



## Implementation of Green Chemistry in Chemistry Learning: A Literature Review

Rama Cahaya Situngkir<sup>1</sup>, Lera Sani Damah Putri<sup>1</sup>, Meilani Azizah<sup>1</sup>, Nurfajriani<sup>1\*</sup>

<sup>1</sup>Universitas Negeri Medan, Medan 20221, Indonesia

### Article Info

#### Article history:

Received: 24-11-2025

Revised: 16-12-2025

Accepted: 26-12-2025

Available online: 01-02-2026

#### Keywords:

Chemistry education; Green chemistry; Learning innovation; Sustainability

#### \*Corresponding author:

[nurfajriani@unimed.ac.id](mailto:nurfajriani@unimed.ac.id)

### Abstract

Green chemistry has been widely introduced as an approach to promote environmentally responsible chemical practices, yet its integration into chemistry learning remains fragmented and inconsistently implemented across educational levels. This condition creates a clear research gap, as existing studies tend to focus on individual practices rather than providing a comprehensive understanding of how green chemistry is applied in instructional settings. Therefore, this study aims to analyze the implementation of green chemistry in chemistry learning through a systematic literature review that examines research trends, instructional strategies, and learning outcomes. An initial search identified one hundred articles published between 2016 and 2025, from which fifteen studies were selected based on inclusion and exclusion criteria, including topical relevance, full-text availability, publication period, and completeness of research structure. The analysis shows that integrating green chemistry into chemistry learning improves students' conceptual understanding, scientific literacy, creativity, and environmental responsibility through approaches such as environmentally friendly laboratory activities, small-scale experiments, and curriculum-based instructional designs. However, several challenges persist, including limited laboratory resources, insufficient teacher preparation, and a lack of supporting learning materials. The findings provide practical implications for educators and policymakers, particularly in designing chemistry instruction that is safe, relevant, and aligned with sustainability-oriented educational goals. Overall, this review highlights the urgency of strengthening green chemistry practices in chemistry learning to support the development of learners who are scientifically competent and environmentally conscious.

**How to Cite:** Situngkir, R. C., Putri, L. S. D., Azizah, M., & Nurfajriani. (2026). Implementation of Green Chemistry in Chemistry Learning: A Literature Review. *Jambura Journal of Educational Chemistry*, 8(1), 46-56. <https://doi.org/10.37905/jjec.v8i1.35585>

## 1. INTRODUCTION

The development of modern science and technology has positioned chemistry as a strategic discipline that significantly contributes to improving the quality of life. However, the rapid growth of the chemical industry has also generated serious risks to human health and the environment (Erlina et al., 2020). This situation requires chemistry education not only to deliver theoretical concepts but also to foster awareness of the environmental impacts associated with chemical use. Laboratory-based learning has become a relevant approach because it enables students to understand

chemical concepts through structured, hands-on experiences aligned with scientific standards. Recent global findings further emphasize that sustainable laboratories (green labs) are emerging as an international trend in reducing the environmental footprint of chemical practices (Freese et al., 2024).

The concept of green chemistry, introduced by Paul Anastas and John Warner in 1998, offers a sustainable framework for designing chemical processes and products that are safe, efficient, and environmentally benign. Its principles guide efforts to minimize waste, reduce the use of hazardous substances, and improve

energy efficiency (Jusniar et al., 2024). Globally, recent research indicates that the integration of green chemistry in chemical education has increasingly focused on project-based learning and problem-based learning to develop a deeper understanding of sustainability (Vaz et al., 2025). In addition, international studies highlight a shift toward comprehensive systems-thinking approaches to strengthen students' understanding of the interconnections between chemical processes, environmental impacts, and sustainable solutions (Morales et al., 2024). In the context of education, the integration of green chemistry principles has the potential to enhance scientific literacy, environmental awareness, and the quality of learning through more applicable and contextualized activities.

Environmental pollution caused by hazardous chemical substances remains a global challenge requiring urgent attention. Addressing this issue calls for a shift in chemistry education so that students not only learn theoretical concepts but also develop a sense of responsibility for the environmental consequences of chemical activities. Within this framework, green chemistry offers an approach that promotes safer and more sustainable chemical products and processes, aligning with sustainable development goals (Aliah et al., 2024). Integrating these principles into chemistry instruction provides considerable potential to cultivate environmentally conscious future generations, as green chemistry-based curricula can strengthen critical thinking, scientific literacy, and ecological awareness through engaging and practical learning experiences. Numerous studies show that such integration improves conceptual understanding, increases motivation, and enhances overall academic performance (Inayah et al., 2022). while also supporting SDGs related to environmental protection and quality education (Anggraeni et al., 2024).

