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Trends in Integrating Green Chemistry and Sustainability into Chemistry Education

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Abstract

The growing urgency of environmental challenges has emphasized the importance of integrating green chemistry and sustainability concepts into chemistry education. Green chemistry provides a framework for promoting environmentally responsible scientific practices, while sustainability fosters long-term thinking and ethical decision-making among learners. This study aims to analyze recent trends in the integration of green chemistry and sustainability in chemistry learning contexts. A Systematic Literature Review (SLR) was conducted following Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Twenty peer-reviewed articles published within the last six years and indexed in Scopus and Science and Technology Index (SINTA) were selected from databases including Google Scholar, Education Resources Information Center (ERIC), and Multidisciplinary Digital Publishing Institute (MDPI). The findings indicate that integrating green chemistry and sustainability enhances students' knowledge, interest, and motivation to adopt environmentally responsible attitudes and practices. Despite these benefits, the integration process faces several challenges, such as limited instructional resources, lack of pedagogical strategies, and insufficient contextualization. The study also highlights various effective strategies for implementation, including the use of student worksheets, multimedia tools, and ethnoscience-based approaches that align chemistry learning with local cultural contexts. These insights contribute to the development of more responsive and sustainable chemistry education models, aligning science instruction with global environmental goals and promoting pro-environmental behaviors among future scientists.

Keywords: green chemistry, pedagogical strategies, sustainability chemistry

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1. Introduction

Along with the rise of higher quality Education programs, in 2015, the United Nations (UN) issued the 2030 Agenda, which sets out seventeen Sustainable Development Goals (SDGs) to be achieved by 2030, among them SDG 4 "Quality Education" in general, and education for sustainable development in particular. An analysis of the United Nations Environment Program (UNEP) Global Chemical Outlook II (GCO II) was also recently published with a focus on chemistry education, among others. GCO II generally states that chemistry is at the core of many of the challenges set out in the SDGs and relates to almost all of them. Since chemistry is at the core of many of the current sustainability challenges, education for sustainable development (ESD) needs to be the main focus of chemistry education at all levels of education, and the idea of environmentally friendly and sustainable chemistry should be part of it (Zuin et al., 2021). Not only related to SDG 4, chemistry also plays a central role in 17 other sustainable development goals, the understanding of sustainable chemistry instilled through education (SDG's 4) is crucial for progress in the management of clean water and proper sanitation where chemistry has an important

role in understanding and addressing water problems (SDG's 6), chemistry is the foundation for many industries where sustainable chemistry practices are important to develop efficient industrial processes, reduce hazardous waste, and be more environmentally friendly (SDG's 9) so that it is hoped that understanding sustainable chemistry can increase awareness of more responsible consumption and production (SDG's 12). This should include teaching chemistry in secondary schools (Burmeister et al., 2012).

In the 1990s, Paul Anastas and John Warner proposed an approach to align chemistry with the needs of a more sustainable future. This is what Green Chemistry (GC) is all about (Warner et al., 2004). Making chemistry safer and more ecologically friendly is the aim. Education focused on green chemistry gives the next generation the tools they need to advance civilization in the age of sustainable living. At different levels, some green chemistry and sustainable concepts have been incorporated into chemistry textbooks; nevertheless, these concepts are typically presented as extra notes or vignettes. Consequently, it is imperative that the fundamental ideas of to integrate the core principles of GC and SC into chemistry education, rather than treating them as separate topics (García-Ferrero et al., 2021). Converting high school ESD courses into chemistry curriculum is becoming more and more advised (Eilks, 2015).

It is increasingly recommended to convert high school ESD courses into the chemistry curriculum, because considering students views and feelings about chemistry and inquiring how they might be changed are part of the updated teaching objectives. In the end, it is believed that adding ESD to chemistry classes will make them more relevant (Eilks, 2015). Learning should focus on how chemistry addresses sustainability issues (Burmeister et al., 2012).

Additionally, it could help pupils improve their systems thinking abilities, which is one of the 21st century's most important competences. (Mahaffy et al., 2019). Green chemistry education is aligned with the goals of ESD in forming a society that cares about the environment and is responsive to sustainability issues. The application of ESD in chemistry learning in Indonesia, whose development is influenced by national curriculum policies such as the Merdeka Curriculum, aims not only to improve environmental understanding but also students' critical thinking skills to face sustainability challenges. However, the implementation of ESD in the science curriculum, especially chemistry, is still constrained, one of which is by teachers' lack of understanding of the concept and its application (Widyawati et al., 2024).

