarthy et al., 1955). This proposal is based on the premise that every way of learning for artificial intelligence or other features of intelligence can be defined so clearly that it can be realized by a machine (Eral, 2024). The integration and utilization of generative artificial intelligence (GAI) applications in science education show significant potential for enhancing students' learning outcomes. Recent research indicates that GAI tools can improve teaching practices, assessment strategies, and student engagement in science-related subjects (Holmes, Bialik, & Fadel, 2019; Zawacki-Richter et al., 2019). By enabling the personalization of learning experiences and fostering higher levels of student interaction, GAI applications contribute meaningfully to academic success (Luckin et al., 2016).

Intelligent tutoring systems and adaptive learning platforms offer tailored educational content that addresses individual learning needs, thereby creating more effective learning environments (Woolf, 2010). Furthermore, GAI technologies have the capacity to analyze student performance data, identify patterns in strengths and weaknesses, and design customized learning pathways that accommodate diverse learning styles (Chen et al., 2020). Intelligent tutoring systems provide real-time feedback that helps students gain a deeper understanding of concepts and instantly correct misconceptions (Good, 1987). In addition, generative artificial intelligence applications, including virtual reality simulations, provide more active learning experiences by increasing students' interest and motivation in science subjects. The use of interactive learning tools encourages active participation by making science education more dynamic and fun.

Studies in the literature demonstrate that the use of GAI based methods in science education offers significant advantages over more traditional teaching approaches (Zawacki-Richter et al., 2019; Chen et al., 2020). These advantages are largely rooted in pedagogical principles that emphasize student-centered learning, where learners are actively involved in constructing their own understanding. For example, Luckin et al. (2016) argue that GAI technologies enable personalized and interactive learning environments that empower students to take ownership of their learning processes. Similarly, Holmes and colleagues (2019) highlight that GAI tools promote inquiry-based and participatory learning models, which align with modern constructivist educational frameworks. The pedagogical possibilities offered by GAI are orientated towards achieving significant learning in students and encourage the visual component, which can take different forms such as simulations, VR, AR, or games. (García-Martínez et al., 2023). Research shows that different generative AI methods not only affect the quantity of students' learning but also lead to higher levels of motivation, which is indicated by a desire to be more engaged in their learning (Holmes et al., 2019; Chen et al., 2020). At the same time, most studies on generative AI have been shown to become more meaningful in STEM knowledge domains, which require higher levels of abstraction and greater complexity in order to accurately understand the information (Luckin et al., 2016; Zawacki-Richter et al., 2019). GAI not only helps students to focus while building things but also encourages their creative ability to shape their thinking (Barak & Zadok, 2009). Similarly, several studies have shown the effectiveness of AI tools in education (Fabregas et al., 2016). Moreover, many educational institutions around the world actively implement the STEM (Science, Technology, Engineering, and Mathematics) teaching methodology to equip students with 21st-century skills such as critical thinking, problem-solving, and technological literacy. Prominent examples include the Massachusetts Institute of Technology (MIT) in the United States, which integrates interdisciplinary STEM education with cutting-edge research; the Imperial College London in the United Kingdom, known for its emphasis on engineering and science innovation; and Tsinghua University in China, which offers comprehensive STEM programs with a strong focus on artificial intelligence and robotics. These institutions serve as global models in promoting inquiry-based learning, interdisciplinary collaboration, and the integration of advanced technologies into education (Bybee, 2013; Marginson et al., 2013). This methodology is characterized by using a set of new and up-to-date tools for teaching different school subjects. This allows the design and development of a computational model based on learning and teaching conditions controlled over any subject with high visual and multimedia content, facilitating the acquisition and understanding of contents through ongoing interaction with the computer (Vlachopoulos & Makri, 2017).

