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# Integration of Artificial Intelligence to Support Inquiry-Based Science Teaching and Learning: A Systematic Literature Review

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**Abstract**

The integration of artificial intelligence (AI) applications into science education can serve as an effective teaching aid to develop 21st-century skills among science students. The use of AI in science education is driven by the need to enhance student engagement, personalised learning, and address persistent conceptual misunderstandings.This study aims to review the strategies employed by teachers in conducting AI-assisted teaching and learning in science education to provide authentic learning experiences while fostering skills such as creativity, collaboration, communication, and critical thinking among primary and secondary school students worldwide. This literature review follows the PRISMA model, analysing 20 articles to address the research questions. The selected articles focus on empirical studies published between 2019 and 2024, sourced from databases such as Scopus, Web of Science (WoS), and ERIC. The findings indicate that AI has the potential to enhance digital-assisted science learning without disregarding the concept of inquiry-based learning, which forms the foundation of modern science education.

**Keywords:** Inquiry, Science Education, Artificial Intelligence, 21st Century Skills, Digital Learning

## Introduction

Inquiry-based science teaching and learning is a modern approach that has been proven effective in enhancing student engagement through authentic learning experiences. Compared to traditional science classrooms, inquiry-based science teaching and learning (T&L) is characterised by questioning scientific phenomena and constructing knowledge to answer these questions through meaningful activities (Grangeat, 2016). Students enganged in inquiry-based science learning are not merely passive consumers of information; rather, they actively engage in the process of knowledge construction, collaborate with peers, immerse themselves in scientific topics, and refine their critical thinking and problem-solving skills(Williams et al., 2017).

Teachers play a crucial role in inquiry-based science education as facilitators, assessors, providers, and flexible leaders in creating a stimulating learning environment that encourages inquiry skills and a deeper understanding of scientific concepts (Constantinou, Tsivitanidou, and Rybska 2018). Despite the widespread integration of digital tools in science teaching and learning today, the framework of inquiry-based science education must remain the primary approach for science educators in managing classrooms to nurture the next generation with a high level of scientific literacy.

The Digital Education Policy (DEP) launched by the Ministry of Education Malaysia (MOE) in 2023 aims to develop a digitally literate society (MOE, 2023). Correspondingly, the MOE has planned various initiatives to achieve the goal of fostering digitally fluent students in response to the challenges of the Fourth Industrial Revolution (4IR). For instance, the continuous upgrade of DELiMa (Digital Educational Learning Initiative Malaysia) platform aligns with thrust five of DEP which aims to provide quality digital content to enhance digital teaching and learning experience. Furthermore, programmes such as Gemini Academy , Experience AI , Apple Learning Coach to enhance teachers' digital and AI competencies shows the implementation of strategic collaboration between MOE and leading technology providers such as Google and Apple to ensure the success of national digital education agenda(MOE, 2024b, 2024a). Thus, teaching and learning in classrooms can no longer overlook technological elements as instructional and facilitation tools.

One of the latest and fastest-growing branches of digital technology in education is the use of Artificial Intelligence (AI). In general, the benefits of AI in education include enhancing personalised learning by adapting content to students' abilities, automating tasks such as grading and scheduling, and providing access to learning without geographical or language barriers (Ketak et al., 2024; Radif, 2024; Ružičić, 2024).

In the context of science education, AI has the potential to improve student achievement and scientific literacy through authentic science learning. For example, AI-assisted virtual lab programmes such as *Labster* offer interactive virtual science experiment experiences where students can explore scientific concepts by directly manipulating variables, obtaining data observations, and receiving real-time feedback (Yılmaz, 2024). This can enhance students' focus and enthusiasm for scientific exploration. Additionally, the use of AI-powered chatbots such as *Socratic* and *SciNote*, which are specialised conversational agents for science topics, can drive the inquiry process by instantly answering students' questions according to their learning levels, thereby enhancing personalised learning. In terms of assessment, intelligent tutoring systems can provide immediate feedback, potentially reducing misconceptions in challenging science concepts (Lin et al., 2023; Yılmaz, 2024).

Based on the abovementioned studies, it is evident that AI can strengthen science teachers' pedagogy, making teaching and learning more effective. Therefore, this systematic literature review explores the role of AI in supporting inquiry-based science teaching. The study examines previous empirical research that demonstrates how AI elements are integrated into science teaching and learning based on an inquiry-based instructional framework.

*Purpose of Study*

The purpose of this study is to assess the impact of integrating artificial intelligence into inquiry-based science classrooms in terms of authentic science experiences and the development of 21st-century skills. The characteristics of authentic inquiry-based science learning refer to a learning approach that mirrors the actual scientific methods practised by scientists. Students who actively participate in real-world scientific practices such as formulating questions, designing experiments, making observations, analysing data, drawing conclusions, and sharing findings, as real scientists do, are considered to be experiencing authentic science learning (Burgin, 2020; Magee & Meier, 2011) . This means that students actively engage in exploring questions, forming hypotheses, collecting and analysing data, and developing conclusions based on the evidence obtained (Chinn & Malhotra, 2002).

Furthermore, inquiry-based science learning has been proven to support the development of 21st-century skills among students, such as critical thinking, problem-solving, collaboration, and communication (Barell, 2012; Ješková et al., 2022) . Therefore, this study examines how artificial intelligence in inquiry-based science teaching and learning can achieve both of these objectives, serving as a reference for science teachers in planning meaningful science instruction.

*Research Questions*

The formulation of the research questions in this study is based on the PICo model, an acronym where “P” stands for “Population” or “Problem,” “I” represents “Interest,” and “Co” refers to “Context” (Lockwood et al., 2015; Mohamed Shaffril et al., 2021).These three elements were carefully examined to derive the research questions.

The findings identified the "Population" element in this study as "AI-based teaching and learning," the "Interest" or main focus as "How can AI be integrated through inquiry-based learning?" and the "Context" as science education within primary and secondary schools (K-12). Consequently, the researcher developed these identified elements into the primary research question:
How can AI integration support inquiry-based science teaching and learning? Subsequently, the research question was further expanded into more specific inquiries:

1. How can the integration of AI technology provide authentic science learning experiences?
2. How can the integration of AI technology support the development of 21st-century skills among students?

The integration of AI-powered teaching tools into inquiry-based science classrooms holds significant potential for fostering the interest of the current generation students in STEM fields. This, in turn, can contribute to the development of an innovative society driven by science and technology, as envisioned by the nation.

## Methodology

*Research Protocol*

In this section, the method used to obtain articles related to the AI approach in inquiry-based science teaching is discussed. The researcher employed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology for data analysis. The updated version of PRISMA by (Page et al., 2021) was used as a reference for conducting this systematic review, encompassing the processes of identification, screening, eligibility assessment, quality evaluation, and data analysis.

*Identification*

Three databases were referred to for article searches in this literature review study: Scopus, Web of Science (WoS), and ERIC. The search terms used included “artificial intelligence” or “AI”, “science” or “science education” or “science teaching and learning”, and “inquiry” or “inquiry-based”. Additionally, the terms “K-12” or “school” were used to focus the search on school-level studies.