The background presented shows the urgency to adopt the trend of integrating green chemistry and sustainability in chemistry learning at the high school and university levels, as has been done in many countries. Although green chemistry education is in line with ESD goals and its implementation in Indonesia has begun through curriculum policies such as the Merdeka Curriculum, various obstacles such as teachers lack of understanding underscore the complexity of this process. Based on this context, this study conducted a review of a number of research articles on green chemistry and sustainability, which resulted in fundamental questions that will be the focus of discussion in this study, including what are the challenges faced when integrating green chemistry and sustainability concepts in chemistry learning and what are the solutions; What are the effective strategies to integrate the concepts of green chemistry and sustainability in chemistry learning.

2. Research Method

This research uses the Systematic Literature Review (SLR) method. The SLR method is one of the important methods in academic research. The SLR method can provide information to research on what is known and topics to be studied by following standard rules to identify and synthesize the results of research that has been done comprehensively

(Xiao & Watson, 2019) The SLR method in this study uses the PRISMA guidelines. PRISMA is a framework in the SLR approach created to choose and recognize pertinent articles (Moher et al., 2009). The process in this research starts by identifying literature sources pertinent to the topic being explored, choosing articles, and then analyzing and categorizing them.

The SLR method in this study was obtained by searching for literature sources using online databases, such as Google Scholar, ERIC, and MDPI with Scopus indexed criteria for international articles and SINTA indexed for national article publications. The keywords used by researchers are "green chemistry in chemistry learning", "green chemistry in education", "green and sustainable chemistry in education". The research method used must method should be articulated in a scientific way, which are rational, empirical and systematic. It is recommended to clearly specify the time and location of the research, along with the data, tools, and materials utilized in the study.

The results of the study obtained 146 articles that were indicated based on the range of the last six years (2018-2024), keywords, type of publication, and level of education level. Starting with the selection of articles based on titles and abstracts, 146 articles were obtained, reduced based on full text reading to 68 articles, and selection based on the quality of sinta indexed articles (sinta 2-3) for national articles, and scopus indexed (Q1-Q3) for international articles. This SLR research can be seen in Figure 1.