Despite these benefits, the integration of green chemistry in educational settings continues to encounter substantial challenges. Research highlights persistent obstacles such as limited laboratory facilities, insufficient teacher training, and the lack of appropriate teaching materials (Sari & Atun, 2023). International investigations further indicate that these issues extend beyond technical limitations and also include structural barriers, such as institutional readiness, the absence of sustainability-oriented educational policies, and unequal access to

laboratories that meet green standards (Advancing Sustainable Chemistry Education: Insights from Real-World Case Studies). Although innovations such as green chemistry modules, eco-friendly laboratory practices, and alignment with the Merdeka Curriculum have been introduced to address these constraints, their implementation across institutions remains inconsistent. At the higher education level, the integration of green chemistry principles in laboratory courses has demonstrated effectiveness in improving practical skills while fostering environmental responsibility among students (Lestari et al., 2024).

A review of existing studies indicates that previous research has primarily focused on developing green chemistry-based learning materials or evaluating learning outcomes within specific instructional contexts. Only a limited number of studies have systematically examined broader aspects, such as global implementation trends, institutional barriers, curriculum-level integration, and competency development for sustainable laboratories. Although there is an increasing international emphasis on sustainability-oriented chemistry education, a comprehensive synthesis of educational pathways and implementation models for green chemistry is still lacking. Therefore, a Systematic Literature Review (SLR) is necessary to consolidate recent findings, identify research gaps, and formulate strategic recommendations for strengthening the incorporation of green chemistry in chemical education both globally and locally.

Operationally, this SLR aims to: (1) identify recent research trends related to the implementation of green chemistry across various educational levels; (2) analyze learning approaches, instructional models, and media used in applying green chemistry principles; (3) evaluate the impact of green chemistry instruction on students' conceptual understanding, scientific skills, and environmental attitudes; (4) identify major challenges in green chemistry implementation and the strategies developed to overcome them; and (5) formulate strategic recommendations for advancing sustainable chemistry education aligned with curriculum demands and the Sustainable Development Goals (SDGs). In line with these objectives, chemistry education becomes a strategic avenue for integrating the principles of green chemistry, which play a fundamental role in fostering environmental awareness, promoting sustainable

practices, and preparing learners to address the challenges of the twenty-first century with responsible and sustainability-oriented scientific understanding (Morales et al., 2024).

## 2. METHOD

### 2.1. Research Design

This study employs the SLR method, namely a systematic literature review. A literature study is a research activity that utilizes secondary data derived from various library studies or literature relevant to the research problem, sourced from books as well as related articles or journals (Sartika et al., 2022). The review is carried out through a comprehensive study based on the interpretation of literature related to a specific topic. This review includes the identification of research questions by exploring and analyzing relevant literature using a systematic approach to simplify the data analysis process. The articles used as sources are focused on original empirical research or studies that present the results of observations or experiments, which are reported in a complete structure consisting of an abstract, introduction, method, results, and discussion.

### 2.2. Research Target

The research target is scientific articles published in reputable journals indexed by Sinta, particularly those that discuss the implementation of green chemistry in chemistry learning.

### 2.3. Research Data

The research data consists of articles obtained from databases such as Google Scholar and Publish or Perish, with a publication range from 2016 to 2025, focusing on the topic of green chemistry in chemistry learning. From the search results, 100 articles were obtained, which were then filtered down to 15 articles that met the inclusion criteria. The articles used are original scientific works (primary sources), in the form of full texts written in either Indonesian or English. The process of searching and filtering articles in this study is illustrated through a literature flowchart in Figure 1.

In the process of selecting articles, this study applied detailed inclusion and exclusion criteria to ensure that the literature analyzed was fully aligned with the research focus. The inclusion criteria comprised scientific articles that explicitly addressed the implementation of green chemistry in chemistry education, including curriculum integration, laboratory-based learning, the

development of instructional materials, and pedagogical approaches grounded in green chemistry principles.

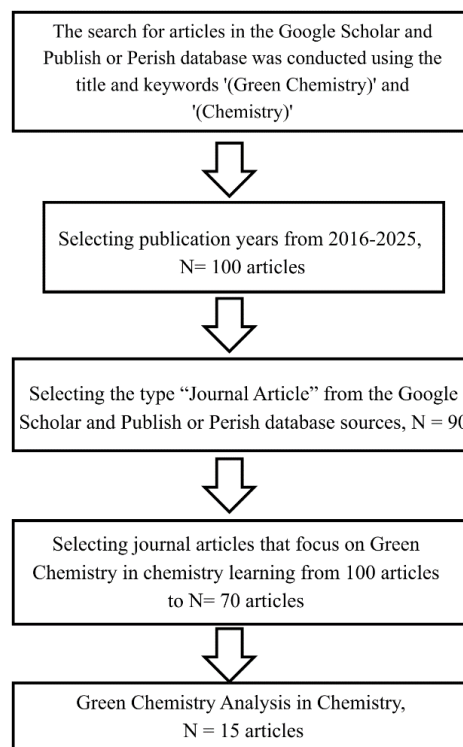


Figure 1. Article Search Stages in the Google Scholar and Publish or Perish Database

Eligible articles were required to be primary research studies with a complete scientific structure consisting of an abstract, introduction, methodology, results, and discussion. In addition, the articles had to be published between 2016 and 2025, available in full-text form, written in either English or Indonesian, and retrieved from the Google Scholar or Publish or Perish databases.

