ARFAK CHEM
Chemistry Education journal
Vol 8 No 2, pp.759-771, 2025
p-ISSN: 2615-627X, e-ISSN: 2615-6255
Available online at: https://journalfkipunipa.org/index.php/accej

Exploring the impact of artificial intelligence in chemistry teaching: A systematic review of empirical research

Nur Indah Sari[1], Fandi Ahmad[2*]

[1] Departmen of Science Education, Universitas Negeri Makassar, Makassar
[2] Department of Chemistry Education, Universitas Negeri Makassar, Makassar
Corresponding Author E-mail: fandi.ahmad@unm.ac.id*

ARTICLE INFO:

Revised: 2025-11-12
Accepted: 2025-12-01
Published: 2025-12-01

Keywords:

Artificial intelligence, chemistry teaching, empirical research, literature review

ABSTRACT

Chemistry education frequently struggles to foster a comprehensive understanding, often because it focuses too narrowly on macroscopic, submicroscopic, or symbolic representations. While Artificial Intelligence offers considerable potential to enhance learning, research specifically examining its impact on chemistry teaching remains scarce. This study aimed to identify, evaluate, and synthesize empirical literature on the effects of AI in chemistry teaching. This study was conducted in accordance with the PRISMA three sequential stages: 1) a comprehensive literature search in scientific databases utilizing keywords such as Artificial Intelligence, Chemistry Teaching, and Empirical Study/Research; 2) a selection process based on the inclusion and exclusion criteria; and 3) systematic data extraction. The literature review incorporated 13 empirical research articles published in Scopus- and Sinta-indexed journals. Findings consistently indicate that AI integration significantly impacts learner performance and instructional effectiveness by facilitating just-in-time, automated, and individualized feedback. Specific AI applications identified include generative tools for conceptual problem-solving, the utilization of ChatGPT/Bing Chat, gamified learning approaches, and AI assistants within remote laboratory settings. Nevertheless, this study highlights the inherent limitations of AI in addressing complex chemical content, alongside prevalent student concerns about AI accuracy, plagiarism, data privacy, and the potential for over-reliance on this technology.

How to cite: Sari, N. I., & Ahmad, F. (2025). Exploring the impact of artificial intelligence in chemistry teaching: A systematic review of empirical research. *Arfak Chem: Chemistry Education Journal, 8*(2), 759-771. https://doi.org/10.30862/accej.v8i2.1083

1. INTRODUCTION

Chemistry education, as part of science education, plays a crucial role in shaping scientific understanding and equipping individuals with the analytical and problem-solving skills essential across various fields of knowledge. In general, the characteristics of chemistry are represented through three levels: macroscopic, submicroscopic, and symbolic (Basimin et al., 2023). The ideal use of multiple representations in chemistry learning involves a strategic approach that makes instruction more effective and coherent (Tonyali et al., 2023). However, several studies have revealed that chemistry teaching often faces significant challenges, such as prioritizing only one of these representation levels, which makes chemistry difficult to understand (Talanquer, 2022). Furthermore, according to Reyes (2025), students are less engaged in learning because they fail to connect abstract concepts with real-world applications, particularly in large and diverse classrooms, where students are less prepared to apply mathematical and chemical concepts and lack motivation (Chi et al., 2024; Hasmarani et al., 2019). Addressing the difficulties in understanding abstract chemical concepts presents a significant challenge for chemistry educators (Blonder et al., 2023), as this may lead to misconceptions and inaccurate understanding among students (Permatasari et al., 2022).

It is precisely in overcoming these inherent complexities and pedagogical challenges that Artificial Intelligence (AI) (Kohnke & Zaugg, 2025) emerges as a transformative force, crucial for enhancing the quality of chemistry instruction. Its integration in education offers opportunities to personalize learning, enhance accessibility, and reduce achievement gaps, fundamentally reshaping pedagogical approaches and assessment practices (Almasri, 2024; Iyamuremye et al., 2024). AI-based systems, such as adaptive learning platforms, intelligent tutoring systems, and automated assessment tools, can provide personalized learning experiences, instant feedback, and individualized resources (Basimin et al., 2023). This technology also creates more engaging and immersive learning experiences by adjusting content difficulty levels and applying gamification in deep learning (Fan et al., 2023).