Different studies on the use of artificial intelligence show that the potential of generative AI on student performance is addressed through applications, simulations, VR, and AR. Regarding applications, the literature shows that their use in education is becoming increasingly common at all levels (Wirjawan et al., 2020). Given their high impact on students, generative AI needs to be effectively utilized in education. Applications vary according to the subject area and the educational level of the student. Some applications allow the user to interact

with the environment, use questions and answers, find some items, find directions, watch tutorial videos, create a portfolio, learn mathematics, play video games, and even give smart lessons (Holmes et al., 2019; Chen et al., 2020; Zawacki-Richter et al., 2019). For instance, applications such as Khan Academy and Socratic use AI to support mathematics learning and problem-solving; Minecraft: Education Edition promotes interactive exploration and game-based learning; and platforms like Duolingo and Quizlet incorporate smart lesson delivery and question-answer interaction to personalize language and content learning (Luckin et al., 2016). Similarly, studies are focusing on the use of some applications at any educational stage (Dunleavy et al., 2019). Moreover, apps tend to be used more frequently by teachers because they require higher levels of literacy and are more accessible (Gao et al., 2021). In addition, there are also studies in which different applications were used with people with autism or people with attention deficit hyperactivity disorder (García-Martínez et al., 2023). This means that this type of artificial intelligence is easier to apply in the design, adjustment, and development of teaching processes for students with special educational needs (García-Martínez et al., 2023). Moreover, in terms of simulations, generative AI offers a variety of scenarios in which students can explore, play games, or solve everyday problems by applying what they have learned to progress at different levels. Its easy accessibility, individualization potential, and low cost are said to be some of the benefits that encourage its widespread use in education (García-Martínez et al., 2023).

GAI allows us to understand complex concepts in subjects categorized as 'difficult' to strengthen and improve students' attitudes towards the subject and, in some cases, to create collaboration strategies among students (Holmes et al., 2019; Chen et al., 2020). Similarly, research using simulations as an AI, augmented reality, and virtual reality module is oriented towards providing students with more real learning situations and shows an effectiveness similar to that in real laboratories (Radianti et al., 2020; Makransky & Mayer, 2022). These experiences allow students to interact with the external environment in the classroom (García-Martínez et al., 2023). In addition, the use of virtual reality in education enables students to interpret signs, whether visual, auditory, or tactile and to construct their knowledge through their movements and interactions with their environment (García-Martínez et al., 2023). To put this technology into practice at school, teachers need to experiment with using generative artificial intelligence, learn how to use it, and then connect the content to the student's environment (Tondeur et al., 2017).

In higher education, university studies in medicine or nursing involve the use of VR to perform surgeries and treatments (Baxter & Hainey, 2019). In the field of science education, a wide range of technologies including Web 2.0 tools, robotics applications, simulations, virtual reality environments, virtual laboratories, digital game-based learning, and various GAI applications are extensively utilized to enrich the learning process (Zawacki-Richter et al., 2019; Holmes et al., 2019). These GAI-driven tools enable students to better grasp abstract concepts, understand content through hands-on experimentation and inquiry, engage in creative design processes, and participate actively in their own learning (Chen et al., 2020; Luckin et al., 2016). Such outcomes represent just a few of the numerous educational advantages that generative artificial intelligence brings to contemporary science education. Although there are many more benefits, the use of productive artificial intelligence in science education should be encouraged. Since artificial intelligence, which enters our lives with the developing technology, has many benefits, its use in education will be very beneficial for students and teachers. Therefore, artificial intelligence should be included in education. It is important to determine whether this technology, which is still new, is included in education, how it is used, how it is used by students, how teachers' competencies in this subject are determined, and whether it is integrated into lessons.

Purpose and Significance of the Study

GAI can perform cognitive processes of human intelligence such as language processing, problem-solving, reasoning, and learning with computer algorithms. Chatbots, which are part of productive artificial intelligence, can respond as if a natural human is being in front of them. Today, the most widely used chatbots are as follows (Basaran & Ozenc- Yesilbas, 2024), ChatGPT, Gemini, and Copilot. The common basic feature of these chatbots is to give informative answers. In addition to giving informative answers, it supports the personal development of individuals and helps the professional life of content producers by having features such as producing creative content, creating visual materials, writing different types of text, programming, and coding (Basaran & Ozenc-Yesilbas, 2024). GAI tools are also used in the field of education and are said to have the potential to be a powerful tool in the field of education (Baidoo-Anu & Owusu -Ansah, 2023; Ucar, 2023).

