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Integrating Artificial Intelligence and Green Chemistry into Innovative Chemistry Education

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Abstract

This study aims to identify the challenges and potential applications of Artificial Intelligence (AI) and Green Chemistry in chemistry education and laboratory practices as innovative approaches to chemistry teaching. The research method uses a Systematic Literature Review (SLR) conducted by referring to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Fifteen peer-reviewed articles published in the last four years and indexed in Scopus were selected from several databases, including the Education Resources Information Center (ERIC) and the Multidisciplinary Digital Publishing Institute (MDPI). The review results show that an effective integration strategy needs to position AI as a pedagogical tool for cognitive scaffolding, an object of scientific evaluation, and a medium for academic reflection, while Green Chemistry needs to be positioned as a framework for assessing the efficiency, safety, and environmental impact of chemical processes. This integration requires strengthening lecturer capacity, utilizing AI as a cognitive laboratory, implementing hybrid assessments, and integrating AI ethics into the curriculum. Thus, the integration of AI and Green Chemistry not only contributes to learning innovation but also has the potential to transform Indonesian chemistry education to be more critical, reflective, ethical, and sustainable. It is suggested that these findings serve as a pedagogical framework for educators and policymakers in navigating the digital era.

Keywords: artificial intelligence, chemical pedagogy, green chemistry, innovation

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1. Introduction

Technological changes in the era of the Industrial Revolution 4.0 and the development towards Society Revolution 5.0 have driven digitalization in all aspects of life, including science and higher education (Pont-Niclòs et al. (2024). Artificial Intelligence (AI) has become one of the most influential technologies in changing the way humans work, learn, and conduct scientific research. AI enables the processing of large amounts of data, the development of predictive models, the automation of work processes, as well as efficient information management in various scientific fields, including chemistry (Akaygun and Kilic, 2025). In the context of education, AI plays a role in helping lecturers and students achieve a more adaptive, effective, and personalized learning process through intelligent tutor systems, chatbots, and learning algorithms based on interactive software. Research by Iyamuremye et al. (2024) shows that AI and machine learning are capable of creating personalized learning environments, providing real-time feedback, as well as supporting simulations and virtual laboratories that enhance student engagement in chemistry learning. Nevertheless, the effectiveness of its implementation still requires further evaluation and appropriate pedagogical strategies.

In addition, AI also plays a role in promoting sustainability-based laboratory innovation by providing safer chemical alternatives, minimizing waste, and aligning with the principles of Green Chemistry, as applied in AI chatbot-assisted cyclohexene synthesis experiments in the academic environment (Kim, 2025).

The research related by technology-assisted learning innovation focuses on the utilization of AI in education. The study of Akaygun Kilic (2025) centers on the experiences of prospective chemistry teachers in creating visualizations of chemistry concepts using GenAI tools. The results suggest that working with GenAI tools can help prospective teachers develop teaching skills, such as critical evaluation through the lenses of digital technology. This research is reinforced by studies on the multimodal capabilities of Generative AI in solving visual chemistry problems, which demonstrate the potential of AI to assist in interpreting graphs, molecular structures, and other visual representations that often become obstacles in chemistry learning (Tassoti, 2024).

Experimental activities in chemistry education face challenges related to safety, the use of hazardous materials, costs, and waste. According to research by Etzkorn Ferguson (2023) and O'Neil et al (2021), the principles of green chemistry are necessary to minimize these risks. In the study by Widyantoro et al. (2025), sustainability efforts are also emphasized to highlight the importance of students' understanding of the ecological impact of laboratory activities. Research by Lestari et al. (2024) shows that the application of Green Chemistry principles can reduce the use of hazardous materials, increase environmental awareness, and strengthen students' problem-solving skills in the context of sustainability.

The integration of AI, as discussed in research conducted by Ruff et al. (2024), can support the optimization of experiments to be safer and more environmentally friendly. Although offering pedagogical and ecological benefits, the integration of AI in chemistry learning also presents epistemic and pedagogical challenges that need to be critiqued.
The integration of AI in chemistry lectures presents new challenges, particularly related to the accuracy of information and the need to maintain students' critical thinking skills (Berber et al., 2025; Feldman-Maggor et al., 2025). Research by Schuessler et al. (2024) indicates that educational institutions need to develop policies and learning strategies that can maximize the benefits of AI while minimizing the risks of technology dependence and violations of academic integrity. Nevertheless, research conducted by Ruff et al. (2024) shows that AI still has the potential to support green chemistry learning if its use is guided through appropriate pedagogical mentoring.