AI's transformation offers various innovative applications to enhance the chemistry teaching process. AI and machine learning can be integrated into laboratory experiments, simulations, virtual laboratories, data analysis, and assessments (Iyamuremye et al., 2024). AI-supported virtual laboratories enable students to conduct experiments in a simulated environment, providing direct learning experiences that overcome the limitations of physical laboratory settings (Iyamuremye et al., 2024). Intelligent tutoring systems can offer real-time feedback and adaptive support, guiding students through challenging concepts (Iyamuremye et al., 2024). Additionally, AI promises applications in feedback and behavior analysis, assessment of conceptual understanding, and investigation of reasoning processes during chemistry tasks (Chiu, 2021). AI can even provide just-in-time, automated, and individualized feedback for chemistry exercises (Eitemüller et al., 2023).

While AI offers significant potential to enhance chemistry education, current research specifically examining its impact on chemistry teaching remains limited, leaving unanswered questions regarding the effectiveness of AI technology in improving chemistry learning outcomes and optimal implementation strategies in the classroom (Iyamuremye et al., 2024). furthermore, student concerns about AI accuracy, plagiarism, data privacy, and the risk of over-reliance (De la

Ossa et al., 2024; Reyes, 2025) highlight the urgent need for research to thoroughly examine the real impact of AI in chemistry education, particularly given its widespread use and vast potential, with this research specifically seeking to address this gap by investigating the effectiveness of AI technologies in enhancing chemistry learning outcomes, identifying optimal implementation strategies in classroom settings, and exploring methods to mitigate student concerns regarding AI accuracy, plagiarism, data privacy, and over-reliance.

To address this gap and provide a clear understanding of the effectiveness, challenges, and future directions for AI implementation in chemistry teaching, a systematic review is the most appropriate approach. This systematic review offers novelty by being the first study to systematically collect and analyze empirical evidence specifically on the impact of AI in chemistry teaching, integrating findings from various studies (Tamim et al., 2021). This method has garnered significant attention in academia, as it provides an in-depth investigation of recommendations and contributes to the development of new knowledge (Pedersen & Caviglia, 2018). Thus, this systematic review aims to explore the impact of Artificial Intelligence on chemistry teaching comprehensively. Through systematic analysis of relevant empirical research, this study seeks to synthesize several aspects, such as how AI is used, its effectiveness on student learning outcomes, challenges in its implementation, and its implications for pedagogical practices and future research directions in chemistry education

2. METHODS

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines to ensure transparency and replicability of the search, selection, and data synthesis processes (Zawacki-Richter et al., 2019). The systematic review will be conducted over a period of 3 months, from August to October 2025. The primary objective of this section is to detail the steps that will be taken to identify, evaluate, and synthesize empirical literature on the impact of artificial intelligence in chemistry teaching.

A. Search Strategy

The literature search strategy will be comprehensively designed to identify relevant studies from various scientific databases. The primary databases to be used include: Scopus, Web of Science, ERIC, and Google Scholar. The following combinations of keywords will be used in the search, tailored to the syntax of each database:

1) Main Topic: (Artificial Intelligence or AI)
2) Field of Study: (Chemistry Teaching or Chemistry Education)
3) Study Type: (Empirical Study or Experiment or Quasi-experiment or Intervention Study OR Effectiveness or Impact)

The keyword combinations to be used are: (Artificial Intelligence or AI and Chemistry Teaching or Chemistry Education) and (Empirical Study or Impact or Effectiveness). The initial search will cover all publication years up to the present to ensure that no relevant studies are missed.

B. Study Selection Process

The study selection process will be carried out in two stages:

1) Title and Abstract Screening: The researchers will independently screen all search results based on titles and abstracts to identify potentially relevant studies. Studies that clearly do not meet the inclusion criteria will be excluded at this stage.
2) Full-text Screening: Full texts of the studies that pass the initial screening will be obtained and independently evaluated. At this stage, the inclusion and exclusion criteria will be strictly applied to determine which studies will be included in the systematic review.
3) Inclusion and Exclusion Criteria

This systematic review will apply strict inclusion and exclusion criteria to ensure the relevance and quality of the articles analyzed, as outlined in Table

Table 1. Inclusion and exclusion criteria

Inclusion Criteria	**Exclusion Criteria**
Articles published between 2023–2025	Articles published before 2023
Focus on empirical research, including the application, impact, or effectiveness of AI in chemistry teaching and learning	Studies that only mention AI without empirical investigation of its impact, effectiveness, or application in chemistry teaching
Articles published in English or Indonesian	Articles in languages other than English or Indonesian
Peer-reviewed journal articles and conference proceedings are available in full-text.	Theses, dissertations, books, book chapters, or reports that have not gone through formal peer-review processes
Involves students or educators (teachers/lecturers) in chemistry teaching	Non-formal education settings.