Boolean operators such as “AND” and “OR” were applied for searches in Scopus and WoS. The advanced search function in Scopus and WoS databases was also utilised. Empirical articles selected for this study were published within the last five years, specifically between 2019 and 2024, to ensure a focus on the most recent applications of AI in science education.

*Screening*

The next step is the article screening process. The initial search and preliminary screening identified 2,398 articles from all selected databases. The articles were then examined based on several selection criteria, including document type, language, and subject area. Only articles providing empirical data were selected. Book chapters and systematic literature reviews were excluded. For language criteria, only articles written in English were included. Regarding subject criteria, only pure science subjects such as Integrated Science, Physics, Chemistry, and Biology, as well as integrated STEM fields, were accepted. Subjects such as Computer Science were removed. Additionally, only articles that featured inquiry-based science teaching and learning characteristics were included for analysis. Table 1 presents the article selection criteria, while Figure 1 summarises the search and selection process following the PRISMA model. The final screening resulted in 20 articles that met the criteria for addressing the research questions (Table 2).

Table 1
*Article Selection Criteria*

| Criteria | Eligibility | Exclusion |
|---|---|---|
| Document Type | Article with empirical data | Book, book chapters, Systematic Literature Review (SLR) |
| Language | English | Articles in other than English language |
| Level | K – 12 | Pre – U and University |
| Subject | Integrated Science, Physics, Chemistry, Biology and STEM | Computer Science and other subjects. |
| Year published | 2019 until 2024 | 2018 or earlier |

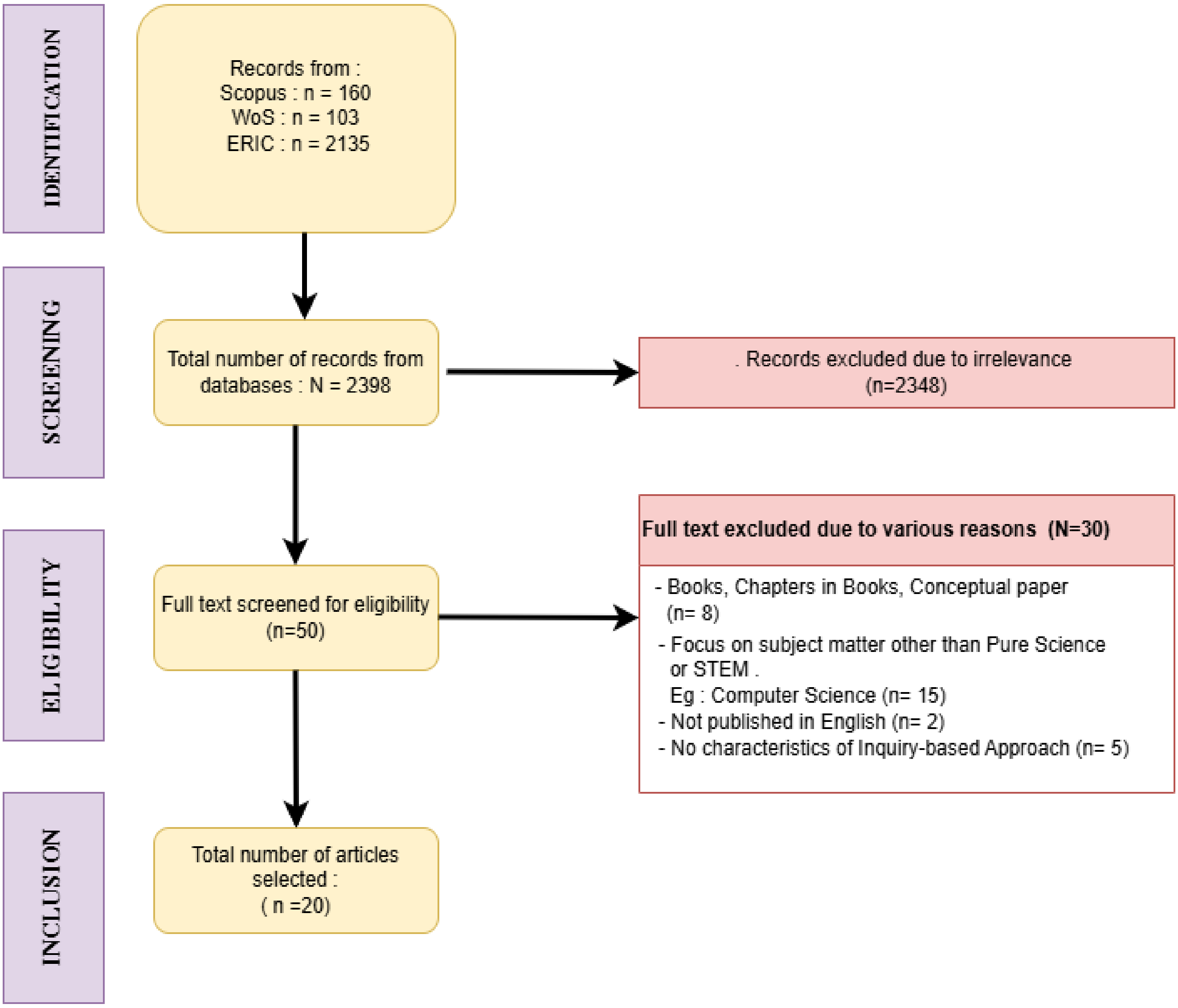


Figure 1 : PRISMA Model Flow Chart
Source : Adapted from PRISMA Model by Page et al. (2021)

*Quality Assessment*

The quality assessment phase for the selected articles involves the application of the Mixed Methods Assessment Tool (MMAT) developed by (Hong et al., 2018), shown in table 3. This assessment instrument is specifically designed to evaluate the quality of studies within systematic literature reviews. After identifying the relevant articles, quality assessment is conducted based on predetermined criteria. The MMAT approach ensures the quality of selected articles by evaluating their research design, whether quantitative, qualitative, or a combination of both (mixed methods), thereby facilitating comparisons between studies. Table 3 shows the result of quality assessment conducted on these articles . Following the application of the MMAT tool, all authors reached a consensus that the chosen papers aligned with the methodological and analytical criteria. A total of 13 papers met all of the evaluation criteria. Additionally, 2 of these papers satisfied a minimum of 4 criteria, whereas 5 publications fulfilled at least 3 criteria, demonstrating fairly significant quality levels. The methodology and analysis of the selected studies consistently adhered to the standards established by the MMAT tool during the quality evaluation process. This comprehensive assessment process underpins the validity and reliability of the findings presented in the mixed-methods systematic review.

