sustainability

Systematic Review

Green Chemistry and Its Impact on the Transition towards Sustainable Chemistry: A Systematic Review

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Abstract: This study presents a systematic review that addresses the didactics of Green Chemistry in the field of chemistry education, and its main goal is to explore the implications of education in Green Chemistry in response to growing environmental concerns. To carry this out, three databases were reviewed—Dialnet, Web of Science, and Scopus—using the PRISMA method and inclusion and exclusion criteria were established. Articles from journals from the last 6 years, in English or Spanish, that addressed the didactics of Green Chemistry at any educational level, and that offered free access to the whole text, were included; studies that did not specifically focus on the didactics of Green Chemistry or that addressed topics not pertinent to the goals of this review, as well as textbooks, laboratory guides, and other educational resources, were left out. The Boolean operators "AND" and "OR" were used with respective keywords, in both English and Spanish, in the different databases to see with which combinations the greatest number of studies fitting the proposed goals were obtained. Finally, 13 of the 695 articles initially selected were included and analyzed (Dialnet: 146; Web of Science: 330; Scopus: 219). The results show how Green Chemistry can play a fundamental role as a learning strategy to promote sustainable development and contribute to the achievement of the Sustainable Development Goals established in the 2030 Agenda.

Keywords: teaching; chemistry; green chemistry; sustainability

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1. Introduction

In recent decades, the increase in environmental problems has generated growing concern and has given rise to the emergence of the concept of sustainability [1]. In the field of chemistry, these issues are particularly urgent, especially concerning the extraction and production processes of everyday products. This creates a critical interface between chemistry and sustainability that requires a specific approach [2]. In order to mitigate the impact of chemical processes upon the environment, a new line of work known as Green Chemistry was developed.

The concept of Green Chemistry emerged at the end of the 20th century and was originally proposed by Anastas et al. [3], based on 12 fundamental principles (Figure 1) [4]. This approach seeks to address the problems associated with experimental chemistry by integrating environmentally friendly practices and considerations at all stages of chemical processes, from conception to disposal. Thus, by adopting the principles of Green Chemistry, the negative impact of chemical processes on the environment is reduced to a minimum, at the same time as encouraging and promoting more sustainable and responsible practices [5]. Green Chemistry, therefore, according to Clark et al. [6], can be considered an approach to carry out chemical processes to obtain maximum benefit, while minimizing the effects that may be harmful to humans and the environment.

Currently, it is a reality that a lot of research is being carried out and many contributions are being made concerning the use of Green Chemistry to minimize the impact of industrial waste and to achieve the adequate management of environmental resources [7]. But if one thing is clear, it is that, for this line to have continuity, a key aspect to take into account is the training of citizens and the incorporation of Green Chemistry when teaching chemistry. Given that Green Chemistry is key to reducing the chemical risks associated with the manufacturing of everyday products, it should be essential to address this concept in the education curriculum, as well as to implement teaching strategies that integrate it into the teaching–learning process [8].

1. Prevention of waste is preferable to having to treat or dispose of it once it is formed.	**7.** Put the use of renewable raw materials before the use of exhaustible sources whenever it is technically and economically viable.
2. Atomic economy: Processes must be designed to maximize the use of materials in the final product.	**8.** Obtaining derived products should be avoided or reduced whenever possible because they encourage the production of waste.
3. Synthesis methods must be designed that use and produce non-toxic and less dangerous products.	**9.** Selective catalytic reagents are preferred over stoichiometric reagents.
4. Design of safe chemicals that maintain their functional efficacy while minimizing their toxicity.	**10.** Products must be designed to degrade safely in the environment and not persist in it.
5. The use of auxiliary substances (solvents, separation, etc.) should be minimized or avoided and used in a harmless manner when necessary.	**11.** Develop analytical methodologies that can be monitored in real time and prevent the formation of dangerous substances.
6. Design synthesis processes that promote energy efficiency, minimizing the use of energy costs and preferably carrying them out at ambient temperature and pressure.	**12.** Substances and methods must be selected that minimize the risk of chemical accidents; that is, the monitoring of safe chemical synthesis must be encouraged.

Figure 1. Twelve fundamental principles of Green Chemistry [4]. (Source: The authors).