C. Data Extraction

Information from each article that meets the inclusion criteria will be extracted using a table containing:

1) General Information: code, publication year, journal index (Scopus/Sinta)
2) Research Design
3) AI Implementation: Types of AI technology used, how AI is implemented in chemistry teaching
4) Outcomes: Measured outcome variables (e.g., learning outcomes, motivation, engagement, conceptual understanding, and key findings)
5) Challenges and Limitations: Barriers faced in implementation or study design.

3. RESULTS AND DISCUSSIONS

The quality assessment of the 13 included articles was conducted independently by two reviewers using the Mixed Methods Appraisal Tool version 2018 (Hong et al., 2018). Discrepancies were resolved through consensus. Overall, the methodological quality of the studies varied. Four studies (31%) were assessed as having a low risk of bias, seven studies (54%) had a moderate risk of bias, and two studies (15%) showed a high risk of bias, primarily due to insufficient detail regarding randomization or handling of missing data. Studies focusing on the effectiveness of AI interventions often lacked adequate blinding, which could influence subjective outcomes such as student perceptions. Nevertheless, most studies reported acceptable validity and reliability for the instruments measuring learning outcomes.

The articles included in this literature review met the specified criteria and underwent thorough data extraction. A total of 13 articles were selected for analysis. The empirical research findings on the impact of artificial intelligence in chemistry teaching have identified existing challenges, the potential of AI, specific applications, expected benefits, as well as the challenges and limitations of AI, which are detailed in Table 2.

Table 2. Results of empirical assessment article analysis

Code/ Year of Issue/ Index	Research Design	AI Implementation	Result	Limitations
A1/2023/Q2	Empirical studies based on chemical problems	AI in general; As an additional tool to clarify complex concepts and improve efficiency	ChatGPT exhibits significant conceptual knowledge difficulties across various categories, especially on representation and deep understanding, which hinders effective knowledge transfer. 1) difficulty understanding and interpreting complex chemical structures or formulas, as well as predicting and explaining the answers with clear reasoning. 2) Difficulty in understanding the chemical rules, properties of compounds, and the reasons behind chemical phenomena. 3) Transfer and translation difficulties have also been observed, possibly due to the textual nature of ChatGPT.	The limitations of AI in dealing with complex subject areas, such as chemistry. ChatGPT, as a text-based AI, struggles in visual representation (cannot generate or display visual images). There is a need for more sophisticated training algorithms and data to improve the conceptual understanding and analytical capabilities of AI.
A2/2023/Q2	A single comparative case study.	AI Generative Chatbots such as ChatGPT and Bing Chat.	Used as "agents-to-think-with" in the simulation of chemistry learning experiences.	Not mention
A3/2024/SINTA 2	Quasi-experimental design	AI technology (gamification)	Learners' performance using AI in chemistry learning, Significant improvement in learners' performance after AI integration, showing the positive impact of AI	Teachers are concerned that overly simplistic answers from AI may hinder students' critical thinking and curiosity.
A4/2025/Q2	Quasi experiment	Generative AI chatbots (e.g., ChatGPT).	Affective factors, engagement, and conceptual understanding	Not mention

