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Integrating Green Chemistry Principles into Chemistry Education for Achieving Sustainable Development Goals (SDGs): A Systematic Literature

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Abstract: Advances in science and technology increase chemical use, raising environmental and health concerns. Consequently, green chemistry has emerged to promote sustainable learning practices. This Systematic Literature Review (SLR) aims to analyze the implementation of green chemistry principles in chemistry education using the PRISMA framework. Data were retrieved from Scopus (via Publish or Perish), ACS Publications, and ERIC for the period from January 2016 up to January 2026. Of the 12,737 total articles retrieved, 57 met the inclusion criteria for final analysis. The results indicate that the most frequently implemented green chemistry principle is prevention, followed by safer solvents and auxiliaries and renewable feedstocks, while others remain rarely implemented, highlighting a critical gap for future research and curriculum development. Implementation occurs through diverse learning activities, particularly laboratory experiments, supported by varied pedagogical models and media. Furthermore, integrating green chemistry positively impacts critical thinking, higher-order thinking, systems thinking, and sustainability awareness. Thus, green chemistry strongly supports more contextual, safer, and sustainability-oriented chemistry learning.

Keywords: Chemistry education; Green chemistry; Green chemistry principles; Sustainability; Systematic literature review

Introduction

Advances in science and technology have significantly increased the use of chemicals across various life sectors. While chemistry drives human progress through advancements in medicine, agriculture, and energy, conventional practices contribute to severe ecological and health problems, including hazardous waste and resource depletion (Das et al., 2022; Warner & Anastas, 1998). In Indonesia, environmental quality and waste management remain critical challenges. According to BPS-Statistics Indonesia (2025), national environmental indicators still reflect urgent issues in toxic waste management, the consumption. of ozone-depleting substances, and provincial waste accumulation.

To address these challenges, green chemistry emerges as a vital framework, emphasizing the design of chemical products and processes that reduce or eliminate hazardous substances (Warner & Anastas, 1998). This approach promotes safer, more efficient practices aligned with global sustainable development goals (Etzkorn & Ferguson, 2023; Zuin et al., 2021). Green chemistry is built upon twelve core principles, ranging from waste prevention and atom economy to the use of renewable feedstocks and design for degradation (Warner & Anastas, 1998). However, while these twelve principles are theoretically cohesive, preliminary literature suggests an imbalance in their practical integration, with a heavier educational focus on waste reduction while complex principles like atom economy or real-time analysis remain largely underrepresented.

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In educational contexts, integrating green chemistry is crucial to foster socio-environmental responsibility alongside conceptual mastery. It enables students to realize that chemical processes involve critical choices regarding safety, materials, and global impacts (Etzkorn & Ferguson, 2023; Zuin et al., 2021). Consequently, green chemistry education serves as a catalyst for developing higher-order thinking skills, systems thinking, and sustainability awareness (Widyantoro et al., 2025). This pedagogical shift is increasingly vital in secondary and higher education, where students actively engage in laboratory investigations and real-world problem-solving (Idul, Jaculbe, et al., 2025; Idul & Walag, 2024).

Recent studies have explored various integration methods, including green curricula, digital media, small-scale laboratory experiments, and student-centered approaches like Process-Oriented Guided Inquiry Learning (POGIL) (Armstrong et al., 2024; Cannon et al., 2023; Idul, Jaculbe, et al., 2025; Lathwesen & Eilks, 2024; Widyantoro et al., 2025). While these individual studies report positive impacts on student outcomes (Chen et al., 2025; de Verteuil et al., 2024; Grieger et al., 2022; Lee et al., 2024; Nwafor et al., 2025), the literature remains highly fragmented. Extant research is scattered across isolated contexts-some strictly focusing on low-waste lab adjustments, while others examine teacher training or assessment design. Consequently, a unified understanding of how specific green chemistry principles systematically map onto distinct pedagogical models and learning outcomes is currently missing. Previous reviews Etzkorn et al. (2023) and Zuin et al. (2021) have addressed the general importance of sustainability in chemistry, but they do not provide a structured taxonomy.

Therefore, this study fills this critical gap. The novelty of this research lies in establishing a comprehensive taxonomy that explicitly correlates specific green chemistry principles with distinct learning activities and student outcomes. Conducting this Systematic Literature Review (SLR) is essential to provide educators and curriculum developers with an empirical roadmap for a balanced, effective integration of green chemistry.