Chatbots have applications such as individualized education, automatic trial scorer, language translation, interactive learning, and adaptive learning to support learning (Baidoo-Anu & Owusu- Ansah, 2023; Gürlek et al., 2023). With the individualized education feature, educational plans can be tailored to students' needs, age,

and cognitive development, allowing for more personalized and effective learning experiences (Luckin et al., 2016; Chen et al., 2020; Vieriu & Petrea, 2025). The automatic essay scorer is a valuable tool that assists teachers in evaluating students' written work efficiently and consistently (Shermis & Burstein, 2013; Uyar & Buyukahiska, 2025). Additionally, chatbots equipped with information delivery functions provide an interactive learning environment by simulating the presence of a virtual instructor, which enhances learner engagement and accessibility (Winkler & Sollner, 2018). Education can also be continuously adapted based on students' progress and the results of formative assessment and evaluation processes, fostering a more responsive and student-centered learning model (Holmes, et al., 2019). These contributions of productive artificial intelligence in the learning and teaching process tend to increase learning outcomes (Dargut- Guler, 2024).

Studies on the effects of artificial intelligence applications on education in the literature say that individuals in the learning process perform deep learning, provide structuring information, and learners have enough knowledge to express themselves and thus increase learning outcomes (Afzaal et al., 2024; Akbulut et al., 2024; Chen et al., 2020). In studies on the use of productive artificial intelligence tools in science courses, the use of chatbot ChatGPT is encountered (Cooper, 2023; Ergun, 2023). Cooper (2023) and Ergun (2023) had a positive approach toward the use of ChatGPT in science education, as there were a wide variety of scenarios, activities, and examples in the science lesson plan with the 5E teaching model prepared by ChatGPT.

When the literature is analyzed, it is seen that the reflections of generative artificial intelligence in education are widely used. However, it is seen that the number of artificial intelligence application examples that can be used in different educational fields (such as science teaching) is low (Incemen & Ozturk, 2024). The fact that chatbots support learning by answering the questions of the learners, explaining, exemplifying, and shaping according to the level and needs of the learner has led to the need to examine the effect of productive artificial intelligence on students' learning outcomes in science education. This study aims to evaluate the effect of generative artificial intelligence on students' learning outcomes in science education through a meta-analysis study. The problem statement of the research was determined as 'What is the effect of productive artificial intelligence applications on students' learning outcomes in secondary school science education?

Method

Systematic literature review (SLR) is defined as the process of comprehensively reviewing all published studies on a specific topic, determining which studies will be included in the research according to the specified criteria, and then synthesizing the findings of these studies and proposing a solution to an existing problem (Davis et al., 2014). This method also aims to make a detailed evaluation by accessing a wide range of scientific resources related to a specific research question or subject area and to shed light on future research by revealing the gaps in the literature (Kitchenham et al., 2009).

Systematic literature review is the process of examining the studies in the literature in a comprehensive, objective, and reproducible manner in line with predefined criteria to find an answer to a specific research question. This method not only selects relevant studies but also synthesizes the data from these studies to provide a structured and scientific answer to the research question (Booth et al., 2016). Systematic reviews include five basic steps: (1) firstly, the research question should be clearly defined, (2) databases and keywords suitable for the research should be identified, (3) after the database is identified, inclusion and exclusion criteria should be established, (4) the literature should be reviewed and analyzed according to the selected criteria, (5) finally, the findings should be reported in a structured manner (Gough et al., 2017).

Systematic literature review is widely used especially in health sciences, education, psychology, and social sciences. This is because systematic reviews enable knowledge-based decisions to be made in the field of research by presenting the existing body of knowledge in a transparent and unbiased manner (Liberati et al., 2009). A systematic literature review compiles and summarizes the existing scientific evidence in the literature through a comprehensive literature review. SLR allows researchers to examine previous research and serves as a basis for developing new research questions (Liberati et al., 2009). SLR can guide future research by pointing out existing research gaps and weaknesses on a particular topic (Dixon-Woods et al., 2006). By focusing on gaps in the literature, researchers can identify areas that require further research and contribute significantly.