Code/ Year of Issue/ Index	Research Design	AI Implementation	Result	Limitations
A5/2024/International Nonquartile	*Mixed methods* to measure learning outcomes and public engagement.	An adaptive AI model that integrates teaching strategies such as IBL, PBL, and collaborative learning.	Develop adaptive AI models by integrating teaching strategies to improve learning outcomes and student engagement.	The use of AI raises concerns regarding its rapid development and ethical implications
A6/2025/Q2	Collaborative with a focus on student interaction.	The AI assistant is integrated with remote labs.	Teachers' perceptions of the use of AI in remote experiments. The use of AI in education has increased, supporting a wide range of teaching and learning activities.	Reducing student interaction.
A7/2025/SINTA 4	Quasi-experimental method with pretest-posttest control group design.	Generative AI and digital media integrated in stoichiometry learning on students' critical thinking and skills	Understanding stoichiometry, critical thinking, and the value of mutual cooperation. Significant improvement in stoichiometric understanding in the experimental group with an N-Gain score of 0.84 (high).	Intervention from learners is needed to ensure age-appropriate and engaging content
A8/2024/SINTA 3	Exploratory research, data collected through observation and rubric assessment	AIs such as ChatGPT, Gemini, and CanvaAI are used to search for and develop ideas and storylines, as well as create images of chemistry teaching ebooks	Involvement of students in *the ebook creation project*. The collaborative nature of the project encourages student ownership and engagement	Thermochemistry material is abstract and difficult to understand, resulting in low motivation and learning outcomes for students.
A9/2024/SINTA 3	Qualitative descriptive with direct observation, questionnaires, and interviews.	AI Chatbot. Used as an interactive learning medium for thermochemistry materials.	The need for chatbot learning media. Chatbots are needed as an innovative learning medium for abstract and elusive thermochemical materials.	Students have difficulty understanding complex concepts
A10/2024/SINTA 5	Survey research with correlation and regression analysis.	Artificial Intelligence-based adaptive learning uses AI-based learning tools.	Student learning achievements. A strong positive relationship between the frequency of use of AI learning tools and academic achievement.	Variations in the ability to use AI based on gender, socio-economic status, and academic ability.
A11/2024/International Nonquartile	Qualitative methodology with a Participatory Action Research approach with four phases including, planning, action,	AI is integrated with the design of pedagogical strategies to create a motivating learning environment.	Increased motivation and student involvement, as well as a positive impact on meaningful learning. Positive perceptions of students towards the implementation of AI.	The need for teacher and student training in the proper management and use of technological resources.

Code/ Year of Issue/ Index	Research Design	AI Implementation	Result	Limitations
	observation, and reflection			
A12/2023/Prociding Q4	Descriptive research on the impact of AI.	AI as a process that shapes human thinking styles so that it can design machines to behave like humans	Improving students' learning achievement by shaping human thinking styles so that they can design machines to behave like humans.	Students have difficulty understanding complex concepts.
A13/2024/ Q4	Quantitative and qualitative approach	An adaptive AI model that integrates teaching techniques such as inquiry-based learning, problem-based learning, and collaborative learning by tailoring information to students' success and integrating evidence-based teaching techniques	Develop effective adaptive AI models to improve learning outcomes and public engagement.	Concerns that adaptive systems might misinterpret temporary student behaviors, thereby constraining learner agency.

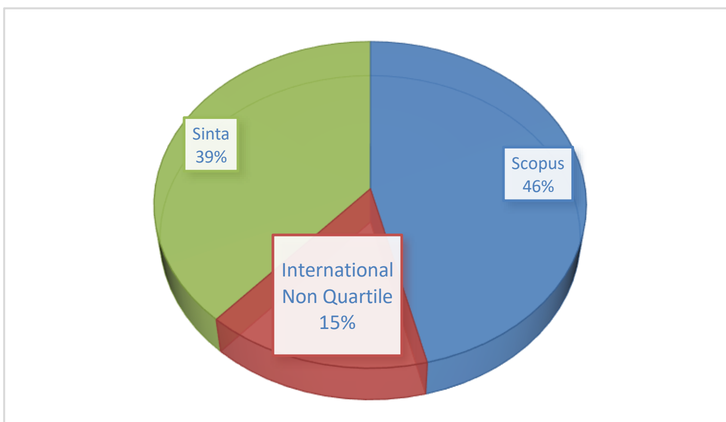

Figure 1. Distribution of articles by indexed journal

Overall, the empirical studies reviewed indicate a strong positive relationship between the use of AI learning tools and academic achievement, coupled with increased student motivation and engagement. AI is recognized as a valuable additional tool for clarifying complex concepts, improving efficiency, and personalizing learning experiences. Several studies demonstrate significant improvements in learners' performance after AI integration, suggesting its capacity to enhance learning outcomes and public engagement, especially when integrated with pedagogical strategies to create motivating environments.