Conversely, exclusion criteria were established to remove articles that did not meet the predetermined standards. Articles were excluded if they did not focus on chemistry education, addressed green chemistry solely within industrial or non-educational contexts, lacked a complete methodological structure, fell outside the specified publication range, or were not available in full-text form. Duplicate articles as well as non-empirical publications such as editorials, opinion pieces, and short conference abstracts were also omitted. The application of these criteria ensured that only relevant, credible, and high-quality literature was incorporated into the final analysis.

## 2.4. Research Instruments

The research instruments used were the Google Scholar and Publish or Perish database for article searches, applying specific criteria to filter relevant and appropriate articles. The research instruments consisted of search keywords adjusted to the topic, namely 'Green Chemistry' and 'Chemistry'.

## 2.5. Data Analysis

Data analysis in this study was carried out using a narrative synthesis approach. Each article that met the inclusion criteria was extracted for information, including the title, author, year of publication, journal, as well as the main content of the article such as the abstract, methodology, results, and discussion. The data obtained were then coded into specific categories, for example research focus, methods used, learning context, and forms of green chemistry implementation. Subsequently, this information was organized in the form of tables or matrices to facilitate the analysis process. The tabulated articles were analyzed narratively to identify key themes, research trends, and to examine similarities and differences among studies. In addition, an evaluation was conducted to ensure the alignment of the articles with the research focus, namely the implementation of green chemistry in chemistry learning, so that only relevant articles were used as the basis for drawing the main findings. Based on this synthesis, the study produced conclusions regarding the forms of green chemistry application, the challenges encountered, and the opportunities for its development in future chemistry education. The following presents the selected articles in Table 1.

Table 1. Selected article results

No	Title	Journal Name	Database Source	Index
1	Model Pembelajaran Penemuan Menggunakan Praktikum Kimia Hijau Untuk Meningkatkan Hasil Belajar Siswa	Journal for Lesson and Learning Studies	Google Scholar	S2
2	Integrasi Green Chemistry Dalam Kurikulum Pendidikan Tinggi: Tinjauan Praktik Internasional dan	Al- Irsyad: Journal of Education Science	Google Scholar	S5

No	Title	Journal Name	Database Source	Index
3	Relevansinya Di Indonesia Education in green chemistry and in sustainable chemistry: perspectives towards sustainability	Green Chemistry	Publish or Perish	Q1
4	Pendekatan Green Chemistry Dalam Modul Praktikum Kimia Lingkungan Untuk Meningkatkan Kreativitas Mahasiswa Calon Guru Kimia	Chemistry Education Practice	Google Scholar	S4
5	The Effect Of Green Chemistry Laboratory Learning On Pre-Service Chemistry Teachers' Environmental Value Orientations and Creative Thinking Skill	Pendidikan Sains Pascasarjana Universitas Negeri Surabaya	Google Scholar	S3
6	Pemahaman Mahasiswa tentang Keberlanjutan dalam Kimia: Kajian Pengembangan pada Proyek Green Chemistry	Jambura Journal of Educational Chemistry	Google Scholar	S3
7	Literature Review: Inovasi Pembelajaran Kimia Berwawasan Lingkungan Melalui Pendekatan Green Chemistry	CHEDS: Journal of Chemistry, Education, and Science	Google Scholar	S5
8	Penerapan Pembelajaran Berbasis Praktikum Untuk Meningkatkan Motivasi Dan Hasil Belajar Peserta Didik Pada Materi Kimia Hijau	SCIENCE : Jurnal Inovasi Pendidikan Matematika dan IPA	Google Scholar	S4
9	Computational Protein Design In Green Chemistry	Rasayan Journal of Chemistry	Publish or Perish	S2
10	Integration Green Chemistry into Learning Process	Jurnal Penelitian	Google Scholar	S3