Systematic literature reviews combine the results of various studies to produce results that can be widely applied. These results can be statistically combined using techniques such as meta-analysis (Borenstein et al., 2009). This makes it easier to determine whether the findings of many studies are consistent or contradictory. SLT makes it possible to examine many research techniques and strategies that can be used to determine which approaches can

have an impact on research findings and which techniques are more successful (Higgins & Green, 2011). One of the most reliable methods of obtaining accurate and reliable information is a systematic literature review. Decision-makers should base their choices on accurate data and information, especially in critical areas such as social sciences, health, and education. As a result, SLT facilitates decision-making (Pope et al., 2007). New and important research questions can be developed by identifying gaps in the existing body of knowledge. A systematic literature review not only reveals the existing body of knowledge but also paves the way for creative research (Torraco, 2005).

Screening Process

Web of Science (WoS) [Social Science Citation Index (SSCI), Emerging Science Citation Index (ESCI)], Elsevier [Scopus], ERIC, and TRDizin electronic databases and indexes were used in the systematic literature review to determine the effect of generative artificial intelligence applications on students' learning outcomes in science education. The keywords 'science', 'science education', 'generative artificial intelligence', 'GenAI', 'artificial intelligence', 'AI', 'secondary school', 'interest', 'motivation', 'attitude', "achievement" and 'learning outcome' were used in the searches made through databases. Different combinations of keywords were reached by using Boolean operators AND and OR. In the scans made with keywords, studies related to computer science education, science teachers, and prospective teachers were found. These studies were not included in the search by using the NOT Boolean operator.

Selection Process

The studies that were related to the effects of artificial intelligence applications on students' outcomes in science education were included in the selection process. Firstly, in this process, the studies whose full text could not be accessed from a university network were eliminated. Then, the publication languages of the studies other than Turkish and English were excluded from the study. In the systematic literature review, studies presented as articles and papers were included. Since the frequency of use of artificial intelligence tools in education has increased as of 2020, those published from 2020 to the present have been included. As a result of these eliminations, the titles of the remaining studies were examined first. Studies with computer science education in the title of the studies that did not include science education were excluded from the selection. While examining the abstracts of the remaining studies in detail, it was paid attention that the method of the studies was experimental and quasi-experimental. By going to the full text of the studies that did not provide information about the method used in the research in the abstract, studies that were not experimental and quasi-experimental in the method section were not included. In the studies examining the effect of artificial intelligence applications in science education, it is among the selection criteria that the research group should be secondary school students. The studies conducted with 5th, 6th, 7th, 8th, and 9th grade students were included. The inclusion and exclusion criteria are presented in Table 1.

Table 1. Inclusion and exclusion criteria

Inclusion Criteria	***Exclusion Criteria***
● Experimental and quasi-experimental research	● Qualitative, review and compilation studies
● Research written in Turkish and English	● Research written in languages other than Turkish and English
● Article, conference paper	● Books, book chapters, letters
● 3rd - 8th grade students	● K -2 / high school / college students
● Research conducted in the last 5 years	● Research older than 5 years
● Full text is accessible from a university network	● Full text is not accessible from a university network

In the selection process, 15 studies on the effect of artificial intelligence on students' learning outcomes in science education were reached by considering the criteria of publication language, publication date, being in the field of science education, method, and grade level of the participants. Each of these studies was read carefully and the results were noted. Findings from 15 studies were classified according to academic achievement, science literacy, nature of science, learning opportunity, multiculturalism, inclusiveness, interdisciplinarity, individual learning, participation, interest, motivation, self-efficacy, and opinion codes. PRISMA protocol was applied in the selection of the studies included in the study. PRISMA protocol is presented in Figure 1. After the implementation of the PRISMA protocol, 12 studies were included in the study. The included studies are presented in Table 2.