However, the analysis also consistently highlights critical limitations and concerns. A prominent issue is AI's difficulty with the nuanced representation and deep understanding required for complex chemical concepts. Generative AI, being primarily text-based, struggles with visual representation, interpreting intricate chemical structures, providing clear reasoning, and facilitating the transfer and translation of knowledge across different chemical representations. Pedagogical and ethical concerns also emerge, including the risk of AI misinterpreting temporary student behaviors, potentially constraining learner agency, and the potential for overly simplistic AI answers to hinder critical thinking and curiosity, implementation challenges involve variations in AI usage ability based on demographics, the necessity for comprehensive training for both teachers and students, and the need for human intervention to ensure age-appropriate and engaging content.

Based on an analysis of 13 articles, the implementation of AI in chemistry teaching shows a wide range of findings, covering significant challenges and potential.

1. Impact of AI in Chemistry Teaching

The implementation of artificial intelligence (AI) in chemistry education has yielded a range of significant findings, encompassing both challenges and the potential of AI. The application of AI in chemistry teaching has demonstrated various positive impacts, particularly in increasing motivation, engagement, and the potential for academic improvement, especially in student learning outcomes and conceptual mastery. Additionally, several 21st-century skills are also supported by the use of AI in chemistry teaching. These studies suggest that AI can be an effective tool to enhance students' learning experiences, particularly at the submicroscopic level, where students often encounter misconceptions (Aldwinarta et al., 2024; Jere & Mpeta, 2025).

One of the most widely studied impacts is the improvement in student motivation and engagement. For example, research by De la Ossa et al. (2024) explicitly evaluated AI as a driver of motivation, finding an increase in motivation and engagement among 10th-grade students in chemistry learning. This key finding confirms that AI implementation can positively affect meaningful learning and shape students' positive perceptions of AI technology. Similarly, other research notes that students value AI as a supportive tool for clarifying complex concepts and improving learning efficiency (Daher et al., 2023). In a more specific context, Halimah et al. (2024) revealed that using AI tools in chemistry e-book creation projects encouraged collaboration and a sense of ownership among students, which, in turn, increased their engagement.

Beyond motivation, AI also contributes to enhancing academic performance and understanding. (Qureshi et al., 2024) found that an adaptive AI model, which integrates evidence-based teaching strategies, improved learning outcomes and public engagement in organic and environmental chemistry subjects. Furthermore, other studies have successfully investigated the impact of affective factors on engagement and conceptual understanding, highlighting the role of generative AI chatbots in this aspect (Jere & Mpeta, 2025). The positive impact lies in AI's ability to offer personalization, interactivity, and engaging content presentation for both students and chemistry educators. With AI, the learning process can be individually tailored, allowing students to learn at their own pace and style, as seen in adaptive AI that adjusts information based on student success (Qureshi et al., 2024). Interactivity is also enhanced through the use of tools like generative AI chatbots, which function as agents for collaborative thinking in chemistry learning experience simulations (P dos Santos, 2023), or through collaborative, engaging content creation and instruction that aids students in using

AI (Halimah et al., 2024). Additionally, AI can present complex chemistry content in a more comprehensible, effective, and efficient manner, providing instant feedback and supporting remote experiments, thereby creating a dynamic and effective learning environment that fosters better conceptual understanding (Lizano-Sánchez et al., 2025).

Overall, the impact of AI in chemistry teaching is to create a more interactive, personalized, and engaging learning environment, which ultimately encourages a deeper understanding and higher academic achievement. This is supported by the study by Lizano-Sánchez et al. (2025), which revealed that the use of AI in education has expanded significantly, supporting various teaching and learning activities, and facilitating personalized learning, continuous assessment, and real-time feedback. Thus, the emergence of AI as a transformative technology is impacting the revolution of pedagogical practices in chemistry teaching and preparing students for future challenges.