According to research carried out by Cortés et al. [8], Green Chemistry in education is considered to be a transversal learning strategy comprising curricular content that must be studied at different educational levels. Furthermore, the incorporation of Green Chemistry into chemistry education represents a significant evolution in the way this discipline is approached. This approach not only offers environmental and public health benefits, but also prepares pupils to face the challenges of the 21st century with comprehensive and sustainable knowledge [9]. Integrating Green Chemistry into the education curriculum can transform the teaching of chemistry, as it not only prepares pupils to be competent and responsible chemists, but also instills in them a deep sense of responsibility towards the environment and society. This is crucial when training the next generation of scientists and professionals who will lead the way towards a more sustainable future [10].

Likewise, taking into account the 12 principles of Green Chemistry formulated by Anastas and Warner [3], the incorporation of some of them, such as the use of renewable raw materials (principle 7), biodegradability (principle 10), and the prevention of contamination (principle 1), in all educational stages constitutes a crucial opportunity since, as González-García et al. [11] point out, linking the knowledge derived from chemistry with the classroom and developing educational proposals that allow a change of action in future generations will promote the sustainability and preservation of the environment. Therefore, it is essential that this approach is reflected in the training of teachers so that they guide their methodological strategies towards the development of activities that not only preserve and conserve the environment, but also facilitate their pupils' teaching–learning process [12] (p. 8).

Given these realities and challenges, the goal of this work is to study the role of Green Chemistry in education with the purpose of contributing towards sustainability and consequently to the transition towards sustainable societies.

According to Mascarell and Vilches [12], achieving sustainability will be difficult without implementing a change in educational plans.

Given the importance of incorporating Green Chemistry into education for a sustainable future, we propose, based on a systematic analytical study, exploring the implications of Green Chemistry education in response to current environmental concerns. To attempt to respond to this general objective, we establish the following specific objectives:

- Determine the definitions, principles, and approaches of Green Chemistry present in the scientific literature.
- Identify and classify the most effective teaching strategies used to teach Green Chemistry.
- Analyze the barriers and facilitators perceived by teachers in teaching Green Chemistry.

2. Methodology

The present study was designed following the recommendations and structure of other systematic review studies and the guidelines of the PRISMA method [13,14]. Through this approach, our aim is to achieve the above-established goals, collect updated information about the topic, and subsequently analyze, synthesize, and compare the various articles selected.

2.1. Eligibility Criteria

To carry out this review, only studies published in the last 6 years, i.e., from 2018 onwards, were included to ensure the timeliness and relevance of the information. The search was limited to articles written in English and Spanish with free access to the full text. The types of studies included are journal articles and review articles that address the teaching of Green Chemistry at any educational level, from primary education to higher education. Also chosen were articles that included research about practices, strategies, methods, or approaches used to teach the principles of Green Chemistry.

All studies that did not specifically focus on the teaching of Green Chemistry or that addressed topics not relevant to the goals of this review were excluded. Also excluded were textbooks, laboratory guides, and other educational resources that did not constitute research articles, studies specific to the area of chemistry but that did not deal with educational aspects or address the concept of Green Chemistry, and educational interventions made outside of Spain.

2.2. Information Sources and Search Strategies

The search for articles began in February 2024. The search strategy was carried out in three databases—Dialnet, Web of Science, and Scopus—to answer the research question and respond to the objectives set. In these databases, studies belonging to the Experimental Sciences and Chemical Sciences, specifically in relation to Green Chemistry and Environmental Education teaching, were searched, with these being the main focus to delimit the systematic review. Likewise, the Boolean operators "AND" and "OR" were used with the respective keywords, in both English and Spanish, in the different databases, to see with which combinations the greatest number of studies fitting to the proposed goals were obtained. The most successful strategies were the following combinations: "Enseñanza AND química verde"; "Enseñanza AND química AND sostenibilidad"; "Teaching AND green chemistry"; "Teaching AND chemistry AND sustainability". The Boolean operator "OR" was not included since it did not generate a large number of articles and those found deviated greatly from the goal of the study.

The search results were exported to Endnote Web in order to facilitate their organization and eliminate any duplicates.

2.3. Study Selection and Data Extraction Process

Once the searches had been carried out in the different databases, the title, abstract and topic of each article were evaluated in order to identify the articles related to the proposed research and discard those that did not meet the eligibility criteria mentioned above. A data collection template was used to classify them. This included the following fields: author;

year of publication and country; study design and sample data; variables and instruments; and main results.

3. Results

3.1. Study Selection

As seen in Figure 2, carrying out the article search with the search strategy in each database yielded a total of 530 articles after removing duplicates.