Table 2
*List of Selected Articles*

| No | Authors and year | Title of Article | Country of Articles' Origin |
|---|---|---|---|
| 1 | Acislik Çelik & Ergin (2022) | *Opinions of Middle School Students on the Concept of Science and the Use of Robotic Systems* | Turkiye |
| 2 | Billings et al. (2024) | *Using Artificial Intelligence to Support Peer-to-Peer Discussions in Science Classrooms* | USA |
| 3 | Callaghan et al. (2020) | *Discovery: Virtual Implementation of Inquiry-Based Remote Learning for Secondary STEM Students During the COVID-19 Pandemic* | Canada |
| 4 | Chang et al. (2023) | *Using an Artificial Intelligence Chatbot in Scientific Inquiry Focusing on a Guided-Inquiry Activity Using Inquirybot* | Singapore |
| 5 | Chen & Liu (2024) | *Impact of AI Robot Image Recognition Technology on Improving Students' Conceptual Understanding of Cell Division and Science Learning Motivation* | Taiwan |
| 6 | Gupta et al. (2024) | *Supporting Upper Elementary Students in Learning AI Concepts with Story-Driven Game-Based Learning* | USA |
| 7 | Haudek & Zhai (2024) | *Examining the Effect of Assessment Construct Characteristics on Machine Learning Scoring of Scientific Argumentation* | USA |
| 8 | Huang & Qiao (2024) | *Enhancing Computational Thinking Skills Through Artificial Intelligence Education at a STEAM High School* | China |
| 9 | Hsu et al. (2022) | *The Effects on Secondary School Students of Applying Experiential Learning to the Conversational AI Learning Curriculum* | Taiwan |
| 10 | Jeon et al. (2024) | *An Inquiry-Based Artificial Intelligence Curriculum for Upper Elementary Students: A Design Case of PrimaryAI* | USA |
| 11 | Kim (2022) | *AI Integrated Science Teaching Through Facilitating Epistemic Discourse in the Classroom* | South Korea |
| 12 | Kusuma et al. (2023) | *Effectiveness of Artificial Intelligent Independent Learning (AIIL) with Physics Chatbot of Global Warming Concept* | Indonesia |
| 13 | Lee [(a)] et al. (2021) | *AI-Infused Collaborative Inquiry in Upper Elementary School: A Game-Based Learning Approach* | USA |
| 14 | Lee [(b)] et al. (2023) | *Improving Science Conceptual Understanding and Attitudes in Elementary Science Classes Through the Development and Application of a Rule-Based AI Chatbot* | South Korea |
| 15 | Mahroof et al. (2020) | *An AI-based Chatbot to Self-Learn and Self-Assess Performance in Ordinary Level Chemistry* | Sri Lanka |
| 16 | Topal et al. (2021) | *Chatbot Application in a 5th Grade Science Course* | Turkiye |
| 17 | Watters et al. (2021) | *An Artificial Intelligence Tool for Accessible Science Education* | USA |
| 18 | Wu & Tegmark (2019) | *Toward an Artificial Intelligence Physicist for Unsupervised Learning* | USA |
| 19 | Zhai et al. (2022) | *Applying Machine Learning to Automatically Assess Scientific Models* | USA |
| 20 | Zhou et al. (2024) | *Creating an Authoring Tool for K-12 Teachers to Design ML-Supported Scientific Inquiry Learning* | USA |

Table 3
*Results of quality appraisal*

| Authors | Research Design | QA1 | QA2 | QA3 | QA4 | QA5 | Number of criteria fulfilled | Article Inclusion |
|---|---|---|---|---|---|---|---|---|
| Açışlı Çelik & Ergin (2022) | MM | √ | √ | √ | x | √ | 4 | √ |
| Billings et al. (2024) | QL | √ | √ | √ | √ | √ | 5 | √ |
| Callaghan et al. (2020) | QD | √ | x | √ | x | √ | 3 | √ |
| Chang et al. (2023) | MM | √ | √ | √ | √ | √ | 5 | √ |
| Chen & Liu (2024) | QR | √ | √ | √ | √ | x | 4 | √ |
| Gupta et al. (2024) | QL | √ | √ | √ | x | x | 3 | √ |
| Haudek & Zhai (2024) | MM | √ | √ | √ | √ | √ | 5 | √ |
| Hsu et al. (2022) | QC | √ | √ | √ | √ | √ | 5 | √ |
| Huang & Qiao (2024) | MM | √ | √ | √ | √ | √ | 5 | √ |
| Jeon et al. (2024) | QL | √ | √ | √ | x | x | 3 | √ |
| Kim (2022) | QL | √ | √ | √ | √ | √ | 5 | √ |
| Kusuma et al. (2023) | QR | √ | √ | √ | √ | √ | 5 | √ |
| Lee et al. (2021) | MM | √ | √ | √ | √ | √ | 5 | √ |
| Lee et al. (2023) | QR | √ | √ | √ | x | x | 3 | √ |
| Mahroof et al. (2020) | QL | √ | √ | √ | x | x | 3 | √ |
| Topal et al. (2021) | MM | √ | √ | √ | √ | √ | 5 | √ |
| Watters et al. (2021) | QR | √ | √ | √ | √ | √ | 5 | √ |
| Wu & Tegmark (2019) | QL | √ | √ | √ | √ | √ | 5 | √ |
| Zhai et al. (2022) | MM | √ | √ | √ | √ | √ | 5 | √ |
| Zhou et al. (2024) | QL | √ | √ | √ | √ | √ | 5 | √ |

QA= Quality assessment; QN= Quantitative; QL= Qualitative; QD= Quantitative Descriptive; QC= Quantitative randomized controlled trials; QR = Quantitative non-randomized; MM= Mixed Method

The next stage was to extract data from the twenty-one studies that was considered relevant. To ensure the thoroughness of the data collection, a data extraction form was developed in this step to record information from the identified research. The content of each article was thoroughly examined to extract data from each study using Microsoft Excel spreadsheets and record the data for each aspect appropriately. Using the Guidelines for the Extraction of Information and Quality Evaluation of Primary Studies in Educational Research (Evidence for Policy and Practice Information and Co-ordinating Centre (EPPI-Centre, 2003), the necessary data was subsequently extracted in accordance with the research questions raised. Most of the studies that were looked at provided qualitative explanations for their findings, even if several of the selected publications contained quantitative and mixed-method research methodology. The various study methodologies used in the selected studies offer a chance to pinpoint instructional approaches unique to the use of computational thinking in inquiry-based science classrooms. Based on qualitative, quantitative and mixed-method research, the strategies evaluate the effectiveness of some of the methods used to integrate CT in inquiry-setting science classes .Concentrated efforts were made on research that addressed the research questions that were found. To find relevant themes and sub-themes, the abstracts were read through first, followed by the complete articles (in-depth). Content analysis was used in qualitative analysis to find themes connected to how CT facilitates inquiry-based teaching and learning. Moreover, the results of analysis are discussed thematically based on the common aspects identified in these studies.

**Results and Discussion**

*Background of Studies*

Six articles selected used a quantitative research design, seven employed a qualitative approach, and another seven adopted a mixed-method design. The integration of various study contexts and methodologies provided a broader and deeper understanding of the research topic. The United States (USA) emerged as the most active country in studying the application of artificial intelligence in science education, contributing nine out of the 20 studies analyzed. This was followed by South Korea, Taiwan, and Turkey, each with two studies, while Canada, China, Singapore, Sri Lanka, and Indonesia each contributed one study. This trend highlights the growing interest of artificial intelligence applications in science education worldwide. Figure 2 presents a bar graph showing the frequency of different research designs, while Figure 3 illustrates a bar graph depicting the frequency of studies origin by country .