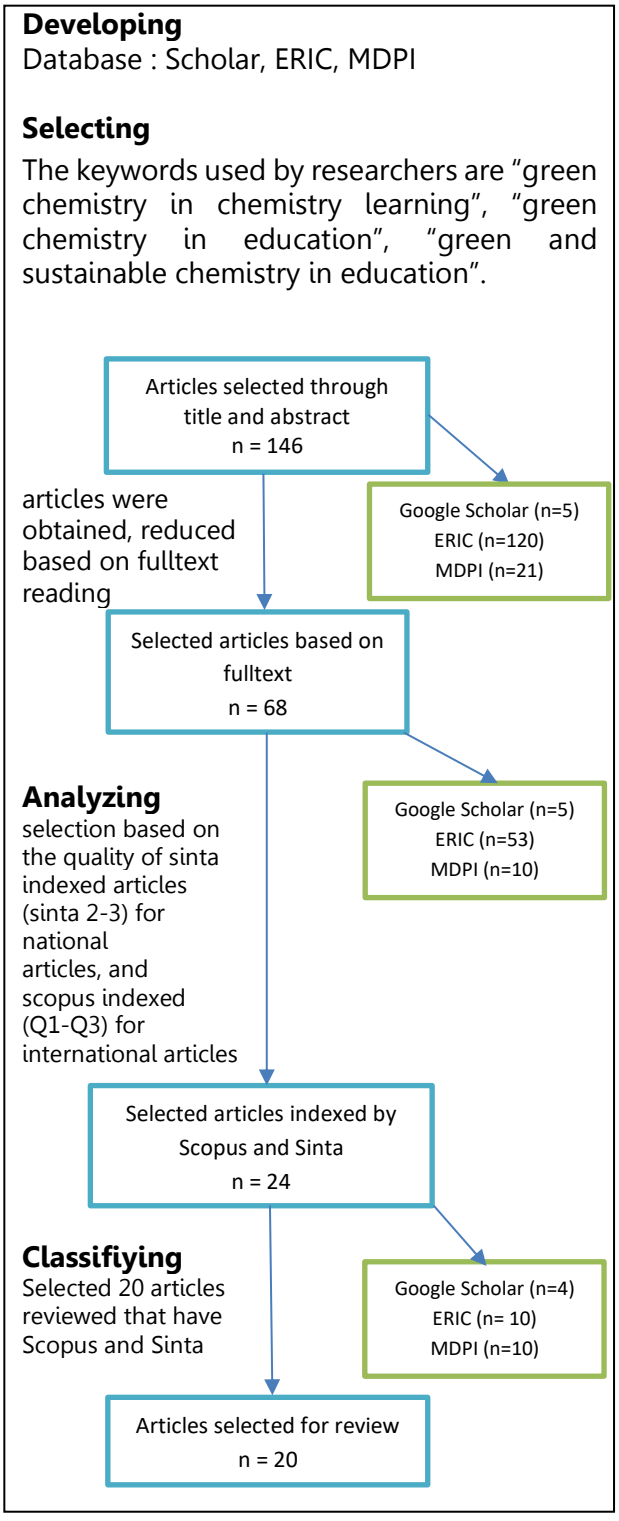

Figure 1. Flow Chart Based on PRISMA Guidelines

The data from the article analysis identifies the author's findings on the topic of the article with several main points as follows challenges faced when integrating the concepts of green chemistry and sustainability in chemistry learning and how to solve them and effective strategies for integrating the concepts of green chemistry and sustainability in chemistry learning.

3. Result and Discussion

Green chemistry is an approach in chemistry that focuses on utilizing materials and processes that are more environmentally friendly, and reduce negative effects on the environment and human health. This principle of green chemistry covers many aspects, such as reducing the use of hazardous substances, energy efficiency, and more effective waste management. Therefore, sustainable chemistry education is in line with ESD goals in building a society that is more environmentally aware and responsive to sustainability challenges (Chen et al., 2020; Marcelino et al., 2019).

According to Anastas (1998) steps to protecting the environment can be achieved through initiatives in education at all tiers of higher learning, acting as both a progressive and final aspect of the educational journey. Non-formal education also plays a role in helping to protect our beloved planet (Mitarlis et al., 2023).

Within the advancement of green chemistry (GC), the OECD (Organization for Financial Participation and Advancement) presented the concept of maintainable chemistry (SC). Although the structure is different, it basically pursues the same goals as GC. Both concepts (GC and SC) are constantly developing and moving nearer to one another (Cavani, 2009) even though some distinctions remain. The shift from GC to SC is becoming more seamless.

Globally, for case at GCO II, there's an expanding trade of terms such as "green and feasible chemistry" (GSC) and "green and feasible chemistry education" (GSCE) (Linkwitz & Eilks, 2022). In terms of communicating GC to the public, many academic institutions have tried to integrate GC into chemistry courses using different teaching materials and methods (Loste et al., 2020).

The integration of green chemistry and sustainability in chemistry learning enables an interdisciplinary approach that teaches students higher-order cognitive skills. It can shift the paradigm of chemistry education from algorithm-based learning towards learning that focuses more on critical thinking skills and real applications. In addition, this approach can improve students' understanding of chemical concepts and arguments (Karpudewan et al., 2016).

In Indonesia, whose development is influenced by national curriculum policies such as the Merdeka Curriculum, aims not only to improve environmental understanding but also students' critical thinking skills to face sustainability challenges. However, the implementation of ESD in the science curriculum, especially chemistry, is still constrained, one of which is by teachers' lack of understanding of the concept and its application (Widyawati et al., 2024).