To achieve this, this study utilizes the PRISMA framework to examine the distribution of the twelve principles of green chemistry within chemistry education literature, while also identifying the specific learning activities utilized for their integration. Furthermore, it characterizes the prevailing pedagogical approaches, instructional models, curricula, and learning media employed in the literature, and synthesizes the specific learning outcomes achieved through these implementations. Through this systematic synthesis, this study provides actionable insights to advance safer, contextual, and sustainability-oriented chemistry education.

Method

Research Design

This study used a Systematic Literature Review (SLR) approach to identify, select, and synthesize articles discussing the application of green chemistry principles in the context of chemistry education. This approach was chosen because it allows for a systematic, structured, and transparent review of the literature, thereby providing a more comprehensive overview of trends in the implementation of green chemistry in chemistry learning. The review process followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 framework to ensure the traceability of the stages of identification, screening, eligibility assessment, and inclusion of article. The data obtained were analyzed using a descriptive-qualitative approach through thematic grouping according to the research focus (Page et al., 2021).

Research Questions

To clarify the study's scope and guide the formulation of research objectives, this review adopted the PICo framework (Population, Interest, and Context), which is highly suited for qualitative and qualitative descriptive systematic syntheses (Hosseini et al., 2014). Within this framework, the Population encompasses students and educators within chemistry education; the Interest is the implementation of green chemistry and its twelve principles; and the Context is formal chemistry instruction across secondary and higher education levels. Guided by this framework, this study addresses four central themes: Referring to this framework, the research questions in this study are as follows:

(1) how is the application of the 12 principles of green chemistry distributed in chemistry education?
(2) what activities are used to integrate green chemistry into chemistry education?
(3) what approaches, models, curricula, and types of media are used in the application of green chemistry principles?
(4) what learning outcomes are reported from the application of green chemistry in chemistry education?

Data Sources and Search Strategy

The literature search was executed across three highly relevant electronic databases: Scopus, ACS Publications, and ERIC. To ensure accuracy and precision, Harzing's Publish or Perish software was utilized to retrieve metadata from the Scopus database, while direct advanced search engines were applied to ACS Publications and ERIC.

The search targeted publications within a ten-year timeframe, spanning from January 2016 up to January 2026. Keywords were combined using Boolean operators and specifically restricted to fields such as Title, Abstract, and Keywords to prevent overly broad and irrelevant returns. The standardized search string structure was defined as follows: "green chemistry" AND "chemistry education" AND (implementation OR laboratory OR practicum).

Table 1. Literature Search Strategy

Database	Initial Number of Results
Scopus via Publish or Perish	94
ACS Publications	11.452
ERIC	1.191
Total	12.737

Inclusion and Exclusion Criteria

Articles obtained through the search process were selected based on inclusion and exclusion criteria to ensure their relevance to the research objectives (Table 2). The inclusion criteria for this review are as follows:
(1) research articles published between 2016-2026;
(2) articles discussing green chemistry in the context of chemistry education;
(3) articles written in English; and
(4) articles available in full-text form for analysis.
The exclusion criteria include:
(1) non-research articles, such as opinion pieces, books, book chapters, or non-scientific notes;
(2) articles that do not focus on the application of green chemistry in chemistry education; and
(3) articles not available in full-text format.

Table 2. Inclusion and Exclusion Criteria

Category	Inclusion Criteria	Exclusion Criteria
Publication year	2016–2026	Before 2016
Language	English	Languages other than English
Document type	Research articles	Opinions, books, book chapters, non-research notes
Article availability	Full text available	Abstract only / full text not available
Topic	Green chemistry in chemistry education	Not related to green chemistry or chemistry education

Article Selection Procedure

Article selection was conducted in stages following the PRISMA 2020 process, including identification, screening, and final inclusion. During the initial identification stage, a total of 12,737 articles were obtained from three sources: 94 articles from Scopus via Publish or Perish, 11,452 articles from ACS Publications, and 1,191 articles from ERIC. Prior to the screening stage, 5 duplicate articles and 3,074 articles that did not meet the specific publication year criteria were removed. Thus, 9,658 articles advanced to the initial screening stage.