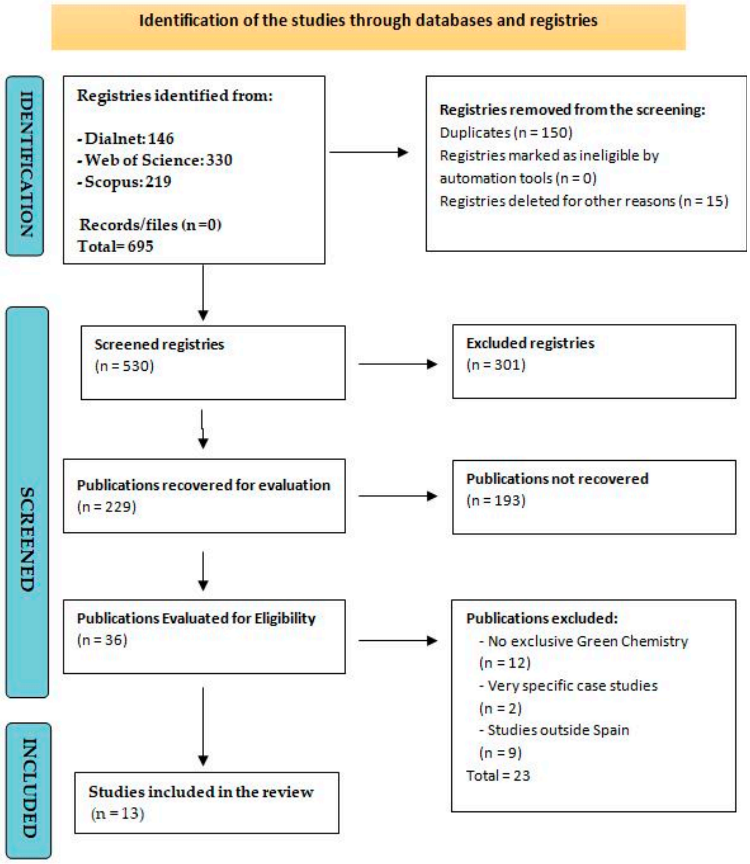

Figure 2. Flowchart. (Source: The authors. PRISMA template).

Once the data had been obtained, a first reading of the information collected from the titles of the studies was carried out, excluding those that did not meet the established inclusion criteria, which resulted in a total of 229 documents. Subsequently, a more exhaustive reading of the abstracts was carried out, eliminating those articles that did not fit the established criteria.

Subsequently, a more exhaustive reading of the abstracts was carried out, eliminating those articles that did not fit the established criteria. Once this initial evaluation was completed, a more detailed analysis of the selected documents was carried out, discarding those that did not meet the inclusion criteria; thus, a total of 36 documents was reached. After obtaining these articles, a further 23 were excluded because they did not provide information relevant to the topic or did not follow the inclusion criteria, thus allowing for an exhaustive analysis of the remaining documents and the extraction of the results and conclusions. This last selection left a total of 13 studies.

3.2. Study Characteristics

Table 1 presents the characteristics of the 13 articles that met the inclusion criteria. The key information of each selected article is collected concisely: the author, year of publication, title, type of study, stated goals, and the most notable results and conclusions.

Table 1. Summary of the articles' results.