2. The Role of Various AI Technologies and Pedagogical Designs in Chemistry Teaching

The success of integrating AI in chemistry teaching heavily depends on the type of AI technology used and the accompanying pedagogical design. Overall, Table 2 presents a broad spectrum of AI types applied, ranging from generative AI chatbots, such as ChatGPT and Bing Chat, for facilitating thought, to adaptive AI models that integrate inquiry-based learning and problem-based learning strategies (Qureshi et al., 2024). The diversity of AI applications encompasses roles such as teaching assistants, content creation tools, and adaptive learning environments, as well as the impact of different intervention designs on outcomes in the context of chemistry teaching and education.

Various approaches have been explored to optimize the benefits of AI. One of the most widely studied forms of AI is generative AI chatbots, such as ChatGPT. P dos Santos (2023) study explores the potential of these AI chatbots as agents to think with in chemistry learning experience simulations, demonstrating their role in supporting students' cognitive processes. Similar research by Jere & Mpeta (2025) investigates how generative AI chatbots can be integrated as teaching aids that help both teachers and students in chemistry teaching, such as solving stoichiometry and thermodynamics problems. In addition to chatbots, AI technology supporting gamification also plays a significant role. Balaquiao (2024) describes how AI integrated with gamification approaches optimizes student performance by creating a more engaging and interactive learning environment.

Adaptive AI models are a powerful technological transformation. Qureshi et al. (2024) highlight the use of adaptive AI models that integrate evidence-based teaching strategies such as inquiry-based learning, problem-based learning, and collaborative learning (Sari & Ahmad, 2024). These models play a role in adjusting information based on student success and enhancing engagement. In the context of laboratories, AI assistants integrated with remote laboratories enable personalized learning, continuous assessment, and instant feedback (Lizano-Sánchez et al., 2025). This shows AI's capability to go beyond theoretical learning and support practical experiences. From a pedagogical design perspective, De la Ossa et al. (2024) emphasize the importance of integrating AI with pedagogical strategies specifically designed to create motivating learning environments. This underscores that AI is not a replacement for teachers but a tool that should be deliberately and strategically integrated to achieve learning and educational goals in general.

3. Challenges and Ethical Considerations in Implementing AI in Chemistry Education

Although the potential of AI in chemistry teaching is vast, several challenges and ethical considerations must be addressed to ensure its responsible and effective implementation. One primary concern is accuracy and academic integrity. Students have concerns about the accuracy of the information provided by AI and the potential for AI to affect academic integrity. This perception indicates that although AI is valued as an additional tool, it is not yet fully trusted for critical tasks. The risk of over-reliance on AI is also a concern highlighted in the same study. Data privacy is another crucial ethical consideration, particularly since AI systems frequently require access to user data for personalization (Daher et al., 2023). Organizations and AI developers must ensure robust data protection.

Furthermore, student and teacher readiness present a significant practical challenge. The need for adequate training for both teachers and students in managing and appropriately utilizing AI technology resources has been identified (De la Ossa et al., 2024). Without sufficient training, the potential of AI may not be fully utilized or may even be misused. Overcoming these challenges requires a multi-faceted approach, involving the development of more reliable and transparent AI technologies, the creation of clear policies regarding AI use, and investment in training and support for all education stakeholders.

Therefore, the findings imply that the successful integration of AI in chemistry education necessitates a strategic and cautious approach. It requires the development of specialized AI tools that can adeptly navigate the visual and abstract nature of chemical concepts, going beyond mere textual explanations. Furthermore, it underscores the importance of comprehensive training for educators and students to ensure effective utilization of AI, mitigate potential pitfalls like over-reliance, and address ethical considerations. The goal should be to leverage AI's strengths in engagement and personalization while consciously designing pedagogical interventions that fill the gaps in AI's current capabilities, thereby fostering genuine critical thinking and deep conceptual mastery rather than simply facilitating information access. This systematic analysis moves beyond a theoretical narrative by grounding these conclusions in empirical observations, allowing for practical recommendations for future AI development and integration in chemistry learning.