Prior to conducting the systematic literature review (SLR), the authors conducted an initial exploration of the high school chemistry curriculum and some commonly used chemistry textbooks to identify patterns of green chemistry (GC) and sustainability integration. This analysis was conducted by searching for key words related to GC (e.g., "green synthesis," "sustainable solvents," "waste reduction") and sustainability concepts (e.g., "environmental impact," "renewable resources," "life cycle of goods"). Findings from the preliminary analysis indicate several significant gaps. First, GC principles are often taught as a separate subject and are less explicitly linked to practical applications in the chemical processes described in the curriculum. Second, economic as well as social aspects of sustainability in the context of chemistry, such as life-cycle costs and social impacts of chemical selection, receive less attention. Third, examples of appropriate GC

applications related to sustainability challenges at the local or global level are lacking in the reviewed teaching materials. This initial recognition of patterns and shortcomings serves as a foundation for framing more targeted research questions and defining more appropriate key terms for SLR.

In line with the background of the issue, this article highlights some of the integrations of green chemistry and sustainability at the high school or college level in various countries as well as Indonesia. So that it will be in line with the discussion on the two research questions in RQ 1 and RQ 2, which is what are the challenges and how effective strategies can be integrated in the chemistry curriculum in Indonesia. The integration of chemistry learning with green chemistry and sustainability concepts can be seen in Table 1.

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Table 1. Integration of Chemistry Learning with Green Chemistry and Sustainability Concept

No	Title	Journal Name	Author	Indexed	Result Review
1	Action Research Teacher's Journey while Integrating Green Chemistry into the High School Chemistry Curriculum	Journal Sustainable	Michael Linkwitz and Ingo Eilks (2022)	Scopus (Q1)	The importance of strengthening students' awareness and perception of green chemistry in chemistry education is also highlighted. The results showed that Green Chemistry can be a significant change in the evaluation of chemistry education, especially in diverse experiments, interesting materials, and students' ownership of the topic.
2	Green and Sustainable Chemistry Teacher Education: Experiences from a Brazilian University	Journal of Sustainable Chemistry	Caroindes J.C Gomes and Vania G. Zuin (2020)	Scopus (Q1)	This research is linked to the principles of green chemistry and the Sustainable Development Goals (SDGs). This linkage is reflected in the resolution that includes the principles of prevention, energy efficiency, and the use of renewable resources, as well as the SDG targets related to health, education, clean energy,
3	Cleaning Our World through Green Chemistry: Introducing High School Students to the Principles of Green Chemistry Using a Case- Based Learning Modul	Journal of Chemical Education	Joy Ballard and Suatzette Reid Moorning (2021)	Scopus (Q1)	Given the success of the green chemistry learning activities presented to high school students here, more green chemistry topics and activities should be permanently added to the classroom to educate insights into sustainability practices.
4	Assessing awareness of green chemistry as a tool for advancing sustainability	Journal of Cleaner Production	Natalia Loste, David Chinarro, etc (2020)	Scopus (Q1)	In the educational environment, efforts have been made to incorporate GC into the chemistry curriculum in various academic institutions. In this context, Massive Open

No	Title	Journal Name	Author	Indexed	Result Review
					Online Course (MOOC) MOOCs have been identified as a potential model for the implementation of GC education.
5	Integrating perspectives from indigenous knowledge and Western science in secondary and higher chemistry learning to contribute to sustainability education	Sustainable Chemistry and Pharmacy	Robby Zidny and Ingo Eilks (2020)	Scopus (Q1)	This research highlights the importance of identifying potential topics that are more suitable for integrating social science issues into the chemistry curriculum. This will enable the development of a better and more relevant curriculum. The findings support a sustainability-focused approach to chemistry education that can help students understand the contribution of chemistry in solving global problems and enhance a broader understanding of science in a cultural and social context.
6	Sustainable Development Goals (SDGs) Priorities of Senior High School Students and Global Public: Recommendations for Implementing Education for Sustainable Development (ESD)	Journal Education Research International	Xingun Yuan, Le Yu Hao Wu, etc (2022)	Scopus (Q3)	ESD needs to be integrated into the regular school curriculum, particularly foreign languages and some science subjects. Non-formal and non-formal education, such as forming student clubs and participating in community activities, can increase students' awareness of the SDGs. Some subjects such as math, physical education and art require special attention to raise students' awareness of sustainable development.
7	The Press as a Resource for Promoting Sustainability Competencies in Teacher Training: The Case of SDG 7	Journal Sustainability	Raquel Chulia-Jordan, Amparano Vilches Pena and Maria Calero (2022)	Scopus (Q2)	The research resulted in a module dedicated to sustainability education to improve science literacy created by 74 teachers on topics related to the topic of renewable energy and how it relates to addressing the global crisis. Press/media-based design and implementation can contribute to knowledge and engagement in achieving the SDGs, particularly SDG 7 (on sustainability), improve critical views of press/media coverage of scientific issues, and open opportunities to