The background of this research emphasizes the importance of applying the trend of integrating AI and Green Chemistry in chemistry lectures at the University levels, as has been implemented in various countries. Based on this context, this study reviews several scientific articles discussing AI and Green Chemistry. The review results in the formulation of the main research questions that are the focus of this study, which are: (1) What challenges arise in the process of integrating AI-based Green Chemistry in chemistry lectures? and (2) What are effective strategies to support the implementation of AI-based Green Chemistry in chemistry lectures?

2. Research Method

This study employed a Systematic Literature Review (SLR) following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2009). The SLR method was chosen because it allows researchers to obtain a comprehensive overview of research developments, research gaps, and the direction of future research through systematic, transparent, and replicable procedures comprehensively (Xiao & Watson, 2019).

2.1. Eligibility Criteria

The determination of eligibility criteria is carried out before the article search process to ensure that the literature reviewed is in accordance with the research objectives. The inclusion and exclusion criteria used are presented in Table 1.

Table 1. Inclusion and Exclusion Criteria of Articles

Aspect	Inclusion Criteria	Exclusion Criteria
Year of Publication	2021 – 2025	Before 2021
Language	English	Langueges other than English
Type of Document	Research Artikel (Original Research Article), Review Article and Systematic Review	Meta-analysis, conference proceeding, editorial, book chapter, short communication
Database	Indexed by Scopus and/or Web of Science	Not indexed by Scopus or WoS
Field of Study	Artificial Intelligence, Green Chemistry, Chemistry Education, Chemistry Learning	Not related to Chemistry Education or Integration of AI and Green Chemistry
Level of Education	Higher Education (collage/university)	Primary and secondary education
Article Acces	Full-text available	Abstract only or full-text not available

2.2. Information Sources

The literature search was conducted directly through reputable international databases, which is Scopus and Web of Science (WoS). These two databases were chosen because they have a wide coverage of international journals, a strict indexing process, and are often used as primary sources in SLR research to minimize publication bias.
The search using a combination of keywords formulated based on the research focus. The keywords used include: "Artificial Intelligence" AND "Chemistry Education", "Artificial Intelligence" AND "Chemistry Lectures", "Green Chemistry" AND "Chemistry Education", "Green Chemistry" AND "Higher Education", "Artificial Intelligence" AND "Green Chemistry", "Artificial Intelligence" AND "Green Chemistry" AND "Chemistry Education".

Boolean operators (AND and OR) were used to broaden and narrow the search results as needed.

2.3. Literature Selection

The literature selection stage was carried out following the PRISMA flow, which consists of four stages: identification, screening, eligibility, and inclusion.

In the identification stage, all articles obtained from Scopus and WoS were collected. The initial search resulted in 60 articles that matched the keywords used.

Next, duplicate articles appearing in both databases were removed. After duplicates were eliminated, articles were screened based on their titles and abstracts to assess their relevance to the research topic. At this stage, 30 articles met the initial criteria.

The next stage was the eligibility assessment through a full-text review. Articles that did not discuss the integration of AI and Green Chemistry in the context of chemistry education, did not focus on higher education, or did not meet the inclusion criteria were excluded from the analysis process.

The final result of the selection process yielded 15 articles that met all the criteria and were used in the data synthesis process. This SLR research can be seen in Figure 1.