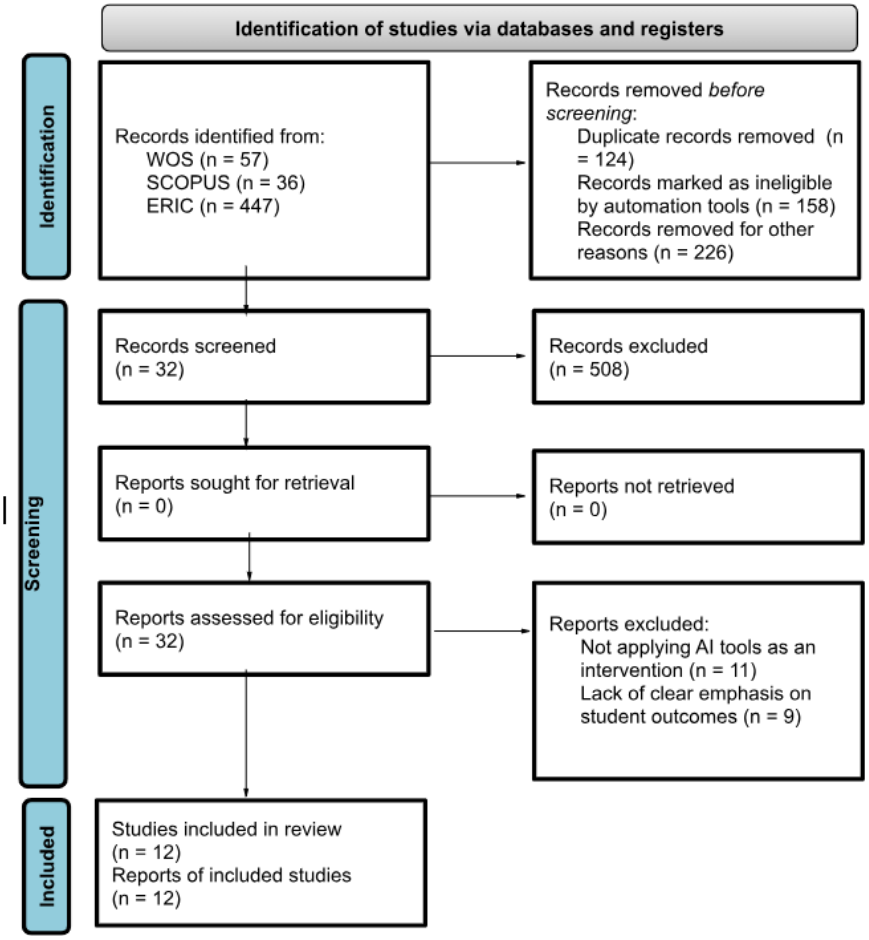

Figure 1. PRISMA flowchart of the study

Table 2. The research analyzed in this study

Study	Intervention	Method	Participants
Deveci -Topal et al. (2021)	Chatbot based learning	Pre-test post-test quasi-experimental design	N = 41, 5. Grade
Chang (2023)	Chatbot in scientific inquiry	Design–based research	N = 18, 6, 7 grades
Ding (2023)	VR-enhanced science learning	Pre-test post-test quasi-experimental design	N=66, 7, 8. grade
Kahila et al. (2023)	AI education	Pre-test post-test quasi-experimental design	N = 213, 4, 7 grades
Lee et al. (2023)	Learning through Rule-based AI Chatbot	Quasi-experimental design with pre-test post-test control group	N = 192, 6. Grade
Mativo et al. (2023) and	Image STEAM workshop	Pre-test post-test quasi-experimental design	N = 116, 6 -8 grade
Ates (2024)	AR with an Intelligent tutoring system	Pre-test post-test quasi-experimental design	N = 58, 8. Grade
Chen and Chang (2024)	AI-assisted game-based learning in science education	Pre-test post-test quasi-experimental design	N = 202, 7. grade
Chen and Liu (2024)	AI robot image recognition technology in science learning	Pre-test post-test quasi-experimental design	N = 81, 7. grade
Cheung et al. (2024)	ChatGPT-generated socio-scientific texts in science learning	Pre-test post-test quasi-experimental design	N= 117, 8, 9. grade
Simbolon et al. (2024)	AI-Driven sociocultural interactive model in science learning	Mixed - method	N = 200, middle school
Wei et al. (2025)	GPA-enhanced 5E model within AR environments	Quasi-experimental design with pre-test post-test control group	N = 60, 6. Grade

Findings

The findings of the studies included in this study were analyzed under the titles of academic achievement, literacy skills, opportunity to learn, and affective characteristics.