No	Title	Journal Name	Author	Indexed	Result Review
					promote science literacy and ESD.
8	The Integration of Green Chemistry Principles in Basic Chemistry Learning to Support Achievement of Sustainable Development Goals (SDGs) Trough Education	Journal of Technology and Science Education	Mitarlis Utiya Azizah and Bertha	Crossef	Knowledge and ability to apply green chemistry and sustainable principles as well as the ability to connect with systems thinking will be prepared to contribute to solving current sustainability challenges by integrating green chemistry in the curriculum. This research is supported by data on the implementation of integrating green chemistry principles in basic chemistry learning.
9	Probing Greek secondary school students' awareness of green chemistry principles infused in context-based projects related to socio-scientific issues	International Journal of Science Education	Dionysios Koulougliotis, Lemonia Antomoglout and Katerina Salta (2020)	Scopus (Q2)	Green Chemistry in secondary education is an important step towards forming responsible citizens who are accurately informed and aware of Socio-Scientific Issues (SSI). This research provides evidence of the possibility to introduce green chemistry in secondary education through the use of SSI to teach specific chemistry content, thus providing an avenue to overcome barriers related to an already crowded curriculum and the lack of appropriate educational materials related to the principles of green chemistry.
10	Toward a Green and Sustainable Chemistry Education Road Map	Journal of Chemistry Education	Jennifer J.MacKeller, David J.C Cosntable, etc (2020)	Scopus (Q2)	Some green chemistry and sustainability concepts have been added to chemistry textbooks at various levels, but these concepts often appear as additional notes or vignettes. Therefore, the integration of the core concepts of green and sustainable chemistry into chemistry education is essential and should not be done in isolation. So that the roadmap vision of "A chemistry education that equips and inspires chemists to help solve the grand challenges of sustainability," will be realized through the implementation of eco-friendly and sustainable chemistry core competencies and embedding a better understanding of systems

No	Title	Journal Name	Author	Indexed	Result Review
					thinking in the chemistry curriculum.
11	Effects of Scrum Methodology on Students' Critical Scientific Literacy: the case of Green Chemistry	Journal Chemistry Education and Practice	Johannes Volgenzang, Wilfried F, etc (2020)	Scopus (Q1)	The effect of using scrum methodology can be seen by increasing conceptual understanding of 12 principles of environmentally friendly green chemistry (Vision I), increasing students' critical thinking by often providing input (Vision II), students are able to combine green chemistry topics in socio-economic issues (Vision III).
12	The Role of the Periodic Table of The Elements of Green and Sustainable Chemistry in High School Educational Context	Multidisciplinary Digital Publishing (MDPI) : Chemistry	Carlos Alberto da Silva, Carla Motais, etc (2024)	Scopus (Q1)	Integration using Periodic Tables - Green Sustainable Chemistry (GSC) is a valuable tool for integrating GSCE into high school chemistry teaching. PT-GSC can help students understand the principles of Green Chemistry and apply them to real-world problems. PT-GSC can also increase students' interest in chemistry and their awareness of the importance of sustainability.
13	High School Sustainable and Green Chemistry: Historical–Epistemological and Pedagogical Considerations	Multidisciplinary Digital Publishing (MDPI) : Chemistry	Teresa Clestino (2023)	Scopus (Q1)	Green Sustainable Chemistry (GSC) plays an important role in various fields of science and society, yet its integration into the education system is still not optimal. Systems thinking and interdisciplinary approaches are recommended as effective ways to teach GSC. This approach allows students to understand the complex relationships between various factors affecting the environment and sustainability.
14	Socio-Problematization of Green Chemistry: Enriching Systems Thinking and Social Sustainability by Education	Multidisciplinary Digital Publishing (MDPI) : Sustainability	Leonardo Marcelino, Jesper Sjostrom, and Carlos Alberto Marques (2019)	Scopus (Q1)	The problem in teaching chemistry today is that there is too much focus on presenting chemistry substantively (what we know and how we explain it) and too little effort in teaching chemistry as a creative activity (how we think and what we can do with this form of reasoning). Chemical thinking involves the knowledge, reasoning, and practice that characterize chemical activity, directed at the development and