During the screening stage, the titles and abstracts of the 9,658 articles were rigorously evaluated against the core criteria. At this point, 6,983 articles were eliminated due to clear thematic irrelevance, leaving 2,675 articles to be assessed for deeper eligibility.

During the eligibility stage, the full texts of these 2,675 reports were sought for retrieval, and all were successfully retrieved (0 reports were unretrievable). Upon evaluating these full texts, 420 articles were excluded due to non-research content (such as opinion pieces, books, book chapters, and non-scientific notes), and 2,198 articles were excluded because they focused on pure chemistry or industrial topics outside the scope of chemistry education. Consequently, after this rigorous, filtration, exactly 57 articles met all inclusion criteria and were included in the final synthesis. The complete article selection process is visually mapped in Figure 1.

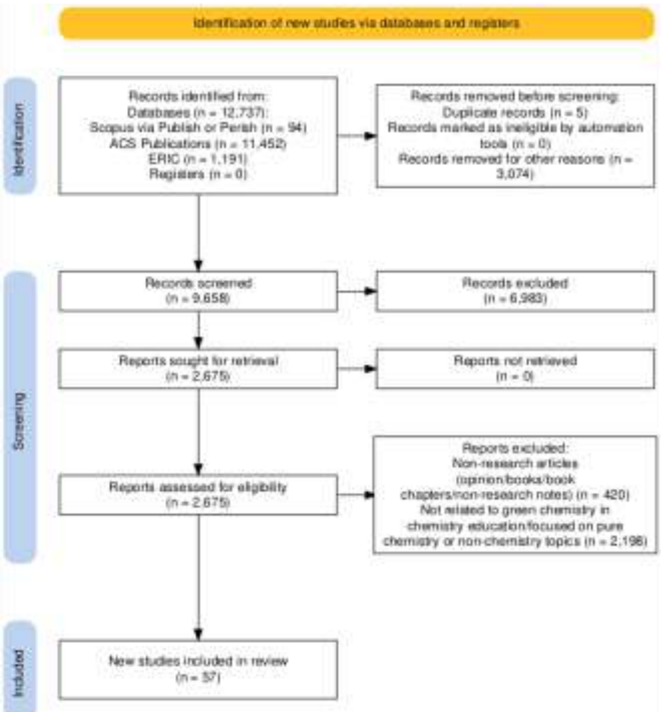

Figure 1. PRISMA 2020 flowchart for the identification, screening, eligibility assessment, and inclusion of articles in a Systematic Literature Review on the application of green chemistry principles in chemistry education.

Data Extraction

Data from the 57 selected articles were systematically extracted to obtain information relevant to the research objectives (Table 3). Information recorded for each article included the author's name and year of publication, article title, journal, green chemistry principles applied, type of learning activity, learning approach or model, media used, and reported learning outcomes. Additionally, the articles were classified based on whether they applied all green chemistry principles or only certain principles. This data extraction process aimed to facilitate the grouping of articles into analysis categories aligned with the research questions.

Table 3. List of Included Articles (n=57)