	Title	Author/Year	Type of Study	Goals	Conclusions
1	A view of Green Chemistry teaching proposals	Marques y Machado (2018) [15]	Bibliographic review	Examine the evolution and consolidation of the Green Chemistry community, identify areas of pending understanding, analyze educational proposals, and explore models for teaching Green Chemistry, considering its relationship with sustainable development and Environmental Education.	The importance of the twelve principles of Green Chemistry in teaching is highlighted, but the authors note a lack of systematization in their application. Three aspects are identified in the educational proposals: punctual insertion, specialized courses, and transversal integration. The need is highlighted from primary education onwards for a Green Chemistry education rooted in an ecological culture, together with Environmental Education.
2	Conceptions about Green Chemistry in prospective chemistry teachers	Franco-Moreno et al. (2020) [16]	Qualitative and interpretive study	Characterize the conceptions about Green Chemistry among prospective teachers. To this end, the study seeks to validate an inquiry resource focused on definitions, projects, and applications of this approach, in addition to promoting its importance in teacher training and laboratory practice.	The study revealed the need for greater transversality in Chemistry bachelor-degree programs to incorporate Green Chemistry on a mandatory basis. Prospective teachers show a superficial understanding of the approach, which suggests the importance of including it in required courses for a deeper understanding. It is essential that prospective teachers focus upon the development of projects and methods that promote reductions in toxic waste and pollution in alignment with the principles of Green Chemistry.
3	Development and evaluation of elements of critical thinking about Green Chemistry in Secondary Education	Meinguer y Pérez (2021) [17]	Qualitative and interpretative study	Design and application of a teaching strategy designed to cultivate critical thinking in the context of higher secondary education, specifically in relation to Green Chemistry, through the characterization of critical thinking and its relevance in scientific education.	The study highlights the success of strategies to promote critical thinking in the teaching of Green Chemistry in secondary education, highlighting the importance of integrating environmental awareness and sustainable development in scientific training. It recognizes the complexity of this task and emphasizes the importance of comprehensive teacher training to promote critical thinking and contextualized science teaching at the higher secondary education level.
4	What lies behind teaching and learning green chemistry to promote sustainability education? A literature review	Chen et al. (2020) [18]	Literature review	Identify effective methods of teaching Green Chemistry and their impact on learning, in addition to analyzing how integration with sustainable education promotes environmental awareness and change towards sustainability.	Integrating Green Chemistry education with other areas can improve Green Chemistry Thinking and Green Chemistry Literacy, deepening pupils' environmental understanding. The importance of promoting systemic thinking, ICT skills, and integration with sustainable development is highlighted in relation to fostering environmental awareness and behavioral changes.

Table 1. *Cont.*

	Title	Author/Year	Type of Study	Goals	Conclusions
5	Education in green chemistry and in sustainable chemistry: perspectives towards sustainability	Zuin et al. (2021) [19]	Descriptive and exploratory study	Integrate Green and sustainable chemistry into educational plans, promote its teaching, and share good practices at a national and international level to transform methods towards more sustainable practices.	The importance of Green and sustainable chemistry for sustainable development is highlighted, and its integration into study plans, teacher training, and international cooperation is proposed. The study suggests involving diverse actors and promoting their integration into sustainable development initiatives worldwide.
6	Developing green chemistry educational principles by exploring the pedagogical content knowledge of secondary and pre-secondary school teachers	Nahlik et al. (2022) [20]	Interpretative and qualitative study	Explore teachers' understanding of Green Chemistry, propose its definition for secondary classrooms, and justify its teaching through observations and case studies in a teacher training program.	The teachers point out the benefits of Green Chemistry for promoting health, safety, and a sustainable mindset in their pupils, and recognize the need for better-adapted resources. They conclude that it offers educational advantages regardless of future interests.
7	The integration of green chemistry principles in basic chemistry learning to support achievement of Sustainable Development Goals (SDGs) through education	Mitarlis et al. (2023) [21]	Qualitative exploratory study and bibliographic review	Integrate Green Chemistry into education to support Sustainable Development Goals (SDGs) and design a learning model focused on Green Chemistry to meet the SDGs.	Integrating Green Chemistry into teaching can support SDGs by reducing waste and promoting safety and efficiency. Specific learning models, such as discussions and practicals, are suggested to facilitate this integration and contribute towards the achievement of the SDGs through education.
8	Integrating Green Chemistry in the Curriculum: Building Student Skills in Systems Thinking, Safety, and Sustainability	Aubrecht et al. (2019) [22]	Literature review	Promote sustainability in chemistry education and society by integrating systemic thinking and Green Chemistry into educational programs by providing tools, teaching strategies, and examples of their implementation.	Systems thinking in chemistry education improves pupils' understanding and addresses global issues. Three key areas are highlighted: educational resources, improving approaches, and application in broad contexts. Collaboration in the educational community is essential to take advantage of this approach and prepare pupils for global challenges.
9	Improvement of a sustainable world through the application of innovative didactic tools in green chemistry teaching: A review	Gawlik-Kobylińska et al. (2020) [23]	Bibliographic review	Analyze the use of new technologies to teach Green Chemistry and promote sustainability in education. The study focuses on e-learning platforms and virtual reality, highlighting the importance of proper instructions and overcoming any technological barriers to move towards sustainability in chemistry education.	Digital tools can improve the teaching of Green Chemistry and sustainability, promoting environmental awareness in pupils. Its implementation requires overcoming technical and human challenges, and integrating teaching with the principles of Green Chemistry. It is essential that teachers become familiar with these tools for a more effective and sustainable education.