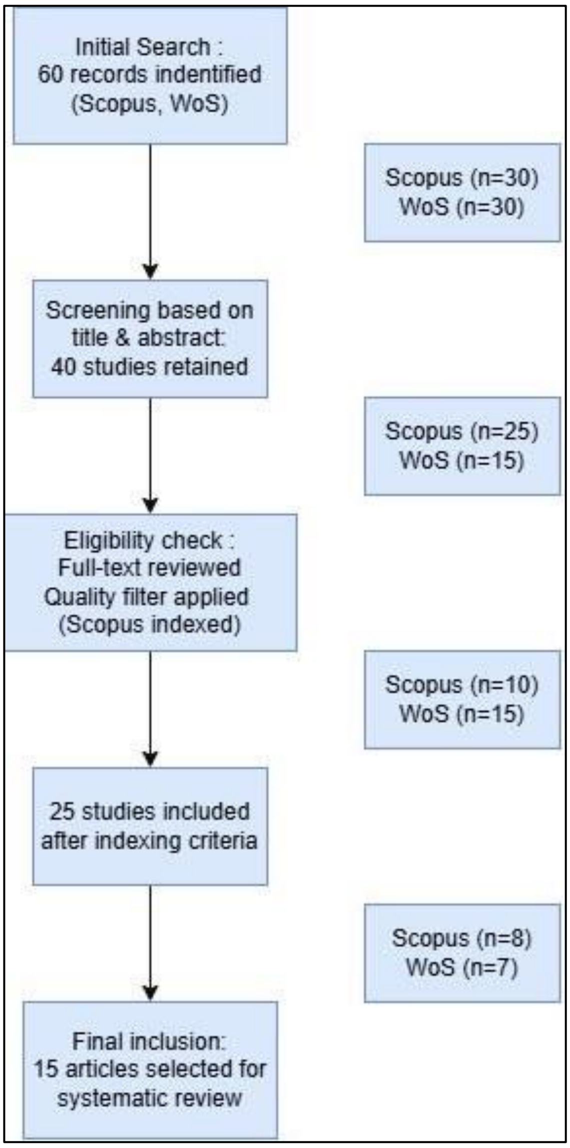

Figure 1. Flow Chart Based on PRISMA Guidelines

2.4. Data Collection and Item Selection

Data from each selected article were extracted using a pre-designed data extraction sheet. The extracted information is presented in Table 2.

Table 2. The Extracted Information

No	Extracted Information
1.	Article identity (author, year of publication, country of origin of the study).
2.	Research objectives.
3.	Research design and methods
4.	Implementation of Artificial Intelligence in chemistry learning.
5.	Implementation of Green Chemistry in chemistry learning.
6.	Learning models or strategies used.
7.	Main research findings.
8.	Challenges in implementing AI and Green Chemistry.
9.	Recommendations or strategies proposed by the researchers.

All obtained data were then analyzed using thematic analysis techniques. Articles were grouped based on the main emerging themes, which are challenges in implementing the integration of AI and Green Chemistry in chemistry lectures and effective strategies for applying the integration of AI and Green Chemistry to improve the quality of chemistry learning in higher education.

The results of this analysis are used to identify research trends, research gaps, as well as opportunities for developing AI and Green Chemistry-based learning models in future chemistry education.

3. Result and Discussion

The review findings indicate that effective integration requires positioning AI as a pedagogical tool for cognitive scaffolding, an object of scientific inquiry, and a medium for academic reflection. Green chemistry should simultaneously be positioned as a framework for evaluating the efficiency, safety, and environmental impact of chemical processes.

The integration of AI and Green Chemistry in chemistry lectures offers great opportunities to enhance learning effectiveness, but at the same time presents several challenges. Conceptually, the development of AI in chemistry has experienced significant acceleration, reflected in the utilization of machine learning, neural networks, and increasingly accurate molecular structure prediction models (Huwer et al., 2025). These advances open up space for the application of AI as an analytical, simulative, and experimental learning tool, enabling students to understand the principles of green chemistry through a data-based approach.

The conceptual approach based on Systems Chemistry proposed by Berber et al (2025) emphasizes that AI has the potential to mimic the dynamics of complex chemical systems, thus can be used to teach principles of sustainability, energy efficiency, and waste minimization through more realistic chemical reaction simulations. Meanwhile, the application of AI in supporting green organic chemistry shows that AI can be used for reaction optimization, selection of environmentally friendly solvents, and sustainable catalyst design, all of which are highly relevant for chemistry lectures aimed at green lab practices (Singh et al., 2024). Despite its promising potential, the implementation of AI in chemistry learning is not without a number of structural and pedagogical obstacles.

However, this integration still faces obstacles, such as limitations in digital infrastructure, educator readiness, and students' data literacy competencies. Uneven technological literacy indicates the need for intensive training for teachers as well as the development of learning modules that combine AI with the principles of Green Chemistry. Overall, the literature emphasizes that the opportunities for integrating AI and Green Chemistry are significant, but must be followed by systematic implementation strategies, strengthening educator capacity, and adaptive curriculum design (Huwer et al., 2025).

Based on this background, this article analyzes the forms of AI and Green Chemistry integration in various countries by highlighting implementation challenges as well as effective strategies to integrate them into the chemistry curriculum in Indonesia. An overview of artificial intelligence and green chemistry into innovative chemistry education is presented in Table 3.