No	Title	Journal Name	Database Source	Index	Author (Year)	Educational Level	Method	Location	Focus of Green Chemistry Implementation
11	Kajian Literatur Penerapan Kimia Hijau dan Tujuan Pembangunan Berkelanjutan dalam Pembelajaran Kimia	Pendidikan IPA Arfak Chem: Chemistry Education Journal	Google Scholar	S5	Idrus et.al. (2020)	Higher Education	Experimental	Indonesia	Green chemistry based environmental chemistry module
12	Software Tools For Green And Sustainable Chemistry	Current Opinion in Green and Sustainable Chemistry	Publish or Pelish	Q1	Wahyuni ngsih et.al. (2015)	Pre-service teachers	Experimental	Indonesia	Environmental values and creative thinking skills
13	How sonochemistry contributes to green chemistry?	Ultrasonics Sonochemistry	Publish or Pelish	Q1	Setianin gsih (2023)	Senior High School	Experimental	Indonesia	Practicum-based green chemistry learning
14	Developments in analytical chemistry initiated from green chemistry	Sustainable Chemistry for the Environment	Publish or Pelish	Q2	Sari & Atun (2023)	Senior High School	Quasi Experimental	Indonesia	Integration of green chemistry into instruction
15	White Analytical Chemistry: An approach to reconcile the principles of Green Analytical Chemistry and functionality	Trends in Analytical Chemistry	Publish or Pelish	Q1	Azzajjad , et. al. (2024)	Higher Education	Development study	Indonesia	Project-based green chemistry learning
					HS, et. al. (2025)	Higher Education	Literature review	Indonesia	Curriculum integration of green chemistry
					Zuin, et. al. (2021)	Higher Education	Literature review	Italy	Green and sustainable chemistry education
					Chatel (2018)	Higher Education	Review	France	Sonochemistry for green chemistry
					Nowak, et. al. (2021)	Higher Education	Review	Poland	White analytical chemistry framework
					Koel (2024)	Higher Education	Review	Estonia	Green analytical chemistry development
					Parikesit & Tambunan (2018)	Higher Education	Computational study	Netherlands	Computational protein design in green chemistry
					Derbenev, et. al. (2022)	Higher Education	Review	Russia	Software tools for green and sustainable chemistry
					Aliah, et. al. (2024)	Higher Education	Literature review	Indonesia	Environmentally oriented chemistry learning
					Anggraeni, et. al. (2024)	Higher Education	Literature review	Indonesia	Green chemistry and SDGs integration

### 3. RESULT AND DISCUSSION

#### 3.1. Result

Based on the selection process, fifteen articles published between 2015 and 2025 met the inclusion criteria. Table 2 shows that most studies were conducted at the higher education level, followed by senior high school settings. The dominant research methods were experimental, quasi-experimental, Literature review, and development studies, while international publications mainly employed conceptual or review-based approaches.

Table 2. Results matrix of green chemistry implementation in chemistry learning

Author (Year)	Educational Level	Method	Location	Focus of Green Chemistry Implementation
Merta (2020)	Senior High School	Quasi Experimental	Indonesia	Discovery learning with green chemistry practicum

The trend of green chemistry topics over the past decade (2015–2025) has focused on themes such as green chemistry learning, implementation of chemistry practicum modules, integration of green chemistry, application of green chemistry principles, chemistry practicum methods, green chemistry approaches, green chemistry projects, green chemistry practicum learning models, principles and functionality of green analytical chemistry, advances in analytical chemistry within green chemistry, principles of green chemistry in sonochemistry, software tools for green chemistry, protein design in green chemistry, laboratory-based green chemistry learning, and the role of green chemistry in sustainable development.

Recently, integrating green chemistry into chemistry education has gained significant attention. Among the 12 guiding principles of green chemistry are prevention, atom economy, safe synthesis design for human health and the environment, and safer chemical design where possible. The implementation of green chemistry has increasingly become a key focus in chemistry education, both in theoretical learning and laboratory practice. The principles emphasize preventing the formation of hazardous waste rather than merely treating or cleaning it up. This includes aspects such as atom economy in synthesis design, safer procedures for human health and the environment, designing chemicals with lower toxicity but retained effectiveness, utilizing environmentally friendly solvents and auxiliaries, and improving energy efficiency through catalysts and renewable feedstocks. The 12 principles collectively enable the integration of green chemistry concepts into chemistry education, thereby minimizing environmental pollution caused by toxic chemical processes and products. Consequently, the application of green chemistry plays an essential role in preventing the negative impacts of hazardous waste (B3) and can be practically implemented in chemistry practicums through the substitution of hazardous materials with safer alternatives and proper waste management procedures (Fadillah, 2022).

### 3.2. Discussion

There is significant potential for implementing green chemistry in chemistry learning by integrating environmentally friendly principles into the curriculum, practical activities, and learning methods. Through this approach, students not only learn theoretical chemistry

concepts but also foster environmental awareness, for example by using natural materials as indicators, conducting small-scale practicals, and implementing problem-based learning. These efforts align with the Sustainable Development Goals (SDGs) and contribute to the development of 21st-century skills, making chemistry learning more contextual, safe, and sustainability-oriented (Anggraeni et al., 2024).

The application of green chemistry in chemistry learning can be achieved by integrating environmentally friendly principles into the curriculum and practical activities. This approach not only helps reduce the use of hazardous chemicals but also encourages student creativity and raises awareness of environmental issues. Research shows that the application of green chemistry can significantly enhance student creativity, making the chemistry learning process more relevant, safe, and sustainability-oriented (Idrus et al., 2020).