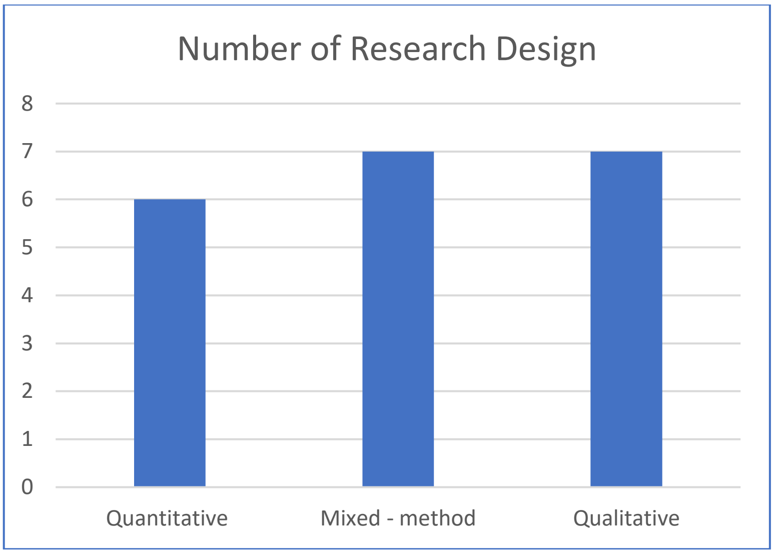

Figure 2 : Bar chart of frequency of research design

The number of articles published by year is as follows: one article in 2019, two articles in 2020, three articles in 2021, four articles in 2022, three articles in 2023, and six articles in 2024. The increasing number of articles published each year indicates a growing research interest among scholars in exploring the potential applications of artificial intelligence in science education. Figure 4 presents a bar graph illustrating the number of articles published over the past five years.

The analysis of the articles identified various AI-based applications used for teaching and learning science. These include the use of chatbots (Billings et al., 2024; Chang et al., 2023; Kusuma et al., 2024; J. Lee et al., 2023; Mahroof et al., 2020; Topal et al., 2021), machine learning-based applications for automated grading (Haudek & Zhai, 2023; Huang & Qiao, 2024; Wu & Tegmark, 2019; Zhai et al., 2022; Zhou et al., 2024). AI-driven game-based learning (Gupta et al., 2024; S. Lee et al., 2021), and the use of simulations and virtual laboratories (Chen & Liu, 2024; Watters et al., 2020; Wu & Tegmark, 2019).

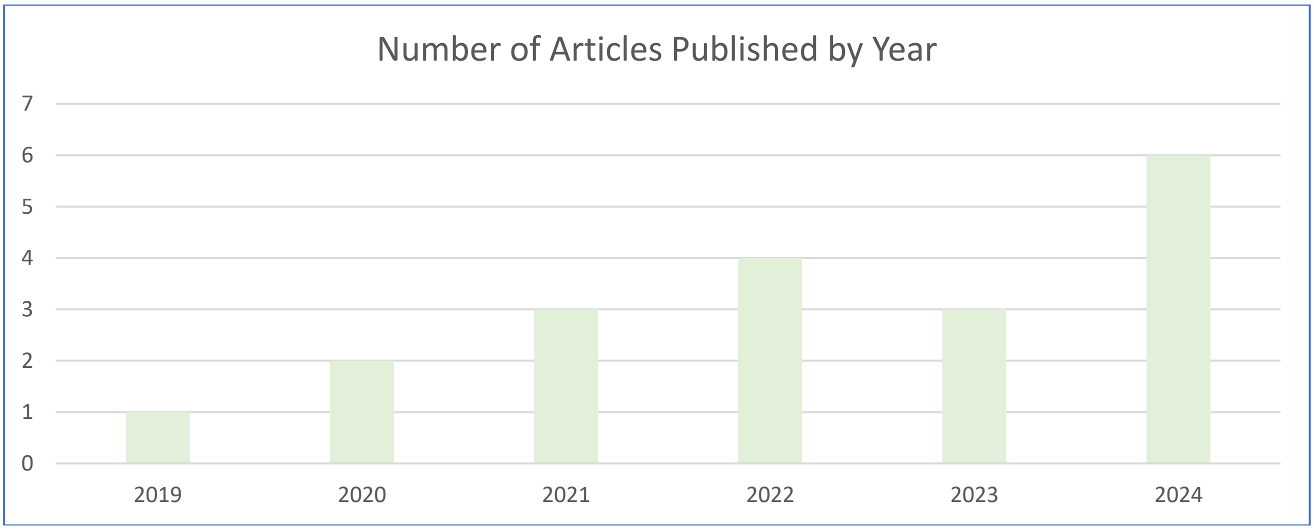

Figure 3 : Bar chart of number of articles published between 2019 and 2024 .

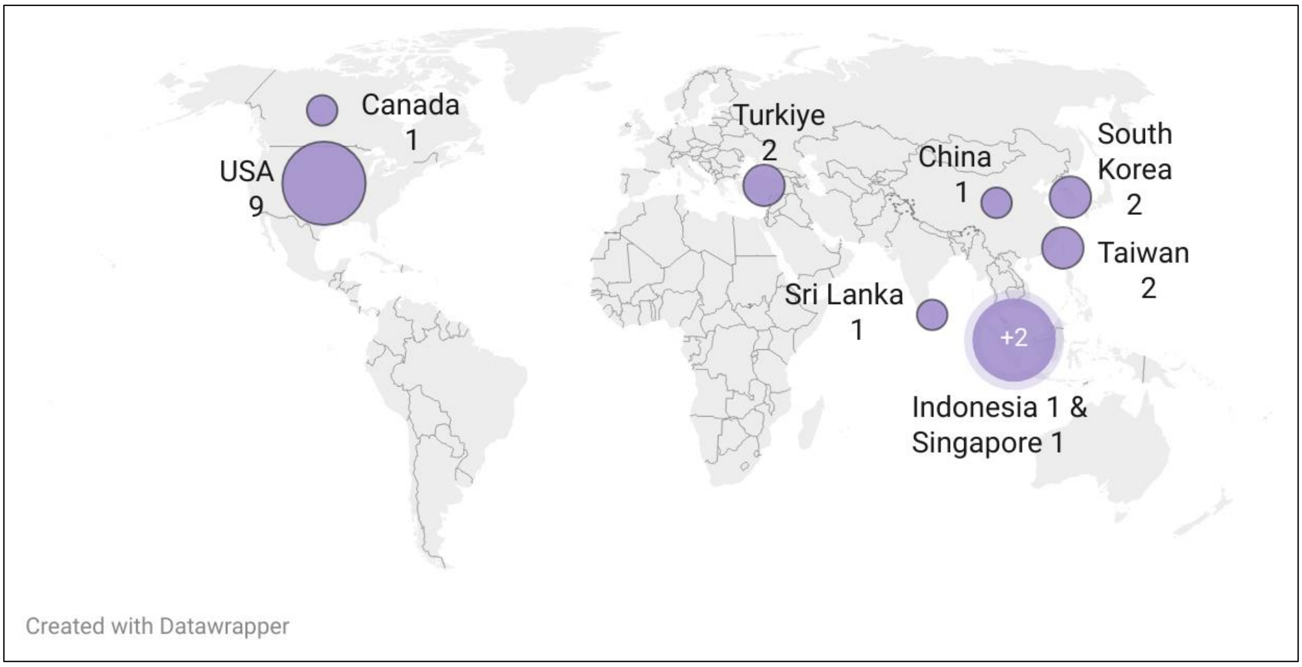


Diagram 1: Map showing the origin country of articles and number of articles published .