Table 3. Integrating Artificial Intelligence and Green Chemistry into Innovative Chemistry Education

No	Title	Journal Name	Author	Indexed	Methodology	Challenges	Strategies
1	Integrating Artificial Intelligence (AI) Chatbots and Green Chemistry Principles in the Synthesis of Cyclohexene	Journal of Chemical Education	Ji Kim (2025)	Scopus (Q2)	Integration of AI chatbots and Green Chemistry in the cyclohexene synthesis practicum through the identification of green catalysts, evaluation based on Green Chemistry principles, literature validation, and laboratory experiments.	AI recommendation accuracy that is not always appropriate, trade-offs between sustainability and reaction yields, low student AI literacy, and the potential for dependence on AI.	Applying a human-in-the-loop approach, validating AI results through literature and experiments, evaluating recommendations based on Green Chemistry principles, and using inquiry-based learning to train critical thinking.
2	AI in Chemistry and Chemical Education	International Journal of Physics and	Johanes Huwer, Nikolai Maurer,	Scopus (Q2)	Conceptual studies and literature analysis on the use of AI in	Accuracy and bias of AI information, lack of algorithm	Integrating AI literacy into the curriculum and teacher education,

No	Title	Journal Name	Author	Indexed	Methodology	Challenges	Strategies
		Chemistry Education	Pauline Mund, Nadja Belova (2025)		chemistry and chemistry education by reviewing AI applications, required competencies, and their implications for learning and teacher training.	transparency, risk of declining critical thinking skills, limited teacher competence, digital divide, and ethical issues such as data privacy and academic integrity.	implementing the DiKoLAN AI framework, developing critical evaluation skills for AI results, and using a responsible AI approach that positions AI as a learning support tool and not a replacement for scientific thinking processes.
3	Artificial Intelligence in Green Organic Chemistry : Pathway to Sustainable and Eco-Friendly Chemistry	Asian Journal of Chemistry	Gurinderdeep Singh, Eashwar Sai Komarla Rajasekhar, Kamati Mounika, K.R. Sri Krishna Tulasi, Tejaswi Dondapati, M. Himasaila, and Sowhanya Pulipati (2024)	Scopus (Q4)	Literature review on the application of AI in Green Organic Chemistry through analysis of AI usage for reaction optimization, selection of green solvents, catalyst design, waste reduction, and development of sustainable synthesis pathways.	Limitations in the availability of quality data, difficulties in integrating AI with laboratory experiments, and low transparency of AI models (black-box problem) which can reduce user trust.	Developing a better Green Chemistry database, integrating AI predictions with experimental validation, implementing explainable AI, and ensuring AI usage remains aligned with the 12 Principles of Green Chemistry to achieve sustainability in chemical processes.
4	Generative Artificial Intelligence (GenAI)	Journal of Chemical Education	Sevil Akaygun and Ilayda	Scopus (Q2)	A qualitative phenomenographic study involving 22	GenAI visuals often contain scientific inaccuracies,	Applying prompt engineering, conducting

No	Title	Journal Name	Author	Indexed	Methodology	Challenges	Strategies
	as the Artist of Chemistry Visuals: Chemistry Preservice Teachers' Reflection on Visuals Created by GenAI		Kilic (2025)		prospective chemistry teachers to create and reflect on visual chemistry concepts using GenAI through questionnaires and interviews, then analyzed using the PCK and TPACK frameworks.	limitations in chemical representation, pedagogical mismatches, potential misconceptions, and difficulties in generating appropriate visuals through the given prompts.	critical evaluation of visuals based on PCK and TPACK, improving AI literacy, and using GenAI visuals as a medium for reflection and discussion before being implemented in teaching.
5	Artificial Intelligence in Chemistry Research Implications for Teaching and Learning	Journal of Chemical Education	Sandra Berber, Mathea Bruckner, Nikolai Maurer, and Johannes Huwer (2025)	Scopus (Q2)	A systematic literature review using Web of Science and PRISMA to identify AI applications in chemical research, followed by workshops for chemistry teachers to explore the implications of AI for teaching and teacher education.	The gap between AI developments in chemical research and their implementation in education, low teacher understanding of scientific AI applications, and limited competence to integrate AI into chemistry teaching.	Organizing AI training and workshops for teachers, strengthening Technological Content Knowledge (TCK), integrating AI case studies into chemistry teaching, and utilizing the TPACK and DiKoLAN frameworks for developing AI competencies in chemistry education.
6	Creativity and Artificial Intelligence : A Study with Prospective Teachers	Digital Education Review	Isabel Pont-Niclos, Yolanda Echeoyen-Sanz, Patricia Orozco	Scopus (Q2)	Mixed methods research with a storytelling intervention involving 42 pre-service teachers. Participants created stories independently,	Risks of reduced originality, dependence on AI, potential academic dishonesty, doubts about the accuracy	Using AI after the independent ideation process, utilizing AI for self-reflection and evaluation, developing