No	Title	Journal Name	Author	Indexed	Result Review
					application of chemical knowledge for the analysis, synthesis, and transformation of matter.
15	Learning about Pesticide Use Adapted from Ethnoscience as a Contribution to Green and Sustainable	Multidisciplinary Digital Publishing (MDPI) : Education Science	Robby Zidny, Ingo Eilks (2022)	Scopus (Q2)	Learning about green and sustainable chemistry can be enriched by considering a perspective of chemistry other than modern Western science, which in our case is the culture of indigenous people (Baduy). With the addition of this perspective, students can learn several important aspects of chemistry, which include: (1) that scientific knowledge is universal and can be inspired from other cultures, such as ethnoscience; (2) that chemical ideas are not limited to the perspective of modern Western science and further insights can be found in students' local cultural environment; and (3) that learning about green and sustainable chemistry concepts and practices can even start from local wisdom that is close to students' cultural environment.
16	Education in Green Chemistry and in Sustainable Chemistry : Perspective Towards Sustainability	The Royal Society of Chemistry	Vania G.Zuin, Ingo Eilks, Myriam Elschami and Claus Kummerer (2022)	Scopus (Q1)	GC concepts and principles can be applied to education at various levels and environments, including high school, university, and professional education. GCE and SCE have been in schools and universities. Various institutions have developed tools and materials to enable the integration of GC and SC at high school and even primary school levels and to adequately address toxicology in the classroom is being introduced in a growing number of research institutions.
17	A Multi-Perspective Reflection on How Indigenous Knowledge and Related Ideas Can Improve Science Education for Sustainability	Springer: Science and Education	Robby Zidny, Jesper Sjostrom, and Ingo Eilks (2020)	Scopus (Q1)	It is important to implement new topics and pedagogies in science teaching and transform teacher education programs. One source of such new topics is sustainability thinking and action, and the associated related educational paradigm called Education for

No	Title	Journal Name	Author	Indexed	Result Review
					Sustainable Development (ESD).
18	Application of Green Chemistry in the Context of Industrial Chemistry: Student Perspectives and Importance for Continuing Studies	Amandemen : Journal of Learning, Teaching, and Education Studies	Monica Lauren Sinuraya, Daffa Alaudin (2024)	Google Scholar	Green chemistry can encourage students to seek deeper knowledge about environmental health and increase their motivation in learning new innovations in the scientific field. Based on the results of the research discussion that has been presented, it can be concluded that the application and utilization of green chemistry in an industrial context is very important for the process of developing environmentally friendly chemicals. The results of the Focus Group Discussion (FGD) also expressed strong support from the students towards the green chemistry implementation program at school, although there is no physical implementation and direct experimentation related to green chemistry.
19	Science Literacy Profile of Vocational Students on the Implementation of Green Chemistry-Based Electroplating Project Learning	Orbital : Jurnal Pendidikan Kimia	Purwanti, Hernani, and Fitri Khairunnisa (2023)	Google Scholar	Science literacy learning is also very good when done with a green chemistry approach so that students can apply the science knowledge they get into a form of choosing a caring or friendly attitude towards the environment. The topic of electroplating based on green chemistry is a suitable topic to improve science knowledge, science competence and science attitudes to be achieved.
20	Development of Green Chemistry-oriented Learner Worksheets (LKPD) to Improve Science Literacy Skills on Acid-Base Material	Jurnal Inovasi Pendidikan Kimia	Amalia Ulandari and Mitaris (2021)	Google Scholar	The purpose of applying green chemistry is to train students in facing the challenges of life in the 21st century, especially environmental issues. The principle of green chemistry in learning is realized by developing LKPD with green chemistry insight.