Table 1. *Cont.*

	Title	Author/Year	Type of Study	Goals	Conclusions
10	Didactic features specific to green chemistry teaching in the journal of chemical education	Marcelino et al. (2023) [24]	Systematic review	Analyze, identify, and discuss methodological aspects and non-traditional teaching strategies and their relationship with the innovative nature of Green Chemistry.	The presence of innovative practices in the area of Green Chemistry is related to its transformative nature and sustainability, and therefore the integration of non-traditional strategies is key to better understanding it. Despite the challenges, there is progress towards more sustainable chemistry and the training of new professionals.
11	Exploring science literature: Integrating chemistry research with chemical education	Ronald (2023) [25]	Literature review	Integrate chemistry education with educational research to strengthen conceptual understandings, provide recent examples of research, and show real-world applications to enrich the teaching of chemistry.	It is crucial to integrate chemical research into education to enrich the understanding of scientific concepts and show their application to global challenges. Highlighting the central role of chemistry in solving global problems and designing curricula that reflect this connection are key actions to foster a deeper understanding of science through research.
12	An integrated vision of the Green Chemistry evolution along 25 years	Marques y Machado (2021) [26]	Systematic review	Evaluate the collected literature to identify and discuss the fundamental characteristics of Green Chemistry and highlight the main alterations in the evolution of Green Chemistry.	The analysis highlights the growth of the Green Chemistry community and its influence on the occupation of chemists. Challenges in chemistry assessment and the integration of GC into education and industrial practice are identified. A better definition of research areas and greater academic–industry integration are required. In summary, GC has made progress toward sustainability, but faces limitations and needs greater integration into chemical practice and education.
13	Socio-problematization of green chemistry: enriching systems thinking and social sustainability by education	Marcelino et al. (2019) [27]	Literature review	Analyze the relationship between Green Chemistry and sustainability, highlight the importance of systems thinking for more transformative practices, and advocate for chemistry education that promotes a broad understanding of sustainability.	The analysis highlights the limited attention given to the social dimension of Green Chemistry (GC), which focuses on technological optimism and the compatibility between the economy and environment. GC tends to be an elite movement, aimed at experts and politicians, without involving other social sectors such as NGOs and environmental movements. Only one article mentions humanitarian objectives, and highlights the need for qualitative metrics to evaluate GC in this respect. More research is required on the relationship between GC, sustainability, and social dimensions.

All of the studies mention the need to orient the teaching of chemistry towards the principles of Green Chemistry given that, in this way, one would be backing a chemical education that promotes a broad understanding of sustainability. Thus, there is a unanimous call for the integration of Green Chemistry into educational programs and for a rapprochement between academia and industry. Regarding the integration of Green Chemistry into educational programs and valid teaching strategies for this, strategies should develop critical thinking and work jointly with other areas of knowledge. These approaches, far from traditional methods, are required in order to achieve environmental awareness and sustainable development, and the digital tools available should be taken advantage of. Finally, the main teaching barrier detailed in one of the articles is the existence of alternative conceptions that hinder pupils' learning, and the main benefits detailed are the importance of Green Chemistry in achieving sustainable development and promoting pupils' health and safety.

4. Discussion

Once all of the studies collected had been reviewed, it was observed that the pedagogical approaches that best promote the learning of Green Chemistry respond to current environmental challenges and the prevailing need to promote more sustainable chemical practices. Therefore, Green Chemistry has emerged as an essential field of study. A discussion based on the stated objectives is now presented.

Objective 1: *Determine the definitions, principles, and approaches of Green Chemistry present in the scientific literature.*

It should be noted that Green Chemistry is a paradigm to follow in the field of chemistry, representing a fundamental approach towards environmental sustainability and social responsibility in the practice of chemistry. Throughout the scientific literature, various definitions, principles, and approaches have been proposed that outline the foundations and evolution of this multidisciplinary field.

The definitions of Green Chemistry, although varying in their nuances, converge in their emphasis on the reduction in or elimination of hazardous chemical substances and processes, the maximization of efficiency in the use of resources and energy, and the promotion of the synthesis of chemical products in a safe and sustainable way [28,29].

According to Zuin et al. [19], since the first formulation of the concept by Paul Anastas and John Warner in the 1990s, the importance of considering the complete life cycle of a chemical product has been recognized, from its design and synthesis to its final disposal, as a central aspect of Green Chemistry. In this sense, those same authors affirm that "*[...] Green Chemistry emerged as a new approach that required chemical syntheses that generate less waste, with less energy and more safety for workers and the environment*" (p. 1595).