No	Title	Journal Name	Author	Indexed	Methodology	Challenges	Strategies
			- Gomez, Antonio Martin-Expeleta (2024)		then used generative AI to support and reflect on the creative process, with data obtained through surveys, story analysis, and participant reflections.	of AI results, and difficulties in composing effective prompts to produce quality outputs.	prompting and critical thinking skills, and positioning AI as a tool to support creativity, not as a replacement for human creativity.
7	Using ChatGPT for Method Development and Green Chemistry Education in Upper-Level Laboratory Courses	Journal of Chemical Education	Emily F. Ruff, Jeanne L. Franz, and Joseph K. West (2024)	Scopus (Q2)	Implementation of learning in Advanced Analytical Chemistry and Inorganic Chemistry courses by utilizing ChatGPT to search for experimental methods and Green Chemistry modifications in research proposals, accompanied by prompt documentation, lecturer evaluation, student reflection, and AI perception surveys.	ChatGPT often produces general information, lacks accuracy, is not specific, or does not adhere to Green Chemistry principles, and rarely provides verifiable references, resulting in students' lack of trust in AI-generated results.	Using AI as an exploratory tool that must be validated through scientific literature and discussions with lecturers, training critical evaluation of AI output, and utilizing reflection to improve AI literacy and understanding of Green Chemistry.
8	Perspectives of Generative AI in Chemistry Education Within the	Journal of Science Education and Technology	Yael Feldman-Maggor, Ron Blonder, Giora Alexan	Scopus (Q1)	A conceptual perspective article analyzing the use of ChatGPT in chemistry education through the	Hallucination, bias and discrimination in AI output, limitations in teachers' ability to evaluate AI	Integrating AI literacy with TPACK, developing prompt engineering and critical evaluation

No	Title	Journal Name	Author	Indexed	Methodology	Challenges	Strategies
	TPACK Framework		dron (2025)		TPACK framework by using teacher–AI dialogue examples to examine the role of prompt engineering, output evaluation, and teacher competence.	responses and compose effective prompts, and the inadequacy of the TPACK framework in accommodating AI literacy.	skills, enhancing teacher training related to AI, and expanding the TPACK framework to include AI competencies and ethical issues in GenAI usage.
9	Integrating Green Chemistry into Chemistry Education	Angewandte Chemie – International Edition	Felicia A. Etzkorn and Jamie L. Ferguson (2023)	Scopus (Q1)	A conceptual article that analyzes the integration of Green Chemistry into the curriculum and chemistry learning through a systems thinking approach, by connecting chemical concepts, safety, chemical life cycles, and sustainability.	The lack of integration of Green Chemistry in the curriculum, limited systems thinking-based learning models, as well as limited teaching materials and assessments that connect chemical concepts with sustainability issues.	Using a systems thinking approach, product life cycle analysis, the application of green metrics, environmentally friendly laboratory practices, and the integration of Green Chemistry into various courses to develop students' understanding of sustainability and problem-solving skills.
10	Fine-tuning AI Models for Enhanced Consistency and Precision in Chemistry	Computers and Education: Artificial Intelligence	Sri Yamtinah, Antuni Wiyarsi, Hayuni Retno Widarti, Ari	Scopus (Q1)	Developing and evaluating Gemini 1.5, Gemini 1.0, BERT, and XLNet models fine-tuned using expert-annotated	General AI models lack understanding of complex chemical terminology and reasoning, resulting in	Conducting fine-tuning based on expert-annotated chemical data, applying gradual unfreezing and