AI enhances authentic scientific experiences by enabling students to engage in real-world inquiry through interactive tools and simulations. It supports question formulation, experiment planning, data analysis, and collaborative discussions by providing real-time feedback and adaptive learning experiences. AI-powered chatbots, virtual labs, and intelligent tutoring systems personalize learning, guiding students through scientific investigations. These technologies mirror real-world scientific practices, fostering deeper understanding, critical thinking, and hands-on exploration. AI also supports peer discussions using natural language processing (NLP), fostering collaborative scientific reasoning. These AI applications replicate real-world scientific practices, promoting deeper engagement and critical thinking.

*How Can the Integration of AI Technology Provide Authentic Science Learning Experiences?*

The use of AI-based chatbots, which leverage Natural Language Processing (NLP) technology, enables machines to naturally understand, analyse, generate, and interpret human language. In the study by Chang et al. (2023), Inquirybot utilised NLP to guide students through scientific inquiry activities, including hypothesis formation, conducting experiments, and drawing conclusions. Similarly, Billings et al. (2024)explored the use of NLP to analyse students' discussions on topics such as plate tectonics, prompting scientific dialogue through adaptive questioning. This approach helps students articulate and defend their scientific ideas in discussions, mirroring the practices of scientists in research communities.

AI chatbots have also been shown to enhance conceptual understanding and foster positive attitudes towards science. For instance, in the study by J. Lee et al. (2023) , students explored concepts of optics, such as refraction and reflection, through active chatbot interactions. Likewise, Topal et al. (2021) demonstrated how students received instant feedback from chatbots to improve their understanding of heat energy and changes in states of matter. Additionally, chatbot-assisted learning encourages self-directed exploration, as illustrated in Kusuma et al. (2024) , where students engaged in inquiry-based discussions to explore the concept of global warming. Beyond self-directed learning, chatbots also facilitate automated and immediate self-assessment, such as inMahroof et al. (2020) , where students used chatbots to test their understanding of chemistry topics.

Machine learning applications also provide significant benefits for inquiry-based authentic science learning. For example, in the studies by Jeon et al. (2024)and Gupta et al. (2024), the PrimaryAI integrated curriculum allowed primary school students to investigate the causes of declining yellow-eyed penguin populations. Through game-based learning and AI-assisted data analysis, students identified patterns and proposed conservation strategies, providing them with authentic scientific experiences where they had to analyse data, recognise trends, and make evidence-based decisions. Similarly, Huang & Qiao (2024) explored how AI enhances students' computational thinking skills by engaging them in real-world scientific problem-solving activities, such as data modelling and algorithm analysis. This approach enables students to connect scientific concepts with AI technology applications to address real-world challenges.

The role of AI in virtual simulations has also been extensively studied. Callaghan et al. (2021) examined the use of Labster simulations in virtual learning for biology and chemistry. Labster facilitates real-time modelling of chemical interactions, biological reactions, and physical systems, offering an immersive and authentic learning experience. Machine learning technology is used to analyse students' experimental outcomes and data interpretation, helping them understand how scientific data is applied in research contexts. These simulations have proven particularly valuable in supporting authentic learning by linking educational activities to real-world research scenarios, such as genetic analysis and chromatographic separation, particularly during the COVID-19 pandemic.

Another example of AI-enhanced authentic learning is found in the study by Chen & Liu (2024), where secondary school students learning about cell division used AI object recognition technology via Pixetto. The study found that students in the experimental group, who engaged in guided inquiry with AI, showed higher conceptual understanding and learning motivation compared to the control group. In this approach, students uploaded microscopic images into an AI-powered object recognition tool, which then analysed and displayed the progression of mitosis or meiosis. This active learning method provided students with hands-on engagement with cutting-edge technology, fostering authentic science learning experiences through interactive AI-based analysis.

By integrating AI into science education, students gain hands-on, inquiry-based experiences that closely mirror real-world scientific research, enabling them to engage in authentic learning through problem-solving, data analysis, and interactive technology-assisted exploration**.**

While many studies highlight that AI tools, such as chatbots and NLP systems, enhance inquiry skills and engagement, few address risks like cognitive overload, shallow inquiry, or overreliance on scripted prompts (Billings et al., 2024). Although AI is intended to foster authentic scientific practices, implementations often constrain student agency, limiting open-ended exploration(Chang et al., 2023). Several studies emphasize motivation gains but neglect deeper scientific reasoning and argumentation (Kusuma et al., 2024). Additionally, authentic data handling and uncertainty, crucial in real science, are often oversimplified (Kim, 2022). Structural issues such as short intervention periods, lack of teacher mediation, and inequities in access also limit the extent to which AI truly supports authentic science learning(Gupta et al., 2024) .

*How Can the Integration of AI Technology Supports the Development of 21st-Century Skills in Students?*

Critical thinking in problem-solving, collaboration, communication, and creativity (4C) are essential 21st-century skills that students must master. Critical thinking refers to the ability to analyze facts to make judgments and solve complex problems. Collaboration involves working effectively in teams, communication refers to students' ability to convey ideas verbally or non-verbally, while creativity refers to thinking outside the box and generating innovative ideas (Suto & Eccles, 2014). At the higher education level, various studies have demonstrated that AI tools can develop these skills Celik et al. (2024). This article explores how AI tools support the development of 4C skills at the primary and secondary school levels.

**Critical Thinking and Problem-Solving**

For critical thinking and problem-solving skills, Haudek & Zhai (2023)explored how lower secondary students used machine learning to evaluate their scientific arguments. The system helped students identify weaknesses in their argument models and improve them based on automated feedback. In the study by Zhai et al. (2022), secondary school students created scientific models, such as weather and ecosystem models, receiving automated feedback from machine learning algorithms to enhance the accuracy of their predictions. Additionally, Wu & Tegmark (2019) examined how students learned physics methods to solve complex problems, such as distinguishing object motion based on Newtonian laws, using a "divide and conquer" strategy taught by an AI learning system.

**Communication**

Effective communication skills are crucial in education and professional life. AI enhances students' communication by providing interactive tools that encourage them to articulate their ideas more clearly. Watters et al. (2020) discussed how AI tools like virtual lab assistants help students structure their experimental results more effectively, facilitating scientific communication in laboratory settings. Kim (2022)emphasized the importance of epistemic discourse in AI-based science education, where AI helps students develop communication skills through structured discussions, enabling them to articulate their scientific understanding better. The study by Zhou et al. (2024) also highlighted that students using the ML4SI tool needed to present their findings to peers and teachers, requiring them to build evidence-based arguments and organize their ideas clearly. This improves both their oral and written communication skills in a learning context.