Academic Achievement

Studies in the literature on the effects of artificial intelligence applications on student outcomes in science education reveal that these technologies make positive contributions in various dimensions. The use of artificial intelligence-based tools can increase students' academic achievement (Wei et al., 2025), and especially in experimental groups where AI robot image recognition technology is used, higher success is observed in understanding cell applications compared to control groups (Chen et al., 2024). In addition, students who worked with AI-supported game examples such as Game GPT performed significantly better than students who only played traditional games (Chen et al., 2024). In students with low academic levels, AI-supported applications increase the level of interest in learning (Lee et al., 2023), and students begin to see themselves as more competent, more knowledgeable in scientific concepts, and more aware individuals in STEM fields (Ramana et al., 2023). In the studies on chatbot-supported science education, although there were significant differences between the pre-test and post-test achievements of students, it was also stated that this method did not show a significant superiority compared to traditional education methods (Deveci -Topal et al., 2021). These findings emphasize the potential of artificial intelligence applications to improve students' cognitive, affective, and academic outcomes.

Recent studies examining the impact of artificial intelligence (AI) applications on student outcomes in science education indicate that these technologies make significant contributions to learning processes. In a study conducted by Chen et al. (2024), it was found that students who participated only in traditional game-based activities reported higher levels of mental fatigue compared to those who used AI-supported applications such as GameGPT. This finding highlights the potential of AI-based systems to reduce cognitive load. Similarly, Wei et al. (2025) revealed that students' Grade Point Average (GPA), which reflects their overall academic performance, had a significant effect on cognitive load. These findings suggest that AI-supported science education applications can enhance the efficiency of the learning process and help students utilize their cognitive resources more effectively. Recent literature further demonstrates that AI technologies in science education have positive effects on conceptual development and levels of understanding. For example, in a study conducted by Chen (2024), AI-assisted instructional practices were reported to facilitate students' transitions from misconceptions to scientific concepts—particularly in the context of meiosis—more effectively than in the control group. Similarly, Ding (2023) emphasized that the visual and interactive features provided by virtual reality (VR) technology ease the comprehension of scientific concepts among multilingual students. Lee et al. (2023) also reported significant improvements in students' understanding of scientific concepts following the use of rule-based chatbot systems in science lessons. These findings illustrate that AI technologies function as powerful tools in supporting conceptual understanding and interactive learning within the context of science education.

Literacy Skills

Findings regarding the impact of AI tools on student outcomes in science education reveal that these technologies have the potential to enhance various dimensions of scientific literacy. In a study by Cheung et al. (2024), which examined students' engagement with AI-supported learning tasks (further details about the study design should be specified), it was found that students perceived content interpretation as the most accessible task, while epistemic evaluation—such as questioning and assessing scientific claims—was experienced as the most challenging. The same study reported that, following a reading-to-learn science intervention, students demonstrated more advanced and tentative views regarding the nature of science. However, only a small number of students were observed to critically evaluate claims related to climate change made by an AI tool like ChatGPT, questioning both the reliability and the non-epistemic nature of such tools. On the other hand, Simbolon et al. (2024) demonstrated that AI-supported, socio-culturally grounded Interactive Digital Modules (IDMs) significantly improved scientific literacy among middle school students in Papua. This study also emphasized that digital educational tools can contribute to the achievement of Sustainable Development Goals (SDGs) by supporting quality education, particularly in under-resourced regions. These findings suggest that AI applications can impact not only conceptual understanding but also higher-order skills such as critical thinking and scientific inquiry, thereby serving as powerful tools for fostering comprehensive scientific literacy.

Opportunity to Learn

AI-supported applications have been found to offer multifaceted contributions to science education for both students and teachers. Chang (2023) demonstrated that the AI-based conversational agent Inquiry Bot enhanced students' inquiry skills by enabling them to engage in more structured learning processes. Through reviewing their chat histories, students were able to reflect on their previous lines of reasoning, thereby reinforcing their learning. Simultaneously, teachers were able to analyze students' thought processes and monitor their learning progression via the chat transcripts, which allowed for targeted guidance within digital environments. Ding's (2023) study further revealed that multisensory content can make learning more accessible and effective. In particular, VR-supported activities enabled students to learn both scientific language and content simultaneously—an advantage that proved especially beneficial for students with low English proficiency in grasping scientific terminology. These findings highlight the potential of AI and VR technologies to create personalized and interactive learning environments that cater to diverse learner profiles.