Green Chemistry is concisely defined as the application or conception of chemical procedures and techniques that reduce or eliminate the production of waste and substances that are harmful to the environment and human health [21]. However, Manahan [30] points out that "*[...] Green Chemistry is a philosophy [...] or motivating concept of real action as a contribution of education to achieving the SDGs*" (p. 235).

According to the United States Environmental Protection Agency (EPA), Green Chemistry is defined *"as the use of chemistry to prevent pollution and the design of chemical products and processes that are beneficial to the environment"* ([26] p. 13).

The 12 fundamental principles of Green Chemistry formulated by Anastas and Warner [3] encompass a series of guidelines for the development and implementation of more sustainable practices in the chemical industry [17].

Regarding key approaches, the scientific literature highlights a wide range of key concepts used to implement the principles of Green Chemistry in practice [21]. As pointed out by Anastas and Zimmerman [31], these approaches include the design and synthesis of alternative solvents, the development of more efficient and selective synthesis methods, the application of biocatalysis techniques, and the use of renewable materials as carbon sources (linked to the principles of Green Chemistry). In addition, integrated approaches are also explored, such as assessing environmental and economic impact throughout the entire life cycle of a chemical using tools such as life-cycle analysis and carbon footprint assessment [21]. Therefore, according to Wardencki et al. [32] "*[. . .] education has a special role in the dissemination of Green Chemistry" (p. 234).*

The integration of Green Chemistry into the field of education is a crucial step in promoting the SDGs [21,22,27]. In this sense, the key concepts that must be integrated into the teaching–learning of chemistry are the following [16,18,20]:

- Sustainability: The concept of Green Chemistry implicitly carries the idea of sustainability (SDG), which implies a delicate balance between environmental, social, and economic aspects. Pupils must understand how chemistry can actively contribute to a world where resources are conserved and environmental impacts are reduced [18,19,21,29].
- Life-Cycle Assessment (LCA): The introduction of life-cycle assessment methods in the curriculum empowers pupils to comprehensively evaluate the environmental impact of chemicals and processes throughout their entire life cycle. This holistic approach considers every stage, i.e., from the extraction of raw materials to synthesis, use, and subsequent disposal [27]. By analyzing the entire life cycle, the pupils can identify opportunities for improvement and optimization, leading to more environmentally friendly and efficient processes [20,27].
- Green metrics: These are indicators that evaluate the aspects of a chemical process in line with the principles of Green Chemistry. In other words, Green Chemistry metrics quantify the environmental performance of chemical processes, facilitating the widespread adoption of more sustainable technologies in the industry [27]. Therefore, providing pupils with the ability to analyze and interpret environmental metrics is essential to promoting more sustainable practices in the chemical industry. This knowledge allows pupils to design and promote more ecological reactions, thus reducing the consumption of resources and waste (principle 1) [27,29].
- Climate change: As pupils immerse themselves in the study of Green Chemistry, they gain a deep understanding of how to mitigate climate change and reduce their carbon footprint [33]. They learn how sustainable practices and innovative technologies can reduce greenhouse gas emissions and combat global warming [17,21,22,26,33].
- Environmental legislation: A crucial aspect of Green Chemistry training involves familiarizing pupils with global regulations and guidelines related to sustainable environmental practices [18,19,21,29].
- Green innovations: Pupils should be provided with real cases that illustrate the positive impact of Green Chemistry in today's world. These case studies reinforce the importance of innovating with sustainable practices, encouraging pupils to contribute to the initiatives that are being carried out worldwide for a more ecological and sustainable future. An example of this would be the future green hydrogen plant in Huelva [25,34].

In line with the above, there are ever more programs of research concerning Green Chemistry [17,25,34] because of its potential contribution to sustainable development. Currently, important initiatives are being carried out to establish, at national and international levels, the principles and practices of Green Chemistry. An example of this is the Green Chemistry Institute [35] in the United States, which has members from various institutions worldwide. This entity was established in 1997 with the objective of supporting the progress of Green Chemistry by means of various activities such as research, education, the organization of conferences and symposia, as well as the dissemination of information to raise public awareness.

Objective 2: *Identify and classify the most effective teaching strategies used to teach Green Chemistry.*

It should be noted that Green Chemistry is an approach that has been gradually incorporated into the field of chemistry education. Its relevance has been growing over time and it is projected to become a fundamental part of scientific education for environmental sustainability [22,25]. In this context, innovative teaching strategies are being sought that can allow chemistry to be taught from a more sustainable and responsible perspective so as to ensure that teachers promote meaningful learning regarding this discipline. It should be remembered that meaningful learning not only involves the acquisition of knowledge, but also its application in today's context [17,18,22,24].