3.1. Challenges and Solutions in Integrating Green Chemistry and Sustainability Concepts in Chemistry Learning

The results of the article analysis in Table 1 show that the concept of green chemistry and sustainability in learning chemistry is able to increase their knowledge and interest in chemistry in sustainable issues. Many research highlights the importance of identifying potential topics that are more suitable for integrating social science issues into the chemistry curriculum. This will enable the development of a better and more relevant curriculum (Zidny & Eilks, 2022). Based on the results of the research discussion that has been presented, it can be concluded that the application and utilization of GC in an industrial context is very important for the process of developing environmentally friendly chemicals (Monica Lauren Sinuraya et al., 2024). "Chemistry" is both a science and a large and important industrial sector. Chemistry is the foundation of industries that produce many products (Sjöström, 2007). It is important to realize that chemistry is not normative, that is, it is not a social convention. Chemical thinking involves knowledge, reasoning, and practice that characterize chemical activity, directed towards the development and application of chemical knowledge for the analysis, synthesis, and transformation of matter (Marcelino et al., 2019). With the development of the GC trend, it is expected to encourage students to seek deeper knowledge about environmental health and increase their motivation in learning new innovations in the scientific field (Zuin et al., 2021).

However, of course, in its application, it cannot be separated from various challenges in the integration of green chemistry and sustainability concepts in chemistry learning. GC education has the potential to change chemistry concepts, attitudes and motivation to act pro-environmental values and can contribute to sustainable development. Although GC is an important foundation for SC, it is not necessarily sustainable, as GC does not address the possible implications of using renewable resources such as total substances, materials, product streams and energy. Thus, both GC and SC require a thorough analysis. While green chemistry (GC) focuses mainly on products, sustainable chemistry (SC) aims to consider all three dimensions of sustainability, So while GC and SC are interrelated and complementary, SC has a broader scope as it seeks to achieve sustainability in the most complete sense, encompassing all aspects of human and planetary life based on an integrated and inter/transdisciplinary approach (Zuin et al., 2021). The concepts of GC and sustainability play an important role in various fields of science and society, but their integration into the education system is still not optimal. Systems thinking and interdisciplinary approaches are recommended as effective ways to teach GSC (Green Sustainable Chemistry). Systems thinking and interdisciplinary approaches are recommended as effective ways to teach GSC, because this approach allows students to understand the complex relationships between various factors affecting the environment and sustainability (Celestino, 2023).

Nevertheless, the integration of green chemistry and sustainability concepts still has challenges where there is still a lack of chemistry teachers who have difficulty in understanding and integrating green chemistry concepts in chemistry learning so that adequate special training is needed in helping chemistry teachers integrate GC (Celestino, 2023). The difficulty chemistry teachers face in understanding and integrating green chemistry concepts into their teaching, necessitating special training, can be attributed to several interconnected factors among GC approaches in chemistry course training in some contexts is still lacking, and one important reason is the lack of curriculum insertion (Etzkorn & Ferguson, 2023), A recent study identified that, in this context, out of 370 institutions offering chemistry courses, only 40 have disciplines that address GC. Given the importance of GC in developing actions aimed at implementing the Sustainable Development Goals (SDGs) and for the essential training of future professionals (Vaz et al., 2025).

3.2. Effective Strategies in Integrating Green Chemistry and Sustainability Concepts in Chemistry Learning

The roadmap vision "A chemistry education that equips and inspires chemists to help solve the grand challenges of sustainability," will be realized through the implementation of green chemistry and sustainability core competencies and embedding a better understanding of systems thinking in the chemistry curriculum (García-Ferrero et al., 2021) and sustainability offers a context for chemistry learning that is rich in possibilities that students connect with (Hofstein, 2014).

As one way strategy in integrating green chemistry and sustainability are the concept of relevance and socio-scientific issues (SSIs) has previously been emphasized (Stuckey et al., 2013). SSIs are real-world issues that are socially significant, rooted in science and generally connected to a systems thinking approach, which is holistic thinking that highlights the interdependence and interaction of chemical system components with one another (Mahaffy et al., 2019) While relevance and SSI are very powerful ways to make green chemistry learning meaningful, their implementation is not without challenges. Its success depends largely on teacher readiness, curriculum support and adequate resources.