The integration of AI applications into science education has also been shown to significantly support the development of students' cognitive and critical thinking skills. In a similar vein, Kahila et al. (2023) emphasized the critical role of co-design processes between researchers and teachers in developing innovative learning environments and applications for machine learning (ML). In the initial workshop, which was grounded in knowledge production and design-based pedagogy, students were encouraged to connect their interests and everyday experiences with classroom discourse and learning materials. This approach facilitated a deeper conceptual understanding of ML among students. Collectively, these findings suggest that AI-based applications not only enhance cognitive development but also foster technological awareness in science education settings.

The role of AI-supported applications in education is becoming increasingly diverse and profound. Simbolon et al. (2024) emphasized that adapting AI-powered Interactive Digital Modules (IDMs) to different regions facing similar educational challenges can contribute to reducing global educational inequalities by enabling more inclusive and culturally responsive learning experiences. This finding suggests that technological tools are not merely facilitators of information transmission but also hold the potential to provide learning environments that are attentive to cultural diversity. Accordingly, AI-supported learning environments can create transformative impacts not only at the pedagogical level but also at societal and cultural levels. Studies investigating the impact of AI-based applications on learning outcomes in science education underscore the importance of inclusivity and cultural diversity in shaping educational experiences.

Simbolon et al. (2024) highlighted that the implementation of AI-supported IDMs in diverse contexts can foster inclusive and culturally sensitive learning environments on a global scale, particularly in under-resourced regions. This approach points to the potential of digital technologies to equalize learning opportunities and close global educational gaps by offering tailored learning experiences that respond to local needs. Thanks to their capacity to adapt learning processes to individual needs, AI-powered IDMs not only enhance pedagogical effectiveness but also promote the universal accessibility of education by demonstrating sensitivity to cultural contexts. Additionally, studies exploring the effects of AI-based applications on learning outcomes in science education emphasize the significance of individualized learning. In a study conducted by Chang (2023), the AI-supported learning tool Inquirybot was shown to allow students to progress at their own pace and engage in personalized, inquiry-based learning processes. By encouraging students to deeply explore topics of personal interest and construct their learning paths, the system amplified the impact of inquiry-based learning. Thus, Inquirybot serves as a compelling example of how AI-supported learning environments can strengthen student-centered and self-regulated pedagogies in science education.

Affective Characteristics

Studies investigating the effects of AI-based applications on learning outcomes in science education have shown that these technologies play a significant role in enhancing students' interest and engagement in the subject. For instance, in a study conducted by Ateş (2024), the integration of Intelligent Tutoring Systems supported by Augmented Reality (ITS-AR) into eighth-grade science classes led to a notable increase in student participation levels. This finding indicates that AI-supported instructional tools not only offer opportunities for personalized learning but also contribute to students becoming more actively and motivationally involved in the learning process. Research findings further suggest that AI-based technologies hold considerable potential to increase student interest, participation, and motivation in science education. Virtual reality-based learning environments have been shown to foster active classroom engagement (Ding, 2023), and even students with relatively lower academic performance have demonstrated greater interest in science classes when supported by AI-driven

instructional applications (Lee et al., 2023). These findings suggest that integrating AI applications into science education can serve as a powerful means of creating more inclusive and interactive learning environments, thereby enhancing the overall quality of learning outcomes.

Findings in the literature on the impact of artificial intelligence (AI) applications on learning outcomes in science education reveal that these technologies significantly enhance student motivation and engagement. In a study conducted by Yu Chen (2024), a notable increase in motivation was observed among students in the experimental group participating in AI-supported science learning. Similarly, Ding (2023) reported that students using AI technologies in both individual and group activities demonstrated greater willingness and interactivity. In addition, the Intelligent Tutoring System–Augmented Reality (ITS-AR) developed by Ates (2024) was found to be effective in enhancing students' motivation toward science education. These findings suggest that AI-based applications positively support student participation and learning processes in science education.