The application of a discovery learning model based on green chemistry labs offers significant potential for development, as it has been proven to improve student learning outcomes, motivation, and interest in chemistry. In this activity, students are invited to experiment using safe, readily available, and environmentally friendly materials such as vitamin C, iodine tincture, lemon juice, baking soda, and chicken liver. In addition to making learning more engaging and meaningful, this activity also fosters environmental awareness, for example by utilizing plastic waste as experimental containers. This learning model aligns with the 2013 Curriculum, which emphasizes active, inquiry-based, and student-centered learning, while simultaneously fostering 21st-century skills such as critical thinking, creativity, and problem-solving. With these advantages, green chemistry labs can be flexibly implemented in various school settings, whether with fully equipped laboratories or limited ones, thus offering significant potential for sustainable implementation in chemistry learning (Merta, 2020).

The potential for implementing green chemistry in chemistry learning can be realized through integration into the curriculum, practical activities, and the development of innovative teaching materials. Green chemistry principles, such as energy efficiency and the use of environmentally friendly materials, help students understand the connection between chemical concepts and real-world environmental issues. The implementation

of micro-scale practicals using natural materials or green chemistry-based modules has been shown to increase student motivation, creativity, scientific literacy, and environmental awareness. Thus, chemistry learning becomes more meaningful, safe, and sustainability-oriented (Aliah et al., 2024).

The application of green chemistry in chemistry learning has great potential to support the realization of sustainable and environmentally friendly education. Green chemistry principles, such as waste reduction, the use of non-toxic materials, and energy efficiency, can be applied in practical activities through simple and resource-efficient methods. The White Analytical Chemistry (WAC) approach emphasizes a balance between scientific (red), environmental (green), and practical (blue) aspects, so that students not only learn about the accuracy of experimental results but also understand the importance of efficiency and sustainability in chemical processes. For example, activities such as the use of natural indicators, the application of microtitration, or analytical methods that produce minimal waste can foster environmental awareness while fostering critical thinking skills. The application of this concept aligns with the objectives of the Sustainable Development Goals (SDGs), particularly in achieving quality education and sustainable chemistry practices (Nowak et al., 2021).

The potential for applying green chemistry in chemistry learning is significant, as it aligns with developments in modern chemical analysis that emphasize efficiency, safety, and sustainability. Green chemistry principles can be applied in laboratory activities to reduce the use of hazardous chemicals, conserve energy, and minimize waste. The learning process can also be directed toward the use of environmentally friendly solvents, derivatization-free analytical methods, and the application of miniaturization techniques such as microextraction or paper-based analysis, which are more efficient in terms of materials and energy use. A quality-by-design (QbD) approach combined with green analytical chemistry (GAC) helps students understand the importance of designing experiments that are not only accurate but also efficient and environmentally friendly. Furthermore, the use of technologies such as simple sensors, smart materials, and smartphone-based digital applications can enrich the learning experience while strengthening the application of sustainability principles.

Thus, the application of green chemistry in learning not only fosters environmental awareness but also equips students with modern scientific skills relevant to the Sustainable Development Goals (SDGs) (Koel, 2024).

The opportunities for applying green chemistry in chemistry learning are vast because this concept aligns with the goal of realizing environmentally conscious sustainable education. Green chemistry principles, such as energy efficiency, waste reduction, and the use of safe and non-toxic materials, can be implemented through practical activities, curriculum development, and the use of digital technology in the learning process. The use of natural materials, simple analytical methods, and software such as green chemistry metrics tools help students understand the relationship between chemical concepts and their impact on the environment. In addition to fostering ecological awareness, this approach also trains critical thinking and creative thinking skills, as well as 21st-century skills that align with the objectives of the Sustainable Development Goals (SDGs). Thus, the application of green chemistry not only improves the quality of chemistry learning but also plays a role in shaping a generation of scientists who care about sustainability and are environmentally responsible (Derbenev et al., 2022).

The opportunity to apply green chemistry in chemistry learning can be realized through the introduction and application of environmentally friendly technologies such as sonochemistry or ultrasonic chemistry. This technology plays a crucial role in supporting the principles of green chemistry by increasing the efficiency and speed of reactions, reducing the use of hazardous solvents, and reducing energy consumption and chemical waste production. In an educational context, sonochemistry principles can be adapted into practical activities to introduce students to more efficient and sustainable modern chemical technologies. For example, the use of ultrasonic waves in the extraction of natural compounds or simple syntheses can be an engaging learning activity while fostering awareness of the importance of environmental sustainability. This approach also teaches students to evaluate a chemical process not only by its results but also by aspects of sustainability, safety, and energy efficiency. Thus, the integration of sonochemistry-based green chemistry concepts into chemistry learning provides a significant opportunity to improve students' scientific literacy,

creativity, and environmental responsibility in accordance with the principles of sustainable development (Chatel, 2018).