No	Title	Journal Name	Author	Indexed	Methodology	Challenges	Strategies
	Educational Assessments		Syahid Shidiq and Dimas Gilang Ramadhani (2025)		chemistry answer datasets through Seq2Seq Grading, Regression Task, and Attention-Based Grading approaches to improve the quality of chemistry assessment.	assessments that are less consistent with experts, and require high-quality, unbiased training data to ensure fairness in assessment.	early stopping, and continuously evaluating the model using indicators of accuracy, consistency, and alignment with expert assessments to improve assessment reliability.
11	Discussing the Ethic of Professional AI Use in Undergraduate Chemistry Course	Journal of Chemical Education	Emily F. Ruff and Jennifer M. O. Zemke (2025)	Scopus (Q2)	Implementation of two AI ethics learning activities through article analysis, class discussions, argument presentations, stakeholder identification, as well as student reflections on the use of AI in chemistry, health, and research.	Low student understanding of the ethical implications of AI, concerns about job loss, protection of intellectual property rights, risk of hallucination, lack of AI transparency, and the potential misuse of AI in scientific research.	Applying case-based discussions and ethical dilemmas, developing AI literacy and critical thinking, and emphasizing responsible use of AI through information verification, transparency, and protection of human contributions.
12	Smart Analytical Chemistry: Integrating Green, Sustainable, White and AI-Driven Approaches in	TrAC – Trend in Analytical Chemistry	Chaudhery Mustansar Hussain, Ghazanfar Hussain, Rustem	Scopus (Q1)	Literature review integrating Green Analytical Chemistry, Sustainable Analytical Chemistry, White Analytical Chemistry, as well as AI, automation, and	High implementation costs, the need for multidisciplinary expertise, lack of system standardization, issues of AI transparency and bias, data privacy issues,	Integrating the principles of Green, Sustainable, and White Analytical Chemistry with AI, implementing miniaturization and portable sensors, using

No	Title	Journal Name	Author	Indexed	Methodology	Challenges	Strategies
	Modern Analysis		Kecili (2025)		miniaturization to build the concept of Smart Analytical Chemistry in modern analysis.	as well as challenges of sustainability and regulation of smart technologies.	machine learning for method optimization, developing explainable AI, and strengthening cross-disciplinary collaboration and regulation.
13	Green Chemistry Teacher Professional Development in New York State High Schools: A Model for Advancing Green Chemistry	Journal of Chemical Education	Amy S. Cannon, Kate R. Anderson, Mollie C. Enright, Donia G. Kleinsasser, Ann R. Klotz, Natalie J. O'Neil and Lucas J. Tucker (2023)	Scopus (Q2)	Professional development program for 224 high school teachers through one-day and three-day train-the-trainer-based workshops, using collaborative approaches, hands-on learning, practicum modifications, and long-term evaluation through surveys.	Low teacher understanding of Green Chemistry, limited learning resources and training, diverse teacher backgrounds, and difficulties integrating safer practicums into the existing curriculum.	Providing practice-based training, ready-to-use Green Chemistry practicum guides, building teacher networks through the train-the-trainer model, and aligning Green Chemistry materials with curriculum standards to support sustainable implementation.
14	Approaches to Incorporating Green Chemistry and Safety into Laboratory Culture	Journal of Chemical Education	Natalie J. O'Neil, Star Scott, Rachael Relph and Ettigounder Ponnus	Scopus (Q2)	A conceptual review based on systems thinking that integrates Green Chemistry, laboratory safety, the RAMP approach, Green	A safety culture that is still compliance-oriented, resistance to changes in laboratory methods, complexity in implementing	Applying systems thinking, integrating Green Chemistry with the RAMP approach, using DOZN 2.0 for risk and sustainability

No	Title	Journal Name	Author	Indexed	Methodology	Challenges	Strategies
			amy (2021)		Laboratories, and the use of DOZN 2.0 metrics to assess the risks and sustainability of chemical experiments.	Green Chemistry in research, and lack of collaboration between researchers, safety professionals, and sustainability managers.	evaluation, developing Green Laboratories programs, and strengthening communication and collaboration among laboratory stakeholders.
15	Teaching Sustainability through Green Chemistry: An Experiential Learning Approach	Journal of Chemical Education	Clarissa Widyantoro, Jia Yi Han, Jonathan Sing Huat Ong, Kien Huay Goh and Fun Man Fung (2025)	Scopus (Q2)	A professional development program for teachers based on experiential learning that integrates Green Chemistry, Sustainability, and Case-Based Learning through workshops, collaborative discussions, case study development, and field visits to Semakau Landfill.	Limited teacher experience in integrating sustainability into chemistry teaching, the significant time required to design case-based learning, and difficulties in connecting chemistry concepts with real-world sustainability issues.	Using Case-Based Learning (CBL) and experiential learning, utilizing authentic case studies and field visits, as well as building teacher collaboration and reflection to develop contextual and sustainability-oriented chemistry teaching.