4. CONCLUSIONS

Based on a systematic review of 13 articles published between 2023 and 2025, the implementation of artificial intelligence in chemistry education has shown a significant transformation in chemistry teaching, positively impacting student motivation and engagement, and fostering meaningful learning by clarifying complex concepts, improving learning efficiency, encouraging collaboration, integrating evidence-based teaching strategies, and facilitating personalized learning, continuous assessment, and real-time feedback. Various AI technologies, such as chatbots, adaptive models, and AI assistants integrated into remote laboratories, play a crucial role in enhancing personalization, interactivity, and engaging content presentation, thus creating a conducive learning environment. However, the implementation of AI faces challenges and considerations, including a notable scarcity of empirical studies specifically focusing on its impact in chemistry teaching, which makes synthesizing a broad body of empirical evidence difficult. Other challenges encompass concerns regarding information accuracy, academic integrity, data privacy, and the potential for overreliance on AI, further emphasizing the need for adequate training for educators and students in the practical and ethical use of AI technology, and its thoughtful, responsible integration.

REFERENCES

Aldwinarta, F. H., Nurdiana, R. & Sulistina, O. (2024). Media pembelajaran berbasis ai chatbot pada materi termokimia di SMA apakah dibutuhkan? *Jurnal Inovasi Pendidikan Kimia*, *18*(1), 1–6. https://doi.org/10.15294/jipk.v18i1.49044

Almasri, F. (2024). Exploring the impact of artificial intelligence in teaching and learning of science: A systematic review of empirical research. *Research in Science Education*, *54*(5), 977–997. https://doi.org/10.1007/s11165-024-10176-3

Balaquiao, E. C. (2024). Optimizing students' performance through artificial intelligence (ai) technology: A gamified approach to smart learning environment. *Journal of Pedagogy and Education Science*, *3*(02), 104–114. https://doi.org/10.56741/jpes.v3i02.515

Basimin, M. Q., Habiddin, H. & Joharmawan, R. (2023). Higher order thinking skills and visual representations of chemical concepts: A literature review. *Hydrogen: Jurnal Kependidikan Kimia*, *11*(6), 1043. https://doi.org/10.33394/hjkk.v11i6.10173

Blonder, R., Rap, S. & Mamlok-Naaman, R. (2023). Frontiers of research in chemistry education for the benefit of chemistry teachers. *Chemistry Teacher International*, *5*(2), 107–111. https://doi.org/10.1515/cti-2023-0041

Chi, M., Zheng, C. & He, P. (2024). Assessing high school students' chemical thinking using an essential questions-perspective framework. *Chemistry Education Research and Practice*, *25*(4), 1143–1158. https://doi.org/10.1039/d4rp00106k

Chiu, W. K. (2021). Pedagogy of emerging technologies in chemical education during the era of digitalization and artificial intelligence: a systematic review. *Education Sciences*, *11*(11), 709. https://doi.org/10.3390/educsci11110709

Daher, W., Diab, H. & Rayan, A. (2023). Artificial intelligence generative tools and conceptual knowledge in problem solving in chemistry. *Information (Switzerland)*, *14*(7), 409. https://doi.org/10.3390/info14070409

De la Ossa, L. A. M., Garzón, N. N., Pérez, C., Puildo, B. E. & Hoyos, J. H. (2024). Evaluation of artificial intelligence as a source of motivation in the teaching of chemistry: A study with tenth grade students at the adventist school of ibagué. *Evolutionary Studies in Imaginative Culture*, 2193, 2193–2208. https://doi.org/10.70082/esiculture.vi.1721

Eitemüller, C., Trauten, F., Striewe, M. & Walpuski, M. (2023). Digitalization of multistep chemistry exercises with automated formative feedback. *Journal of Science Education and Technology*, *32*(3), 453–467. https://doi.org/10.1007/s10956-023-10043-2

Fan, Z., Yan, Z. & Wen, S. (2023). Deep learning and artificial intelligence in sustainability: A review of SDGs, renewable energy, and environmental health. *Sustainability (Switzerland)*, *15*(18), 13493. https://doi.org/10.3390/su151813493

Halimah, N., Degeng, M. D. K. & Soepriyanto, Y. (2024). Peranan tingkat penerimaan learning management system terhadap kemampuan self regulated learning. *JKTP: Jurnal Kajian Teknologi Pendidikan*, *7*(3), 118. https://doi.org/10.17977/um038v7i32024p118

Hasmarani, S., . R. & . R. (2019). Analisis kemampuan peserta didik dalam menyelesaikan soal asam basa pada tingkat keterampilan berpikir kritis dan berpikir kreatif di kelas XI IPA SMA/MA di kec. bulukumpa. In *Chemistry Education Review (CER)* (Vol. 2, Issue 2). https://doi.org/10.26858/cer.v2i2.8954