Research on the effects of AI-supported applications on learning outcomes in science education also indicates that these technologies contribute to increases in students' perceived competence and self-efficacy levels. In a study by Ching-Huei Chen et al. (2024), students in the GameGPT group reported higher levels of perceived competence compared to those who only participated in traditional game-based activities. Likewise, the ITS-AR system developed by Ateş (2024) was found to have a positive effect on students' self-efficacy perceptions. These findings highlight the important role that AI-based learning environments play in strengthening students' confidence and beliefs in their academic capabilities. The impact of AI applications in science education extends beyond academic achievement to include transformative changes in students' professional perceptions. In a study by Ramana et al. (2023), it was found that students who participated in AI-supported workshops developed more active perceptions of artists and revised their views of coders and engineers. The same study also revealed that students tended to feel a stronger identification with scientists after participating in these workshops. Furthermore, Wei et al. (2025) reported that students developed positive perceptions of Extended Reality (XR)-based applications. These findings suggest that AI-based educational applications positively influence students' professional identity development and their attitudes toward technology.

Discussion

In this study, the multidimensional effects of generative artificial intelligence (GAI) applications on students' learning outcomes in science education were examined, and significant findings consistent with the existing literature were obtained. The results demonstrate that GAI technologies contribute not only to academic achievement but also to conceptual understanding, science and technology literacy, personalized learning, affective engagement, and professional identity development. Firstly, the findings related to academic achievement align with studies such as those by Zengin et al. (2023) and Chen et al. (2024). AI-supported instructional environments were reported to facilitate students' conceptual understanding and to yield higher levels of achievement, particularly in complex biological processes (e.g., cell division), compared to traditional methods. Similarly, the potential of immediate feedback during instruction to enhance student performance, as emphasized by Good (1987), has become more accessible through AI-based intelligent tutoring systems. In terms of science literacy and critical thinking skills, the studies conducted by Cheung et al. (2024) revealed that students not only gained access to scientific information but also improved their abilities to question and interpret that information. These findings support the "self-regulated and critical learning environments" approach advocated by García-Martínez et al. (2023), indicating that GAI provides cognitively rich learning contexts. With regard to diversified learning opportunities, applications such as Inquiry Bot were reported by Chang (2023) and Kahila et al. (2023) to enable students to construct their learning paths, thereby supporting personalized learning experiences. These tools accommodate different learning styles and individual needs, enabling pedagogical differentiation and, in turn, promoting inclusivity in education.

In terms of affective outcomes, the development of positive attitudes and increased motivation levels among students toward AI-supported applications is supported by studies such as Ateş (2024), Lee et al. (2023), and Barak & Zadok (2009). These findings highlight the significant role that AI-based technologies can play in sustaining student interest—particularly in STEM fields—and in supporting the development of scientific identity. The observed increase in students' self-efficacy, in particular, suggests that these technologies may also enhance students' academic self-esteem (Chen et al., 2024). However, as the literature also indicates (Erkoç & Çolak, 2024), teachers' attitudes toward AI technologies and their lack of pedagogical integration skills may pose barriers to the effective use of AI in educational settings. Moreover, the pedagogical design and ethical implementation of such applications are among the key factors determining whether teachers are able to successfully integrate technology into classroom environments (Tondeur et al., 2017). In conclusion, the findings of this study

demonstrate that GAI applications contribute meaningfully to science education processes on structural, pedagogical, and cognitive levels. These results are consistent with current literature and underscore the importance of integrating such technologies into educational environments in an effective, inclusive, and ethically sound manner.

Conclusion

This systematic literature review presents important findings by examining the effects of generative artificial intelligence (GAI) applications on the learning outcomes of middle school students in science education from a multidimensional perspective. In line with the existing literature, the study shows that GAI technologies have a positive impact not only on academic achievement, but also on conceptual learning, scientific and digital literacy, opportunities for personalized learning, affective engagement, and professional attitudes. The main conclusions drawn from the research can be summarized as follows:

- Academic achievement increases significantly in AI-based learning environments.
- Conceptual understanding and scientific thinking skills are strengthened.
- Science and technology literacy develop with AI.
- Learning opportunities increase and become more individualized.
- Affective development and self-efficacy are supported.

As a result, GAI applications are considered powerful tools that strengthen both the cognitive and affective aspects of science education and respond to the digital educational needs of the age.

Recommendations

The following recommendations can be developed in line with these findings:

- Teachers' AI literacy should be increased and professional development should be supported.
- Ethical awareness should be integrated into educational content.
- Interdisciplinary and culturally sensitive designs should be prioritized.
- Future research should examine the impact of AI in the long term and various contexts.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in JESEH journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

Funding

No funding support was received

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APPENDICES

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