Code	Author, Year	Article title	Journal	Level	Region
A1	(Idul, Walag, et al., 2025)	The LUNTIAN Project: Strengthening Collaboration and Sustainability Mindset in the Academic Community through Green Chemistry Integration	Journal of Chemical Education	High School	Philippine
A2	(Idul & Walag, 2024)	Integrating Green Chemistry and Sustainability Principles to a Secondary Science Curriculum: A Mixed-Methods Needs Assessment	Journal of Chemical Education	Teachers	Philippine
A3	(Vogelzang et al., 2021)	Scrum Methodology in Context-Based Secondary Chemistry Classes: Effects on Students' Achievement and on Students' Perceptions of Affective and Metacognitive Dimensions of Their Learning	Instructional Science	High School	Netherlands
A4	(Grieger & Leontyev, 2024)	Evaluation of the Open-Ended Green Chemistry Generic Comparison (GC)² Prompt for Probing Student Conceptions about the Greenness of a Chemical Reaction	Journal of Chemical Education	Undergraduate	United States
A5	(Mistry & Hurst, 2022)	A Simple Setup to Explore Fog Harvesting as a Clean and Sustainable Source of Water	Journal of Chemical Education	High School	United Kingdom
A6	(Armstrong et al., 2024)	Behind the Scenes of Teaching Green: An Iterative Approach to Curriculum Design and Implementation in the General Chemistry Laboratory	Journal of Chemical Education	Undergraduate	United States
A7	(Lathwesen & Eilks, 2024)	Can You Make it Back to Earth? A Digital Educational Escape Room for Secondary Chemistry Education to Explore Selected Principles of Green Chemistry	Journal of Chemical Education	High School	Germany
A8	(Ruff et al., 2024)	Using ChatGPT for Method Development and Green Chemistry Education in Upper-Level Laboratory Courses	Journal of Chemical Education	Undergraduate	United States
A9	(O'Neil et al., 2021)	Approaches to Incorporating Green Chemistry and Safety into Laboratory Culture	Journal of Chemical Education	Undergraduate	United States
A10	(Cannon et al., 2023)	Green Chemistry Teacher Professional Development in New York State High Schools: A Model for Advancing Green Chemistry	Journal of Chemical Education	Teachers	United States
A11	(Widyantoro et al., 2025)	Teaching Sustainability through Green Chemistry: An Experiential Learning Approach	Journal of Chemical Education	Teachers	Singapore
A12	(Nwafor et al., 2025)	AI4Green4Students: Promoting Sustainable Chemistry in Undergraduate Laboratories with an Electronic Lab Notebook	Journal of Chemical Education	Undergraduate	United Kingdom
A13	(Manarisip et al., 2025)	Boosting Creative Thinking and Entrepreneurial Attitude in Manado High School Students: Applying Scrum with Etnochemistry Context in Green Chemistry	Journal on Efficiency and Responsibility in Education and Science	High School	Indonesian
A14	(Grieger et al., 2022)	Development of the Assessment of Student Knowledge of Green Chemistry Principles (ASK-GCP)	Chemistry Education Research and Practice	Undergraduate	United States
A15	(Hardy et al., 2021)	Potential for Chemistry in Multidisciplinary, Interdisciplinary, and Transdisciplinary Teaching Activities in Higher Education	Journal of Chemical Education	Undergraduate	United Kingdom

Code	Author, Year	Article title	Journal	Level	Region
A16	(Finster & Jackson, 2021)	Comprehensive Undergraduate Safety Instruction	Journal of Chemical Education	Undergraduate	United States
A17	(Chen et al., 2025)	Design, Implementation, and Evaluation of Authentic Learning Activities to Introduce Chemistry Students to Systems Thinking through Green Chemistry	Journal of Chemical Education	Undergraduate	Australia
A18	(Sheppard, 2021)	Integration of Laboratory Safety and Green Chemistry: Implementation in a Sophomore Seminar and an Advanced Organic Laboratory	Journal of Chemical Education	Undergraduate	Georgia
A19	(Subarkah et al., 2020)	Implementation of Green Chemistry-Based Electrolysis Learning Media to Develop Higher Order Thinking Ability	Journal of Physics: Conference Series	Undergraduat (physical chemistry)	Indonesian
A20	(Chowdhary et al., 2025)	Upcycling Waste Polycarbonate into N,N′-Diphenylethylurea: A Hands-On Experiment for Undergraduate Chemistry Laboratories	Journal of Chemical Education	Undergraduate (organic chemistry)	Germany
A21	(Yimkosol & Dangkulwanich, 2025)	Glucose Concentrations in Coconut Water via Microplate Spectrometry and Digital Image Colorimetry	Journal of Chemical Education	Undergraduate (analytical chemistry)	Thailand
A22	(Love et al., 2024)	Development and Implementation of a Research-Preparative General Chemistry Laboratory Course: Chemistry of Beverages	Journal of Chemical Education	Undergraduate	United States
A23	(Miller et al., 2019)	Green Machine: A Card Game Introducing Students to Systems Thinking in Green Chemistry by Strategizing the Creation of a Recycling Plant	Journal of Chemical Education	Undergraduate and Graduate	United States & United Kingdom
A24	(Karmakar et al., 2023)	Introducing the 3R Program in Teaching Laboratories to Promote Sustainability Science through Miniaturization Studies on the Spectrophotometric Determination of Organic Carbon and Phosphorus in Soil	Journal of Chemical Education	Undergraduate and graduate	India
A25	(Giani & Baffelli, 2025)	Bridging Education and Process Design with Atom Economy via Reaction SMILES	Journal of Chemical Education	Undergraduate	Switzerland
A26	(Rodríguez-Berríos et al., 2025)	Synthesis of Benzoylferrocene by Friedel–Crafts Acylation: Reinforcing Recrystallization and Spectroscopic Techniques in the Undergraduate Organic Chemistry Laboratory	Journal of Chemical Education	Undergraduate (organic chemistry)	United states
A27	(Sharma et al., 2023)	Rapid Amide Coupling in Water for Undergraduate Laboratories	Journal of Chemical Education	Undergraduate (organic chemistry)	United states
A28	(Rojanarata et al., 2016)	Fabrication of Chromatographic Devices for Screening Cosmetics for Hydroquinone and Retinoic Acid as a Chemistry Project to Connect with the Community	Journal of Chemical Education	Undergraduate (Analytical chemistry)	Thailand
A29	(Ravi, 2023)	Spectroscopic Methods for Pollution Analysis─Course Development and Delivery Using the Integrated Course Design Framework	Journal of Chemical Education	Undergraduate	United Kingdom
A30	(de Verteuil et al., 2024)	Integrating Simple Environmental Impact-Based Metrics into the Undergraduate Curriculum	Journal of Chemical Education	Undergraduate	Canada
A31	(Idul, Jaculbe, et al., 2025)	Green Modules: Integrating Green and Sustainable Chemistry Principles to Secondary Chemistry Modules through Process-Oriented Guided Inquiry Learning	Journal of Chemical Education	High School	Philippine
A32	(Montag, 2023)	Utilizing the Imine Condensation in Organic Chemistry Teaching Laboratories to Reinforce Steric Effects, Electronic Effects, and Green Chemistry Principles	Journal of Chemical Education	Undergraduate (organic chemistry)	United States
A33	(Rosales Martínez et al., 2022)	Green Reductive Regioselective Opening of Epoxides: A Green Chemistry Laboratory Experiment	Journal of Chemical Education	Undergraduate	Spain