Iyamuremye, A., Niyonzima, F. N., Mukiza, J., Twagilimana, I., Nyirahabimana, P., Nsengimana, T., Habiyaremye, J. D., Habimana, O. & Nsabayezu, E. (2024). Utilization of artificial intelligence and machine learning in chemistry education: a critical review. *Discover Education*, *3*(1), 00197–5. https://doi.org/10.1007/s44217-024-00197-5

Jere, S. & Mpeta, M. (2025). Integrating generative artificial intelligence chatbots into chemistry teaching: Impact of affective factors on engagement and conceptual understanding. *Eurasia Journal of Mathematics, Science and Technology Education*, *21*(10). https://doi.org/10.29333/ejmste/17077

Kohnke, S. & Zaugg, T. (2025). Artificial intelligence: An untapped opportunity for equity and access in STEM education. *Education Sciences*, *15*(1). https://doi.org/10.3390/educsci15010068

Lizano-Sánchez, F., Idoyaga, I. J., Orduna, P., Rodriguez-Gil, L. & Arguedas-Matarrita, C. (2025). Students' interactions with an artificial intelligence assistant in a remote chemistry laboratory. *Frontiers in Education*, *10*. https://doi.org/10.3389/feduc.2025.1712743

P dos Santos, R. (2023). Enhancing chemistry learning with ChatGPT, bing chat, bard, and claude as agents-to-think-with: A comparative case study. In *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.4629567

Pedersen, A. Y. & Caviglia, F. (2018). Researcher or fellow citizen? Looking for a role model in the humanities. *Proceedings of International Conference of the Learning Sciences, ICLS* , *2*(2018-June), 945–948.

Permatasari, M. B., Rahayu, S. & Dasna, I. W. (2022). Chemistry learning using multiple representations: A systematic literature review. *Journal of Science Learning*, *5*(2), 334–341. https://doi.org/10.17509/jsl.v5i2.42656

Qureshi, M. D. A., Ayaz, S., Amjad, F., Ramzan, M. F., Ikram, M., & Hussain, I. (2024). Innovating chemical education: Leveraging artificial intelligence and effective teaching strategies to enhance public engagement in environmental and organic chemistry. Indus Journal of Social Sciences, 2(2), 253-271. https://doi.org/10.59075/ijss.v2i2.189

Reyes, R. L. (2025). Integrating real-world problems into chemistry curricula: Enhancing relevance and student engagement. *Forum for Education Studies*, *3*(2), 2177. https://doi.org/10.59400/fes2177

Sari, N. I. & Ahmad, F. (2024). Studi komparatif: Model pembelajaran kooperatif tipe jigsaw dan number head together dalam pembelajaran ipa pada siswa sekolah menegah pertama. *Jurnal Studi Guru Dan Pembelajaran*, *7*(2), 850–861. https://doi.org/10.30605/jsgp.7.2.2024.4396

Talanquer, V. (2022). The complexity of reasoning about and with chemical representations. *JACS Au*, *2*(12), 2658–2669. https://doi.org/10.1021/jacsau.2c00498

Tamim, R. M., Borokhovski, E., Bernard, R. M., Schmid, R. F., Abrami, P. C. & Pickup, D. I. (2021). A study of meta-analyses reporting quality in the large and expanding literature of educational technology. *Australasian Journal of Educational Technology*, *37*(4), 100–115. https://doi.org/10.14742/ajet.6322

Tonyali, B., Ropohl, M. & Schwanewedel, J. (2023). What makes representations good representations for science education? A teacher-oriented summary of significant findings and a practical guideline for the transfer into teaching. *Chemistry Teacher International*, *5*(4), 413–425. https://doi.org/10.1515/cti-2022-0019

Zawacki-Richter, O., Kerres, M., Bedenlier, S., Bond, M. & Buntins, K. (2019). Systematic reviews in educational research: Methodology, perspectives and application. *Systematic Reviews in Educational Research: Methodology, Perspectives and Application*, *64*(3), 1–161. https://doi.org/10.1007/978-3-658-27602-7