The application of green chemistry in chemistry learning can be developed through bioinformatics and computational protein design approaches. These approaches play a crucial role in increasing the efficiency and sustainability of chemical processes by optimizing enzymes and proteins at the molecular level. By utilizing molecular dynamics simulations, students can learn how mutations in enzyme active sites can enhance protein stability, reduce energy requirements, and reduce waste generation and the use of hazardous chemicals. This concept can be applied in chemistry learning to introduce students to the use of digital technology and bioinformatics as a means of implementing green chemistry principles. Through simulation-based activities or case studies, students learn that innovation in modern chemistry focuses not only on reaction outcomes but also on efficiency, safety, and environmental impact. Therefore, the integration of computational green chemistry into chemistry learning has great potential to foster scientific awareness, technological capabilities, and concern for environmental sustainability (Parikesit & Tambunan, 2018).

The application of green chemistry in chemistry learning can be achieved through practical activities based on green chemistry principles. This practical-based learning method has proven effective in increasing student motivation and learning outcomes. One example is the activity of making soap from used cooking oil, which is a concrete application of green chemistry concepts in school laboratories by transforming waste into useful and environmentally friendly products. Through this approach, students not only understand the concepts theoretically but also gain hands-on experience in applying the principles of waste reduction and the use of environmentally friendly materials. Furthermore, green chemistry-based practical activities help students develop critical thinking skills, collaborate in groups, and foster awareness of the importance of sustainability in chemistry. Thus, the application of green chemistry through practical activities is an effective strategy for improving scientific competence while developing environmentally conscious character in students (Setianingsih, 2023).

The potential for applying green chemistry in chemistry learning is vast, as it integrates the values of sustainability, safety, and efficiency into the teaching and learning process. Applying green chemistry principles in the laboratory, such as the use of environmentally friendly materials, waste reduction, and the reuse of reaction residues, not only helps students understand chemical concepts but also fosters ecological awareness. Through green chemistry-based lab activities, students are trained to think critically and creatively in finding solutions to various environmental problems using a scientific approach. Furthermore, this learning can be linked to the concept of Education for Sustainable Development (ESD), which fosters students' responsibility for the environment while honing their innovative skills in designing safe and efficient chemical processes. Thus, the application of green chemistry in learning not only deepens students' understanding of chemical concepts but also instills values of sustainability and a sense of responsibility for environmental preservation (Wahyuningsih et al., 2015).

The potential for applying green chemistry in chemistry learning is enormous because it can help students think more scientifically while fostering awareness of the importance of environmental sustainability. Green chemistry education can be implemented through curricula, practical activities, and research projects that emphasize waste reduction, energy efficiency, and the use of safe and renewable chemicals. Learning based on green chemistry principles helps students understand the relationship between chemistry and its impact on the environment, while fostering a sense of responsibility for the wise use of natural resources. Through simple experiments such as synthesizing environmentally friendly materials or recycling chemicals, students can hone their critical thinking, creativity, and scientific problem-solving skills. Thus, the application of green chemistry in learning not only deepens understanding of chemical concepts but also fosters a generation of students who care about environmental sustainability and safety (Zuin et al., 2021).

The potential for implementing green chemistry in chemistry learning is significant, as it plays a crucial role in developing a generation of scientists who care about sustainability and are environmentally responsible. Green chemistry principles can be integrated into the curriculum through project-based learning,

environmentally friendly practical activities, and the use of materials and experimental methods that minimize chemical waste and hazards. This concept aligns with the Sustainable Development Goals (SDGs), particularly in creating quality education and encouraging responsible production and consumption patterns. Through this approach, students not only understand chemical concepts theoretically but also learn to apply systemic thinking, uphold scientific ethics, and foster ecological awareness in real-world practice. With the support of educational policies, training for educators, and the development of green laboratories, chemistry education in Indonesia has the potential to become a key driver in realizing sustainable, innovative, and globally competitive science learning (HS et al., 2025).

The potential for applying green chemistry in chemistry learning is enormous, as it not only helps foster environmental awareness but also enhances students' scientific skills. Through the concept of green chemistry, students learn to understand how chemical activities can impact the environment, while also being encouraged to reduce the use of hazardous materials and develop more sustainable innovations. When these principles are integrated into the curriculum and practical activities, students not only learn theory but also gain hands-on experience through various projects that emphasize the efficiency of chemical processes, waste management, and the use of environmentally friendly materials. This approach fosters critical thinking and research skills, as well as fosters ethical awareness about the importance of social and environmental responsibility. Therefore, green chemistry-based learning has great potential to produce a generation of scientists and educators capable of creating safe and efficient chemical solutions that support the achievement of sustainable development goals (Azzajjad et al., 2024).