**Collaboration**

Collaboration is a key element of modern education, allowing students to work together to solve problems and develop critical thinking. Acisli Celik & Ergin (2022) examined the role of robotics and AI in science education for secondary school students. Their findings indicated that AI integration in robotics learning encouraged students to collaborate in handling tasks, sharing information, and solving challenges collectively. Meanwhile,Huang & Qiao (2024) found that AI education within the STEAM curriculum enabled students to engage in group work to solve problems related to data analysis and algorithms. This fosters collaborative skills as students work together to build machine learning models, share roles, and refine problem-solving strategies collectively. Watters et al. (2020)also discussed how AI contributes to making science laboratories more inclusive for visually impaired students. Their research showed that AI-assisted tools helped students collaborate with their peers in conducting experiments more actively, reducing their reliance on human assistants.

**Creativity**

AI also enhances student creativity by allowing them to explore new solutions and think beyond conventional approaches. Kim (2022)supported the idea that AI in science education helps students develop a deeper understanding through creative exploration of concepts. This was evident in student-designed AI agents aimed at solving real-world scientific problems relevant to their interests. Engaging students in such creative processes helps them connect their real-life experiences with scientific concepts and AI applications. In an empirical study byHsu et al. (2022) , secondary school students interacted with AI conversational tools like Amazon Alexa via MIT App Inventor, exposing them to emerging technologies. Understanding and working with these AI tools not only builds digital literacy but also fosters innovation and creativity as students develop their own conversational agents.

Huang & Qiao (2024)also demonstrated that AI education integrated with the STEAM model significantly enhances student creativity. After implementing this interdisciplinary approach, students in the experimental group showed higher post-test creativity scores compared to the control group. This suggests that the STEAM framework not only nurtures interest in AI but also enhances creative thinking, enabling students to solve problems more innovatively. By incorporating artistic elements into AI projects, students are encouraged to explore innovative designs and problem-solving approaches. Artistic components also support critical thinking and allow students to express their understanding creatively, as seen in AI-related projects involving digital painting and image recognition.
Table 4 provides an overview of the AI tools used in the study and the 21st-century skills they support.

From the analysis of these studies, there is broad consensus that AI tool such as chatbots, machine learning, image recognition, and inquiry-driven games effectively boost students' engagement, motivation, and understanding of scientific concepts (Chang et al., 2023; Huang & Qiao, 2024; Jeon et al., 2024). However, gaps remain regarding the development of 21st-century skills. Many interventions emphasize cognitive outcomes but seldom assess long-term skill transfer beyond the immediate learning tasks (Kusuma et al., 2024; Mahroof et al., 2020). Risks such as over-reliance on AI tools and reduced metacognitive growth are rarely discussed (Chang et al., 2023; Billings et al., 2024). Although inclusivity is advocated, few studies systematically explore gender, achievement gaps, or access inequities (Lee et al., 2023; Zhou et al., 2024). Future work must address these contradictions to fully realize AI's potential for fostering 21st-century skills.

**Implication of Study**

*Teachers' Practice*

Science instructors should use AI tools (like chatbots or inquiry games) to help students learn science by doing real scientific work, not just memorizing facts. In the classroom, AI should help students ask their own questions, solve problems, analyse data, and explain their ideas, just like real scientists. AI tools should not give students all the answers. Instead, they should support students to think critically, be creative, work with others, and communicate clearly. Teachers need training to design learning activities where students lead their own investigations and learn to manage and reflect on their own thinking (metacognition). Professional development programs should include training on AI ethics and bias handling, not just technical use. This way, AI becomes a tool to enhance authentic inquiry experiences, not to replace human thinking.

*Education Policy*
Policymakers should make sure that AI is used in schools to support real science inquiry and 21st-century skills, not just to deliver information. Curriculum standards should also encourage students to investigate problems, build arguments, collaborate, and think creatively using AI. Funding should also help all schools, especially those in remote areas, to have access to AI tools and teacher training programs. Policies should make sure AI is used ethically and fairly, helping all students develop skills they need to succeed in a technology-driven world.

*Implications for Research*
Researchers should study how AI can really help students learn through inquiry and develop critical 21st-century skills over time, not just short-term content knowledge. Future studies should focus on how students use AI tools to ask questions, design experiments, analyse information, and solve real-world problems. Research should also investigate whether AI helps different groups of students (different genders, backgrounds, and achievement levels) equally. Lastly, researchers should investigate whether AI sometimes makes students too dependent, and how to design AI curricula that still encourages independent thinking, creativity, and problem-solving.

Table 4
*Summary of AI tools and 21st-century skills inculcated into students*

| **Author(s)** | **AI tools used** | **21st century skills** | | | |
|---|---|---|---|---|---|
| | | **Critical thinking** | **Creativity** | **Collaboration** | **Communication** |
| Acisli Çelik & Ergin (2022) | Not specified | | | x | |
| Callaghan et al. (2020) | Natural Language Processing (NLP) for peer discussions | x | | x | |
| Chang et al. (2023) | Virtual Implementation of Inquiry-Based Remote Learning | x | x | | x |
| Chen & Liu (2024) | AI chatbot (Inquirybot) for scientific inquiry | x | | | x |
| Gupta et al. (2024) | AI Robot Image Recognition Technology | x | | | x |

| Author(s) | AI tools used | 21st century skills | | | |
|---|---|---|---|---|---|
| | | Critical thinking | Creativity | Collaboration | Communication |
| Haudek & Zhai (2024) | AI-based Chatbot for Chemistry Learning | x | | x | |
| Hsu et al. (2022) | Conversational AI Learning Curriculum | x | x | | |
| Huang & Qiao (2022) | AI-Integrated Science Teaching with Epistemic Discourse | x | | | |
| Jeon et al. (2024) | An AI-Based Chatbot for Self-Learning in Chemistry | x | x | x | x |
| Kim (2022) | AI for Computational Thinking in STEAM Education | x | x | | |
| Kusuma et al. (2023) | AI-Infused Collaborative Inquiry (PRIMARYAI) | x | | | |
| Lee et al. (2021) | Rule-Based AI Chatbot for Elementary Science | x | | | x |
| Lee et al. (2023) | AI Chatbot in a 5th Grade Science Course | x | | | |
| Mahroof et al. (2020) | Machine Learning for Automatic Scientific Model Assessment | | x | x | |
| Topal et al. (2021) | AI for Physics Learning (AI Physicist) | x | x | x | |
| Watters et al. (2021) | ML-Supported Scientific Inquiry (ML4SI) | x | x | x | |
| Wu & Tegmark (2019) | Story-Driven Game-Based AI Learning | x | | x | x |
| Zhai et al. (2022) | AI in Inquiry-Based AI Curriculum (PRIMARYAI) | x | x | | |
| Zhou et al. (2024) | Using AI for Peer-to-Peer Science Discussions | x | x | x | x |

**Recommendation for Future Research**
The use of AI in science education has demonstrated significant potential in supporting authentic inquiry-based science learning. Further research is needed to assess the impact of AI integration on enhancing students' understanding of scientific methods. A more structured AI-integrated science curriculum is also essential to ensure that AI is not only utilised as a teaching aid but also established as a field of study within science education. Additionally, the long-term effectiveness of AI in science education should be examined to determine how AI can improve learning outcomes and develop 21st-century skills among students.