In line with the above, more and more research programs about Green Chemistry [17,25,34] are being undertaken due to its potential contribution to sustainable development. Currently, important initiatives are being carried out to establish, at national and international levels, the principles and practices of Green Chemistry.

The appropriate selection of teaching methods is important; there is need for a holistic approach [18,19] that incorporates both the cognitive and affective dimensions of learning. In this sense, the most effective teaching strategies for teaching Green Chemistry are as follows:

- Active and participatory learning: Methods that actively involve pupils, such as project-based learning, cooperative learning, problem-based learning, and service learning, have been found to be highly effective in fostering a deep understanding of the principles of Green Chemistry. These approaches promote pupil engagement and the practical application of content [17,18,21,22,24].
- Use of case studies and contextualization: The integration of real case studies related to Green Chemistry provides pupils with a deeper understanding of how the principles apply in specific situations. This facilitates the connection between theory and practice, as well as the development of problem-solving skills [17,20,22,25].
- Interdisciplinary approach: This strategy proposes the inclusion of Green Chemistry content in other areas of the curriculum, thus transcending traditional disciplines. It has been observed that interdisciplinary approaches that integrate knowledge from various areas help pupils appreciate the complexity of environmental problems and develop comprehensive solutions [17,18]. For example, environmental sustainability issues can be addressed in chemistry, biology, technology and engineering, and the environmental sciences; in this way, pupils can understand how the principles of Green Chemistry are applied in different contexts [18,19].
- Focus on atomic design and sustainable experimentation: The principles of Green Chemistry promote the design of more efficient chemical reactions; therefore, promoting laboratory practices that follow these principles is essential. This involves reducing the use of toxic substances, minimizing waste production, and seeking more "green" alternatives for the environment [26]. For example, to undertake this, teachers can focus on explaining how chemicals can be synthesized in a way that uses non-volatile solvents, efficient catalysts, and reactions in fewer steps to generate fewer byproducts [16].
- Application of digital technologies and virtual experiments: The incorporation of digital tools and virtual experiments offers opportunities to teach Green Chemistry interactively, allowing pupils to explore chemical phenomena in a safe and accessible way. These tools provide practical experiences that complement traditional teaching and facilitate the understanding of the abstract concepts of Green Chemistry. For example, the use of simulations, molecular models, and molecular design software encourages pupils to explore how chemical structures can be modified to achieve more sustainable products [18,23].
- Research projects: Involving pupils in original research projects related to Green Chemistry, for example, researching new materials, cleaner synthesis processes, or applications of Green Chemistry in industry, encourages critical thinking and creativity [17]. These projects allow pupils to apply scientific methods and develop innovative solutions to environmental challenges [17,18,21,22,24].
- Development of transversal skills: In addition to scientific knowledge, it is essential to develop transversal skills such as effective communication, teamwork, and critical

thinking [17,18,22,24]. These skills enable pupils to develop projects in an ethical, responsible, and collaborative manner in the field of Green Chemistry [22].

- Formative evaluation: Providing continuous and formative feedback during the teaching–learning process allows pupils and teachers to identify areas of improvement and consolidate their understanding of the content of Green Chemistry, promoting reflective and autonomous learning [16,18,20].

In short, it is important to use innovative methods because these result in more effective and meaningful learning for pupils. By actively involving them in their own learning process, these strategies foster a deeper understanding of the content, promote the development of critical and creative skills, and prepare pupils to face real-world challenges in the field of Green Chemistry. Furthermore, by incorporating these teaching strategies, teachers can better adapt to the needs and learning styles of their pupils, creating an inclusive and stimulating learning environment [28,36,37].

Objective 3: *Analyze the barriers and facilitators perceived by teachers in teaching Green Chemistry.*

The summary table below (Table 2) includes all of the facilitating and barrier factors [19,20,24,26] that influence, positively or negatively, the Green Chemistry teaching–learning process.

Table 2. Facilitating factors and barriers in teaching Green Chemistry.

Facilitating Factors	Barrier Factors
Access to technology and educational tools.	Lack of interdisciplinary collaboration.
Training and professional development.	Resistance to changing methods.
Support from institutions.	Lack of teacher training.
Practical application of contents.	Time limitations in the education curriculum.
Innovative pedagogical approaches.	Lack of understanding about the benefits of Green Chemistry.

Source: The authors.