The potential for applying green chemistry in chemistry learning is vast, as it connects chemical concepts with environmental issues and sustainable development. This approach encourages students to think critically and creatively, and to take responsibility for the impact of chemical activities on the environment. Integrating green chemistry principles can be achieved through various means, such as project-based practicums, the use of environmentally friendly materials, or the development of learning media in the form of modules, textbooks, and educational games. Green

chemistry concepts can also be applied to a variety of topics, such as soap making, learning about fossil fuels, chemical reactions, and even plastic waste processing. By applying green chemistry principles such as waste prevention and the use of renewable materials students not only understand scientific theory but also learn to care more about the environment. This implementation aligns with the spirit of the Independent Curriculum, which emphasizes the formation of environmentally conscious characters and the development of sustainability-oriented scientific thinking skills (Sari & Atun, 2023).

The application of green chemistry in chemistry learning has great potential to realize sustainable and environmentally conscious education. Green chemistry principles, such as waste reduction, energy efficiency, and the use of safe materials, can be implemented throughout the curriculum, practical activities, and learning projects. Numerous studies have shown that this approach can improve students' learning outcomes, creativity, and environmental awareness. Furthermore, green chemistry also helps develop 21st-century skills, such as critical thinking and scientific problem-solving. Thus, the application of green chemistry not only deepens understanding of chemical concepts but also fosters students' character that is caring, creative, and responsible for environmental sustainability.

#### 4. CONCLUSION

This systematic literature review shows that research on green chemistry has grown significantly over the past decade, particularly in supporting sustainability in chemistry education. The reviewed studies indicate that the application of the twelve principles of green chemistry through curriculum integration, laboratory-based learning, and project-based approaches can improve students' conceptual understanding, scientific literacy, creativity, and environmental awareness. However, studies that specifically examine comprehensive classroom implementation remain limited, as most research still focuses on isolated aspects such as teaching material development or short-term learning outcomes, with additional limitations related to database selection, publication range, and the number of analyzed articles.

Future research should expand its scope by involving more academic databases, applying longitudinal and experimental research designs, and

examining the role of educational policies and institutional readiness in green chemistry implementation. At the practical level, educators are encouraged to integrate green chemistry principles into everyday learning through microscale experiments, natural indicators, inquiry-based learning, and digital tools. Collaboration among teachers, institutions, and policymakers is essential to develop greener laboratories, strengthen professional development, and ultimately prepare learners who are scientifically competent, environmentally responsible, and supportive of sustainable development goals.

## 5. ACKNOWLEDGEMENTS

The authors sincerely extend their profound appreciation to Dr. Ir.Nurfajriani, M.Si our supervisor, for her exceptional guidance, thoughtful advice, and ongoing support throughout the preparation of this literature review, as her expertise and constructive insights have been instrumental in enhancing the overall quality of this manuscript. We are also deeply grateful to the Postgraduate Program in Medan for the academic assistance, access to scholarly materials, and the supportive research environment that enabled the successful completion of this work. Lastly, the authors acknowledge all individuals and institutions whose indirect contributions have meaningfully supported the development of this study, and their assistance is genuinely appreciated.

## 6. REFERENCES

- Aliah, N., Wati, D. S., Fitriani, D. N., Olli, N. Y. P., & Sukemi. (2024). Literature Review: Inovasi Pembelajaran Kimia Berwawasan Lingkungan Melalui Pendekatan Green Chemistry. *CHEDS: Journal of Chemistry, Education, and Science*, 8(2), 250–257.
- Anggraeni, E. S., Putri, R. A., Tristania, A. W., Maharani, T., Wirhanuddin, W., & Rahmadani, A. (2024). Kajian Literatur Penerapan Kimia Hijau dan Tujuan Pembangunan Berkelanjutan dalam Pembelajaran Kimia. *ARFAK CHEM: Chemistry Education Journal*, 7(2), 604–616.
- Azzajjad, M. F., Ahmar, D. S., & Kilo, A. K. (2024). Pemahaman Mahasiswa tentang Keberlanjutan dalam Kimia : Kajian Pengembangan pada Proyek Green Chemistry. *Jambura Journal of Educational Chemistry*, 6(1), 11–20.
- Chatel, G. (2018). Ultrasonics Sonochemistry How sonochemistry contributes to green chemistry? *Ultrasonics Sonochemistry*, 40, 117–122. <https://doi.org/10.1016/j.ultsonch.2017.03.029>
- Derbenev, I. N., Dowden, J., Twycross, J., & Hirst, J. D. (2022). ScienceDirect Software tools for green and sustainable chemistry. *Green and Sustainable Chemistry*, 35(100623), 1–7. <https://doi.org/10.1016/j.cogsc.2022.100623>
- Erlina, E., Silaban, R., & Nurfajriani, N. (2020). Development of Green Chemistry Practicum Guidelines Based on Discovery Learning. *Proceedings of the 5th Annual International Seminar on Transformative Education and Educational Leadership (AISTEEL 2020)*, 488, 147–150.
- Fadillah, E. (2022). Pengaplikasian Prinsip-Prinsip Green Chemistry Dalam Pelaksanaan Pembelajaran Kimia. *Jurnal Riset Rumpun Ilmu Teknik*, 1(1), 127–132.
- Freese, T., Elzinga, N., Heinemann, M., Lerch, M. M., & Feringa, B. L. (2024). The relevance of sustainable laboratory practices. *Royal Society of Chemistry*, 2(5), 1167–1622. <https://doi.org/10.1039/d4su00056k>
- HS, S. M., Sattuang, H., Wulandari, R., Aeni, N., Rifkah, A., & Ansarif. (2025). Integrasi Green Chemistry Dalam Kurikulum Pendidikan Tinggi: Tinjauan Praktik Internasional dan Relevansinya Di Indonesia. *Journal of Education Science*, 4(2), 416–428.
- Idrus, S. W. Al, Hadisaputra, S., & Junaidi, E. (2020). Pendekatan Green Chemistry Dalam Modul Praktikum Kimia Lingkungan Untuk Meningkatkan Kreativitas Mahasiswa Calon Guru Kimia. *Chemistry Education Practice*, 3(2), 69–73. <https://doi.org/10.29303/cep.v3i2.2110>
- Inayah, S., Dasna, I. W., & Habidin, H. (2022). Implementasi Green Chemistry Dalam Pembelajaran Kimia: Literatur Review. *Hydrogen: Jurnal Kependidikan Kimia*, 10(1), 42–49.
- Jusniar, A., Auliah, A., Fadly, D., Zubair, S., Ahmad, F., & Ruslan, Z. . (2024). Textbook of Green Chemistry (for senior high school). In *Eureka Media Aksara*.
- Koel, M. (2024). Developments in analytical chemistry initiated from green chemistry. *Sustainable Chemistry for the Environment*, 5(100078), 1–7. <https://doi.org/10.1016/j.scenv.2024.100078>