Furthermore, there is a need to bridge the digital divide between urban and rural schools in accessing AI in science education (Kumar & Mohd, 2024). Research can be conducted to identify the most effective strategies for improving AI technology accessibility to all students, ensuring equal access to learning opportunities.

## Conclusion

The integration of artificial intelligence (AI) in science education represents a significant shift towards enhancing learning experiences and educational outcomes across various levels of education. Collective research highlights the potential of AI technologies, such as chatbots and image recognition tools, in fostering student engagement and improving academic performance in science disciplines. As the demand for AI literacy continues to grow in an increasingly digital world, this systematic literature review underscores the importance of developing and implementing an AI-integrated curriculum that not only provides students with foundational knowledge but also promotes the development of 21st-century skills. The implementation of AI in inquiry-based learning environments enhances educational experiences, equips students with essential critical skills for the future, and prepares them to engage with the evolving digital and AI-driven world while simultaneously fostering strong scientific literacy. By embedding AI in authentic, problem-based learning environments, students gain not only content knowledge but also critical thinking and digital literacy, preparing them for a data-driven future. Overall, AI enriches science education by bridging pedagogical gaps and fostering deeper, more engaging learning experiences.

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## References

Acisli Celik, S., & Ergin, I. (2022). Opinions of Middle School Students on the Concept of Science and the Use of Robotic Systems. *International Journal of Technology in Education*, *5*(1), 154–170. https://doi.org/10.46328/ijte.232

Barell, J. (2012). *How Do We Know They're Getting Better? Assessment for 21st Century Minds, K-8*. Corwin Press. https://doi.org/10.4135/9781452275376

Billings, K., Chang, H. Y., Lim-Breitbart, J. M., & Linn, M. C. (2024). Using Artificial Intelligence to Support Peer-to-Peer Discussions in Science Classrooms. *Education Sciences*, *14*(12), 1441. https://doi.org/10.3390/educsci14121411

Burgin, S. R. (2020). A three-dimensional conceptualization of authentic inquiry-based practices: a reflective tool for science educators. *International Journal of Science Education*, *42*(9), 1465–1484. https://doi.org/10.1080/09500693.2020.1766152

Callaghan, N. I., Khaira, S., Ouyang, A., Cadavid, J. L., Chang, H. H., Co, I. L., Diep, P., Ivanov, N., Li, G., Li, N. T., Tran-Nguyen, N., Smith, C., Davenport Huyer, L., & Kilkenny, D. M. (2021). Discovery: Virtual Implementation of Inquiry-Based Remote Learning for Secondary STEM Students During the COVID-19 Pandemic. *Biomedical Engineering Education*, *1*(1), 87–94. https://doi.org/10.1007/s43683-020-00014-z

Celik, I., Gedrimiene, E., Siklander, S., & Muukkonen, H. (2024). The affordances of artificial intelligence-based tools for supporting 21st-century skills: A Systematic Literature Review. *Australasian Journal of Educational Technology*, *40*(3), 19–38. https://doi.org/10.14742/ajet.9069

Chang, J., Park, J., & Park, J. (2023). Using an Artificial Intelligence Chatbot in Scientific Inquiry: Focusing on a Guided-Inquiry Activity Using Inquirybot. *Asia-Pacific Science Education*, *2*(2), 1–31. https://doi.org/10.1163/23641177-bja10062

Chen, P. Y., & Liu, Y. C. (2024). Impact of AI Robot Image Recognition Technology on Improving Students' Conceptual Understanding of Cell Division and Science Learning Motivation. *Journal of Baltic Science Education*, *23*(2), 208–220. https://doi.org/10.33225/jbse/24.23.208

Chinn, C. A., & Malhotra, B. A. (2002). Epistemologically Authentic Inquiry in Schools: A Theoretical Framework for Evaluating Inquiry Tasks. *Science Education*, *86*(2), 175–218. https://doi.org/10.1002/sce.10001

Constantinou, C. P., Tsivitanidou, O. E., & Rybska, E. (2018). What Is Inquiry-Based Science Teaching and Learning? In *Contributions from Science Education Research* (Vol. 5, pp. 1–23). Springer Science and Business Media B.V. https://doi.org/10.1007/978-3-319-91406-0_1

EPPI-Centre. (2003). *Review Guidelines for Extracting Data and Quality Assessing Primary Studies in Educational Research.*

Grangeat, M. (2016). Dimensions and Modalities of Inquiry-Based Teaching: Understanding the Variety of Practices. *Education Inquiry*, *7*(4), 29863. https://doi.org/10.3402/edui.v7.29863

Gupta, A., Lee, S., Mott, B., Chakraburty, S., Glazewski, K., Ottenbreit-Leftwich, A., Scribner, A., Hmelo-Silver, C. E., & Lester, J. (2024). Supporting Upper Elementary Students in Learning AI Concepts with Story-Driven Game-Based Learning. *Proceedings of the AAAI Conference on Artificial Intelligence*, *38*(21), 23092–23100. www.aaai.org

Haudek, K. C., & Zhai, X. (2023). Examining the Effect of Assessment Construct Characteristics on Machine Learning Scoring of Scientific Argumentation. *International Journal of Artificial Intelligence in Education*. https://doi.org/10.1007/s40593-023-00385-8

Hong, Q. N., Fàbregues, S., Bartlett, G., Boardman, F., Cargo, M., Dagenais, P., Gagnon, M.-P., Griffiths, F., Nicolau, B., O'Cathain, A., Rousseau, M.-C., Vedel, I., & Pluye, P. (2018). The Mixed Methods Appraisal Tool (MMAT) version 2018 for information professionals and researchers. *Education for Information*, *34*(4), 285–291. https://doi.org/10.3233/EFI-180221

Hsu, T.-C., Abelson, H., & Van Brummelen, J. (2022). The Effects on Secondary School Students of Applying Experiential Learning to the Conversational AI Learning Curriculum The Effects on Secondary School Students of Applying Experiential Learning to the Conversational AI Learning Curriculum. *International Review of Research in Open and Distributed Learning*, *23*(1), 82–103.

Huang, X., & Qiao, C. (2024). Enhancing Computational Thinking Skills Through Artificial Intelligence Education at a STEAM High School. *Science and Education*, *33*(2), 383–403. https://doi.org/10.1007/s11191-022-00392-6

Jeon, M., Jantaraweragul, K., Ottenbreit-Leftwich, A., Hmelo-Silver, C., Glazewski, K., Mott, B., Lester, J., & Ringstaff, C. (2024). Inquiry-based Artificial Intelligence Curriculum for Upper Elementary Students: A Design Case of PrimaryAI. *International Journal of Designs for Learning*, *15*(3), 94–108. https://doi.org/10.14434/ijdl.v15i3.36757

Ješková, Z., Lukáč, S., Šnajder, Ľ., Guniš, J., Klein, D., & Kireš, M. (2022). Active Learning in STEM Education with Regard to the Development of Inquiry Skills. *Education Sciences*, *12*(10), 686. https://doi.org/10.3390/educsci12100686

Ketak, R., Mittal, S., Gupta, V., & Gupta, H. (2024). Online Edtech Platform with AI Doubt Assistance. *2024 2nd International Conference on Disruptive Technologies (ICDT)*, 1395–1399. https://doi.org/10.1109/ICDT61202.2024.10489310