3.1. Challenges in Integrating AI and Green Chemistry in Chemistry Lectures

The analysis results of the article in Table 3 show that the integration of AI and Green Chemistry in chemistry lectures has developed into an innovative approach capable of improving the quality of learning. However, this research also faces various challenges, which are epistemological, pedagogical, chemistry learning culture, structural, and academic integrity challenges. The first challenge lies in the epistemological issue, which is the limitation of AI in producing scientifically valid chemical knowledge. In chemistry education, this issue is very crucial because generative AI like ChatGPT can produce answers that appear linguistically convincing but are not necessarily chemically correct. Ruff et al. (2024) show that ChatGPT often generates experimental recommendations that are inaccurate, too general, and less relevant to green chemistry principles, especially in the development of laboratory methods. This research confirms that AI cannot be positioned as a scientific authority in chemistry learning. If students accept AI answers without verification, then AI potentially reinforces chemical misconceptions rather than correcting them. In the pedagogical context, this issue is serious because chemistry students, especially in the early semesters, often do not have a sufficient conceptual foundation to distinguish answers that appear scientific from those that are scientifically correct. This risk makes AI not only a learning aid but also a potential source of pseudo-understanding, a condition where students feel they understand a concept just because they can produce an answer, whereas they do not understand the scientific basis. Besides epistemological issues, the next challenge relates to the pedagogical readiness of educators in meaningfully integrating AI. Huwer et al. (2025) emphasize that the effectiveness of AI in chemistry education highly depends on the pedagogical competence of teachers and lecturers in managing the relationship between chemistry content, pedagogy, and technology. This is reinforced by Feldman-Maggor et al. (2025), who show that digital technology is still insufficient to address the challenges of AI in chemistry education because it does not yet encompass aspects of AI literacy, such as the ability to understand bias, hallucinations, algorithmic discrimination, and the epistemological limitations of generative models. In chemistry education, this issue is significant because lecturers are not only required to be able to use AI but also must be able to teach how AI needs to be questioned, tested, and evaluated scientifically. This pedagogical challenge indicates that the main barrier to AI integration does not lie in the technology itself but in the capacity of educators to transform AI from an automation tool into an instrument for reflective learning. Besides the pedagogical aspect, another obstacle arises from the chemistry learning culture, which is still dominantly procedural and transmissive, especially in the context of higher education in Indonesia. In general, chemistry learning in Indonesia still tends to position students as recipients of concepts and executors of procedures, rather than as evaluators of scientific decisions.

Chemistry internships are still largely oriented towards verifying theory and the success of reaction outcomes, rather than evaluating process efficiency, experimental safety, and environmental impact. In fact, Etzkorn and Ferguson (2023) emphasize that chemistry education globally still lags behind industry in adopting sustainable practices. In education in Indonesia, this condition is more complex because chemistry learning is still often oriented towards memorizing concepts, solving algorithmic problems, and rigid laboratory procedures. As a result, students are less accustomed to assessing why a method is used, whether the reaction is safe, how much waste is produced, and whether greener synthesis alternatives are available. This condition indicates that AI integration risks becoming merely a new digital layer over old pedagogy that remains passive and procedural.

At the institutional level, the challenges become even more complex due to structural limitations of educational institutions in Indonesia. The integration of AI and Green Chemistry demands support in digital infrastructure, internet access, computing devices, adequate laboratories, and trained lecturers. However, in reality, chemistry education in Indonesia shows significant disparities among universities, especially between institutions in urban and non-urban areas. Therefore, AI integration has the potential to widen the quality gap in learning if implemented without adaptive strategies.
Similarly, the implementation of Green Chemistry requires laboratory facilities that support micro-scale experiments, waste management, and the use of safer materials—something that is not yet widely available. Cannon et al. (2023) and O'Neil et al. (2021) indicate that the success of green chemistry education heavily depends on systematic training, a laboratory safety culture, and evaluation tools. Therefore, the challenge is not only about adopting the concept but also the institutional readiness to gradually change the laboratory culture.

Besides structural limitations, there are issues of ethics and academic integrity. Ruff and Zemke (2025) emphasize that the use of AI in chemistry education demands the explicit integration of AI ethics into the curriculum. Based on the reality of higher education in Indonesia, this challenge becomes even more critical because AI can easily be used to generate reports, assignment answers, or practical analyses without adequate intellectual involvement from students. If not clearly regulated, AI has the potential to reinforce plagiarism, technological dependency, and the blurring of boundaries between digital assistance and independent scientific work. The implications for chemistry education are quite serious, as the learning objective is not only to produce correct answers but to shape an honest, critical, and responsible scientific way of thinking.