- Lestari, N. A., Sulistyowati, D., Dellatiani, Y., Irawan, N. Z. P., Fadhilah, A., & Muyassaroh, A. (2024). Implementation of green chemistry approaches in chemistry labs instruction : A systematic literature review. *Jurnal Pendidikan Kimia (JPKIM)*, 16(3), 263–277.
- Merta, L. M. (2020). Model Pembelajaran Penemuan Menggunakan Praktikum Kimia Hijau Untuk Meningkatkan Hasil Belajar Siswa. *Journal for Lesson and Learning Studies*, 3(3), 461–468.
- Morales, R. S., Lopez, P. saenz, & Perez, M. A. de las H. (2024). Green Chemistry and Its Impact on the Transition towards Sustainable Chemistry : A Systematic Review. *Sustainability*, 16(6526), 1–14.
- Nowak, P. M., Wietecha-Posluszny, R., & Pawliszyn, J. (2021). Trends in Analytical Chemistry White Analytical Chemistry : An approach to reconcile the principles of Green Analytical Chemistry and functionality. *Trend in Analytical Chemistry*, 138(116223), 1–10.  
<https://doi.org/10.1016/j.trac.2021.116223>
- Parikesit, A. A., & Tambunan, U. S. F. (2018). Computational Protein Design in Green Chemistry. *Rasayan Journal Chem*, 11(3), 1133–1138.
- Sari, W. P. P., & Atun, S. (2023). Integration Green Chemistry into Learning Process. *Jurnal Penelitian Pendidikan IPA*, 9(10), 921–928.  
<https://doi.org/10.29303/jppipa.v9i10.5012>
- Sartika, M. D., Andika, W. D., & Sumarni, S. (2022). Literature Review: Motivasi yang Diberikan Kepada Anak Dalam Mengonsumsi Sayuran. *Jurnal Pendidikan Anak*, 11(1), 30–39.  
<https://journal.uny.ac.id/index.php/jpa>
- Setianingsih, N. (2023). Penerapan Pembelajaran Berbasis Praktikum Untuk Meningkatkan Motivasi dan Hasil Belajar Peserta Didik Pada Materi Kimia Hijau. *SCIENCE : Jurnal Inovasi Pendidikan Matematika Dan IPA*, 3(3), 189–193.
- Vaz, C. R. S., Morais, C., Pastre, J. C., & Junior, G. G. (2025). Teaching Green Chemistry in Higher Education : Contributions of a Problem-Based Learning Proposal for Understanding the Principles of Green Chemistry. *Sustainability*, 17(2004), 1–33.
- Wahyuningsih, A. S., Poedjiastoeti, S., & Suyono. (2015). The Effect of Green Chemistry Laboratory Learning on Pre-Service Chemistry Teachers' Environmental Value Orientations and Creative Thingking Skill. *Pendidikan Sains Pascasarjana Universitas Negeri Surabaya*, 5(1), 848–858.
- Zuin, V. G., Eilks, I., Elschami, M., & Kummerer, K. (2021). Education in green chemistry and in sustainable chemistry: perspectives towards sustainability. *Green Chemistry* 23, 23, 1594–1608.  
<https://doi.org/10.1039/d0gc03313h>