Code	Author, Year	Article title	Journal	Level	Region
A34	(Andrew et al., 2022)	A Greener Synthesis of the Antidepressant Bupropion Hydrochloride	Journal of Chemical Education	Undergraduate	United Kingdom
A35	(Ridley et al., 2024)	Using a Temporal Systems Thinking Framework to Design and Redesign a Biorefinery	Journal of Chemical Education	Undergraduate	United Kingdom
A36	(Tantayanon et al., 2025)	Teachers' Perceptions and Design of Small-Scale Chemistry Driven STEM Learning Activities	Chemistry Teacher International	Teachers	Thailand
A37	(Colacino et al., 2019)	Introducing Students to Mechanochemistry via Environmentally Friendly Organic Synthesis Using a Solvent-Free Mechanochemical Preparation of the Antidiabetic Drug Tolbutamide	Journal of Chemical Education	Undergraduate (organic chemistry)	France
A38	(Zhang et al., 2021)	Reaction of Diphenyldiazomethane with Benzoic Acids in Batch and Continuous Flow	Journal of Chemical Education	Undergraduate (organic chemistry)	United States
A39	(Rand et al., 2016)	Development and Implementation of a Simple, Engaging Acid Rain Neutralization Experiment and Corresponding Animated Instructional Video for Introductory Chemistry Students	Journal of Chemical Education	Undergraduate	United States
A40	(López-Fernández et al., 2025)	Chemistry Inquiry Conducted by Secondary School Students into Material Degradation in the Context of Sustainability	RSC Sustainability	Secondary school	Spain
A41	(Wang et al., 2024)	Using Soapnut Extract as a Natural Surfactant in Green Chemistry Education: A Laboratory Experiment Aligning with UN SDG 12 for General Chemistry Courses	RSC Sustainability	Undergraduate	United States
A42	(Rayner, 2025)	A Research-Led Undergraduate Group Mini-Project: Optimizing the Use of Polymethylhydrosiloxane for Stereoselective Ketone Reduction	Journal of Chemical Education	Undergraduate (organic chemistry)	United Kingdom
A43	(Johnson et al., 2022)	A Low-Cost and Simple Demonstration of Freezing Point Depression and Colligative Properties with Common Salts and Ice Cream	Journal of Chemical Education	Undergraduate	United States
A44	(Streuli et al., 2025)	A Second Chance for Expired Medication: Teaching Green Analytical Chemistry in an Analytical Chemistry Laboratory Course for Undergraduate Students	Journal of Chemical Education	Undergraduate (analytical chemistry)	Switzerland
A45	(Stephanie et al., 2020)	Jambolan Fruit Peels (Syzygium cumini L. Skeels) as Substitute for Synthetic Acid Base Indicators: Implementation of the ESD Concept	Journal of Physics: Conference Series	High School	Indonesian
A46	(De Waard et al., 2022)	Engaging Preuniversity Students in Sustainability and Life Cycle Assessment in Upper-Secondary Chemistry Education: The Case of Polylactic Acid (PLA)	Journal of Chemical Education	High School	Netherlands
A47	(Oliveira et al., 2025)	Synthesis of Iron Oxide Nanoparticles and Their Application in Photo-Fenton Process: An Undergraduate Experiment in Chemistry	Journal of Chemical Education	Undergraduate	Brazil
A48	(Ho et al., 2026)	A Greener Synthesis of the Nonsteroidal Anti-inflammatory Drug Celecoxib	Journal of Chemical Education	Undergraduate	United Kingdom
A49	(Bru et al., 2023)	Learning Green Chemistry Principles by Comparing Three Synthetic Routes to a Copper-NHC Complex	Journal of Chemical Education	Undergraduate	Belgium
A50	(Campbell et al., 2024)	Applying a Guided Inquiry Approach to a Classic Practical on Chemoselective Reduction	Journal of Chemical Education	Undergraduate (organic chemistry)	United Kingdom
A51	(Josephson et al., 2019)	Student-Driven Development of Greener Chemistry in Undergraduate Teaching: Synthesis of Lidocaine Revisited	Journal of Chemical Education	Undergraduate (organic chemistry)	Sweden