Another strategy by Zidny & Eilks (2022) uses an ethnoscience approach in introducing green chemistry and sustainability where learning about green and sustainable chemistry can be enriched by considering perspectives of chemistry other than modern western science, which in this case is culture. With the addition of this perspective, students can learn several important aspects of chemistry, which include that scientific knowledge is universal and can be inspired from other cultures, such as ethnoscience, that chemical ideas are not limited to the perspective of modern Western science and further insights can be found in students' local cultural environment, and that learning about green and sustainable chemistry concepts and practices can even start from local wisdom that is close to students' cultural environment

Another effective strategy that can develop the integration of green chemistry and sustainability concepts in chemistry learning is to use learning tools/media that attract students' interest in learning chemistry. As done by (da Silva Júnior et al., 2024) integration using the Periodic Table - Green Sustainable Chemistry (GSC) is a valuable tool for integrating GSCE into high school chemistry teaching. PT-GSC can help students understand the principles of Green Chemistry and apply them to real-world problems. PT-GSC can also increase students' interest in chemistry and their awareness of the importance of sustainability. In addition, (Loste et al., 2020) efforts have been made to incorporate GC into the chemistry curriculum in various academic institutions. In this context, Massive Open Online Course (MOOC) MOOC has been identified as a potential model for the implementation of GC education. This interdisciplinary approach, which combines GC and sustainability through online education, contributes to a broader understanding of the relationship between chemistry, sustainability, and education.

Statements highlighting the use of engaging learning tools/media, such as the Periodic Table - Green Sustainable Chemistry (PT-GSC) (da Silva Júnior et al., 2024) and the utilization of Massive Open Online Courses (MOOCs) (Loste et al., 2020) as effective strategies in integrating green chemistry and sustainability have significant strength. These strategies are robust because they are supported by scientific references, which show that these approaches have been explored and validated academically. The main advantage lies in the concrete and innovative solutions offered, such as PT-GSC that not only enhances students' understanding of green chemistry principles but also arouses their interest and awareness towards sustainability. Moreover, the utilization of MOOCs demonstrates forward thinking in leveraging technology for education, offering the potential for scalability and wide reach in disseminating green chemistry concepts globally, while encouraging an interdisciplinary approach that links chemistry with sustainability and education holistically.

However, this strategy also has some drawbacks that need to be addressed. One of the main challenges is the lack of context-specific implementation details, such as how teachers can effectively integrate PT-GSC in resource-constrained classrooms or how MOOCs can be aligned with existing curricula. There are potential accessibility and infrastructure challenges, especially in areas with limited internet connectivity, which may hinder the adoption of MOOCs. In addition, the effectiveness of this strategy largely depends on the quality of the design and content of the learning medium or MOOC itself. This statement also fails to highlight the central role of teachers no matter how great the tools are, without teachers who are trained and motivated to utilize them effectively, the impact will not be maximized. Lastly, while the examples provided are relevant, they may not cover the entire spectrum of other interesting learning tools or approaches, which may limit the perspective of the strategies offered.

4. Conclusion

The findings from the literature review covering the past 6 years (2018-2024) of both international and national articles indicate that incorporating GC and SC concepts into chemistry education is crucial. This study found several major obstacles in integrating green chemistry (GC) and sustainability into chemistry education (RQ1). The main barriers include the lack of sufficient understanding and training among chemistry teachers, limitations in relevant teaching resources, as well as resistance to ongoing curriculum changes. To address these challenges, this review suggests some promising methods (RQ2). Focused and continuous training for teachers is key in providing educators with the necessary knowledge and skills. In addition, the development and application of innovative and contextualized teaching materials, coupled with the application of active pedagogical approaches such as project-based learning and case studies, proved effective in improving students' understanding and participation in GC and sustainability concepts. The use of ethnoscience approaches also emerged as an important strategy to link scientific concepts with local wisdom and sustainability challenges at the regional level. Thus, an organized collaboration between policy makers, educational institutions, and teachers is needed to address the challenges and widely apply these effective methods for a more sustainable and meaningful chemistry education.

This research, which adopted a Systematic Literature Review (SLR) approach, has inherent limitations related to the availability and quality of published studies within the specified time span. To overcome this limitation and further develop the understanding of the integration of green chemistry and sustainability more specifically, future research could conduct a qualitative meta-synthesis analysis to integrate the findings more deeply or conduct an intervention study to test the effectiveness of the identified approaches in a real context.

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