Kim, W. J. (2022). AI-Integrated Science Teaching Through Facilitating Epistemic Discourse in the Classroom. *Asia-Pacific Science Education*, *8*(1), 9–42. https://doi.org/10.1163/23641177-bja10041

Kumar, I., & Mohd, N. (2024). Ways of Using Computational Thinking to Improve Students' Ability to Think Critically. In *Infrastructure Possibilities and Human-Centered Approaches With Industry 5.0* (pp. 253–266). IGI Global Scientific Publishing. https://doi.org/10.4018/979-8-3693-0782-3.ch015

Kusuma, A. A. K., Maharani, W. A. D., Wibowo, F. C., Nasbey, H., & Costu, B. (2024). Effectiveness of Artificial Intelligent Independent Learning (AIIL) with physics chatbot of global warming concept. *Momentum: Physics Education Journal*, *8*(1), 42–54. https://doi.org/10.21067/mpej.v8i1.8942

Lee, J., An, T., Chu, H. E., Hong, H. G., & Martin, S. N. (2023). Improving Science Conceptual Understanding and Attitudes in Elementary Science Classes through the Development and Application of a Rule-Based AI Chatbot. *Asia-Pacific Science Education*, *13*(2), 365–412. https://doi.org/10.1163/23641177-bja10070

Lee, S., Mott, B., Ottenbreit-Leftwich, A., Scribner, A., Taylor, S., Park, K., Rowe, J., Glazewski, K., Hmelo-Silver, C. E., & Lester, J. (2021). AI-Infused Collaborative Inquiry in Upper Elementary School: A Game-Based Learning Approach. *The Thirty-Fifth AAAI Conference on Artificial Intelligence (AAAI-21)*, *35*(17), 15591–15599. www.aaai.org

Lin, C.-C., Huang, A. Y. Q., & Lu, O. H. T. (2023). Artificial intelligence in intelligent tutoring systems toward sustainable education: a systematic review. *Smart Learning Environments*, *10*(1), 41. https://doi.org/10.1186/s40561-023-00260-y

Lockwood, C., Munn, Z., & Porritt, K. (2015). Qualitative research synthesis. *International Journal of Evidence-Based Healthcare*, *13*(3), 179–187. https://doi.org/10.1097/XEB.0000000000000062

Magee, D., & Meier, A. J. (2011). Science Education and Culture: Inquiry-Based Learning. *Journal of Intercultural Communication*, *11*(3), 1–14. https://doi.org/10.36923/jicc.v11i3.538

Mahroof, A., Gamage, V., Rajendran, K., Rajkumar, S., Rajapaksha, S., & Wijendra, D. (2020). An AI based chatbot to self-learn and self-assess performance in ordinary level chemistry. *ICAC 2020 - 2nd International Conference on Advancements in Computing, Proceedings*, 216–221. https://doi.org/10.1109/ICAC51239.2020.9357131

MOE. (2023). *Digital Education Policy (Dasar Pendidikan Digital)*. Ministry of Education Malaysia. https://www.moe.gov.my/storage/files/shares/Dasar/Dasar%20Pendidikan%20Digital/Digital%20Education%20Policy.pdf

MOE. (2024a). *KPM Sambut Baik Pelaburan Google di Malaysia, Perkukuhkan Pelaksanaan Dasar Pendidikan Digital*. Ministry of Education Malaysia. Press Release . https://www.moe.gov.my/storage/files/shares/Kenyataan%20Media/KM2024/KM%20KPM%20Sambut%20Baik%20Pelaburan%20Google%20Di%20Malaysia%2C%20Perkukuhkan%20Pelaksanaan%20Dasar%20Pendidikan%20Digital.pdf

MOE. (2024b). *Apple Learning Coach Perkasakan Kompetensi Digital Guru*. Ministry of EducationMalaysia. Press Release.

https://www.moe.gov.my/storage/files/shares/Kenyataan%20Media/KM2024/KM%20Apple%20Learning%20Coach%20Perkasakan%20Kompetensi%20Digital%20Guru.pdf

Mohamed Shaffril, H. A., Samsuddin, S. F., & Abu Samah, A. (2021). The ABC of systematic literature review: the basic methodological guidance for beginners. *Quality & Quantity*, *55*(4), 1319–1346. https://doi.org/10.1007/s11135-020-01059-6

Page, M. J., Moher, D., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., Mcdonald, S., … Mckenzie, J. E. (2021). PRISMA 2020 explanation and elaboration: Updated guidance and exemplars for reporting systematic reviews. In *The BMJ* (Vol. 372). BMJ Publishing Group. https://doi.org/10.1136/bmj.n160

Radif, M. (2024). Artificial Intelligence in Education: Transforming Learning Environments and Enhancing Student Engagement. *Educational Sciences: Theory and Practice*, *24*(1), 93–103.

Ružičić, V. (2024). Overview and Implementation of Artificial Intelligence in the Improvement of Educational Process. *Journal of Scientific & Industrial Research*, *83*(5). https://doi.org/10.56042/jsir.v83i5.3192

Suto, I., & Eccles, H. (2014). The Cambridge approach to 21 st Century skills: definitions, development and dilemmas for assessment IAEA Conference, Singapore, 2014 Irenka Suto and Helen Eccles, Cambridge Assessment. *IAEA Conference*, 1–10.

Topal, A. D., Dilek Eren, C., & Kolburan Geçer, A. (2021). Chatbot application in a 5th grade science course. *Education and Information Technologies*, *26*(5), 6241–6265. https://doi.org/10.1007/s10639-021-10627-8

Watters, J., Liu, C., Hill, A., & Jiang, F. (2020). An artificial intelligence tool for accessible science education. *IMCIC 2020 - 11th International Multi-Conference on Complexity, Informatics and Cybernetics, Proceedings*, *1*, 147–150. https://doi.org/10.14448/jsesd.13.0010

Williams, P. J., Nguyen, N., & Mangan, J. (2017). Using technology to support science inquiry learning. *Journal of Technology and Science Education*, *7*(1), 26–57. https://doi.org/10.3926/jotse.234

Wu, T., & Tegmark, M. (2019). Toward an artificial intelligence physicist for unsupervised learning. *Physical Review E*, *100*(3), 033311.

Yılmaz, Ö. (2024). Personalised learning and artificial intelligence in science education: current state and future perspectives. *Educational Technology Quarterly*, *2024*(3), 255–274. https://doi.org/10.55056/etq.744

Zhai, X., He, P., & Krajcik, J. (2022). Applying machine learning to automatically assess scientific models. *Journal of Research in Science Teaching*, *59*(10), 1765–1794. https://doi.org/10.1002/tea.21773

Zhou, X., Tang, J., Lyu, H., Liu, X., Zhang, Z., Qin, L., Au, F., Sarkar, A., & Bai, Z. (2024). Creating an Authoring Tool for K-12 Teachers to Design ML-Supported Scientific Inquiry Learning. *Conference on Human Factors in Computing Systems - Proceedings*, 1–7. https://doi.org/10.1145/3613905.3650762