3.2. Effective Strategies in Integrating Artificial Intelligence and Green Chemistry in Chemistry Lectures

To address these challenges, the strategy of integrating AI and Green Chemistry in chemistry education must begin with repositioning AI as a pedagogical tool, not as an answer-giving machine. Kim (2025) shows that the use of AI chatbots in cyclohexene synthesis learning effectively helps students explore alternative syntheses, consider more environmentally friendly solvents and catalysts, as well as improve digital literacy and sustainability awareness. However, the pedagogical value of AI in this context does not lie in its answers, but in its function as cognitive scaffolding. AI needs to be used to encourage students to explore possibilities, compare alternatives, and build hypotheses, while scientific validation is still conducted through discussion, literature, and chemical reasoning. Thus, AI functions not as a substitute for thinking, but as a trigger for thinking.

At the pedagogical level, the most important strategy is to change the function of AI from a source of answers to an object of scientific evaluation. Research by Ruff et al. (2024) actually shows that AI's weaknesses can be utilized as pedagogical strengths because students can be trained to identify errors, biases, and inaccuracies in AI outputs. This approach in chemistry education is far more valuable than merely using AI to answer questions. Students need to be trained to critique the reasons AI recommends certain solvents, assess whether the choices are greener, check their safety, and consider their feasibility in the context of educational laboratories. This approach strengthens critical thinking skills, scientific evaluation, and evidence-based reasoning, which are actually the core of chemistry education.

The most relevant strategy that can be applied in Indonesia is the reorientation of chemistry pedagogy from procedural learning to reflective and decision-based learning. The integration of AI and Green Chemistry should not be placed as additional material, but as a new framework for teaching chemistry. Students should not only understand reaction mechanisms but also be trained to evaluate atom efficiency, material toxicity, energy consumption, experiment safety, and environmental impact. Thus, Green Chemistry is not taught as an additional topic but as a lens to assess the quality of chemical decisions. Therefore, AI serves to enrich the evaluation process, not replace it (Widyantoro et al., 2025).

The next strategy is strengthening lecturers' capacity through pedagogical training based on AI literacy and Green Chemistry literacy. Huwer et al. (2025) emphasize the importance of developing lecturers' competence in utilizing AI ethically and effectively, meanwhile, Cannon et al. (2023) showed that workshop-based lecturer training is very effective in improving readiness to teach green chemistry. This model is relevant to be applied in Indonesia through community of practice-based lecturer training, lesson study, and the development of contextual modules. The focus is not only on technical skills in using AI, but on the ability to design learning that encourages students to think critically about AI recommendations and their sustainability implications.

In the institutional context, the most realistic strategy is to utilize AI as a cognitive laboratory through simulations, virtual experimentation, and scenario analysis. This approach allows students to evaluate experimental designs, assess risks, and compare synthesis alternatives before real practice is conducted. This strategy is relevant to the Indonesian context because it is more cost-effective, reduces waste, and aligns with the principles of Green Chemistry Hussain et al. (2025). In addition, AI can function as a safe and efficient experimental thinking space, not as a replacement for the laboratory, but as a bridge to more mature laboratory practice.

At the evaluation stage, the integration of AI in chemistry education must be accompanied by hybrid assessments and strong ethical education. Research by Yamtinah et al. (2025) shows that fine-tuned AI can support more consistent and precise formative assessments.

However, pedagogically AI should be used for formative feedback, not final assessment. Evaluation of scientific arguments, ethical considerations, and sustainability decisions must remain under the authority of the lecturer. Additionally, the integration of AI ethics should be an explicit part of the chemistry curriculum so that students understand the limits of AI use, academic responsibility, and the importance of scientific integrity (Hussain et al., 2025).

4. Conclusion

The literature synthesis shows that integrating AI and Green Chemistry has significant potential to promote more critical, reflective, and sustainability-oriented chemistry education. However, its effectiveness depends on using AI as a pedagogical tool that supports chemical reasoning, scientific evaluation, and responsible decision-making rather than as a source of instant answers.

The review identifies major challenges, including the scientific validity of AI outputs, educators' pedagogical readiness, procedural learning practices, infrastructure disparities, and ethical concerns. In Indonesia, these challenges highlight the need to shift chemistry education toward more contextual, evaluative, and sustainable learning.

Effective integration requires AI to function as cognitive scaffolding and Green Chemistry to serve as a framework for evaluating the efficiency, safety, and environmental impact of chemical processes. This should be supported by lecturer capacity building, hybrid assessment, and AI ethics integration.

This SLR is limited by the availability and diversity of relevant publications. Future research should employ qualitative meta-synthesis or empirical intervention studies to further examine the effectiveness of AI and Green Chemistry integration in chemistry education.

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