The analysis of the perceived barriers and facilitators in the teaching of Green Chemistry is crucial so as to understand and improve the implementation of this discipline in the educational field [24].

Teachers play a fundamental role in transmitting their knowledge of Green Chemistry to pupils, but they may face various barriers in their teaching. One of the main barriers is the lack of interdisciplinary collaboration to address the principles and practices of Green Chemistry effectively in different areas of the curriculum with a holistic approach [18].

Resistance to change can also represent a significant barrier. The implementation of Green Chemistry often requires a change in the traditional approaches to teaching chemistry, which may be met with resistance from some teachers who are accustomed to more conventional methods [24]. Additionally, curricular demands and time constraints may cause teachers to feel that they do not have enough time to dedicate to teaching new concepts, such as those related to Green Chemistry [22].

The lack of teacher training in the field of Green Chemistry is a significant barrier to effective teaching in this field. Teachers may lack a deep understanding of the principles and practices of Green Chemistry, as well as adequate pedagogical strategies to effectively convey these concepts to their pupils. This may be due to the absence of initial or ongoing training courses focused on Green Chemistry in teacher training programs, as well as the lack of resources and opportunities for professional development in this field [16].

On the other hand, there are various facilitators that can promote the effective teaching of Green Chemistry. One of the main ones is the availability of appropriate and up-to-date educational resources and materials [36]. This includes textbooks, virtual laboratories, educational software, and laboratory materials that focus on Green Chemistry and provide concrete examples of its real-life application [18,20,23].

Both the training and professional development of teachers in the field of Green Chemistry are also key facilitators [20]. Initial and ongoing educational programs can help teachers acquire the knowledge and skills necessary to teach this topic meaningfully, as well as keep up to date with advances in the discipline [16,26].

Furthermore, the support of governmental and non-governmental institutions is essential to promoting the teaching of Green Chemistry. In this sense, the LOMLOE [38] framework is aligned with the policies and programs that promote the integration of Green Chemistry into the educational curriculum [15,19,21,38].

The practical application of Green Chemistry content involves integrating real examples and concrete situations into teaching to help pupils understand how theoretical principles are applied in the real world, thus promoting more meaningful learning and the development of problem-solving skills [17,20,22,25,36].

Finally, innovative pedagogical approaches, such as project-based learning or the use of digital technology [18,23,37], allow for the creation of more interactive and personalized learning experiences, increasing pupils' participation and commitment, and encouraging the development of transversal skills with which to address environmental challenges [22,25,34].

5. Conclusions

Advances in the didactics of Green Chemistry have been notably influenced by a variety of interrelated factors, reflecting a complex intersection between educational policies, pedagogical practices, and cultural changes. This study highlights the importance of understanding these influences to promote the effective teaching of Green Chemistry.

A crucial aspect that emerges from this research is the need for a broad spectrum of support for the teachers and pupils involved in the teaching and learning of Green Chemistry. Access to specialized educational resources, teacher training programs, and professional support networks has been shown to play a significant role in the success and sustainability of teaching this discipline. These resources provide guidance, information, and practical tools that can increase teachers' confidence and competence in teaching Green Chemistry, as well as pupils' engagement and participation in the learning process.

Educational and environmental policies also play a crucial role in advancing the teaching of Green Chemistry. On the one hand, the importance of implementing Green Chemistry stands out as a concept in current curricula and educational programs at both school and university levels. The inclusion of content and activities related to Green Chemistry in the education curriculum ensures that pupils have the opportunity to learn about this field in a systematic and meaningful way, which contributes to their academic and professional development in the field of environmental sustainability, in line with the Sustainable Development Goals (SDG). On the other hand, the adoption of policies that encourage interdisciplinary collaboration and the integration of Green Chemistry into other fields of study are key elements for the development and dissemination of the teaching of this discipline.

In summary, this review highlights the importance of adopting a holistic and multidimensional approach when teaching Green Chemistry—an approach that takes into account not only the technical and scientific aspects of the discipline, but also its socio-cultural, political, and economic context. By understanding and addressing these factors comprehensively, one can move towards more effective and relevant teachings of Green Chemistry, preparing pupils to face current environmental challenges and contribute to the construction of a more sustainable future.

However, in light of the scarcity of recent research on the topic compared with that existing in the years prior to 2018, it is important to call for continued research and progress in this crucial area for the sustainable development of our planet. In addition, it would be interesting and helpful to construct a systematic review covering studies from around the world that address Green Chemistry methodologies and education.

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