Code	Author, Year	Article title	Journal	Level	Region
A52	(Benedetto et al., 2023)	CD-MOF-1 for CO2 Uptake: Remote and Hybrid Green Chemistry Synthesis of a Framework Material with Environmentally Conscious Applications	Journal of Chemical Education	Undergraduate and High School	United States
A53	(D'eon et al., 2024)	Welcome to 310 Environmental Working Group! A Group Project That Places Students in the Role of Consultants Helping Businesses Choose the Most Climate Friendly Fluorinated Gas	Journal of Chemical Education	Undergraduate	Canada
A54	(Lee et al., 2024)	A Citrus Serenade: An Improved Procedure for the Imine Condensation Reaction in Undergraduate Laboratories	Journal of Chemical Education	Undergraduate (organic chemistry)	United States
A55	(Schwantes et al., 2025)	Green Beginnings: Creating an Affordable Advanced Enquiry-Based Experimental Nanochemistry Learning Module with Catalytically Active 'Green' Iron Oxide Nanoparticles (IONPs)	RSC Sustainability	Undergraduate (inorganic chemistry)	United States
A56	(Knutson et al., 2017)	Polymeric Medical Sutures: An Exploration of Polymers and Green Chemistry	Journal of Chemical Education	Undergraduate and High School	United States
A57	(Gomes & Afonso, 2023)	Preparation of Aminals under Continuous Flow Conditions	Journal of Chemical Education	Undergraduate (organic chemistry)	Portugal

Study Quality Assessment

To enhance the rigor of the review, articles that met the inclusion criteria were evaluated using a study quality assessment rubric. The assessments were conducted on six indicators: (1) clarity of research objectives; (2) clarity of the research methods or design; (3) clarity of the study context or subject; (4) clarity of green chemistry implementation; (5) clarity of main results or findings; and (6) relevance to the review's research questions. Each indicator was scored from 0–2, resulting in a total score for each article ranging from 0 to12. The total score was then categorized as high (10–12), moderate (7–9), low (4–6), and very low (0–3). This assessment was used to support the accuracy of the synthesis and to provide an overview of the reporting quality of the articles included in this review.

Data Analysis and Synthesis Techniques

The extracted data were analyzed using a descriptive-qualitative approach. The analysis was conducted by grouping articles based on: (1) the distribution of the application of the 12 green chemistry principles; (2) the learning activities used to integrate green chemistry; (3) approaches, models, curricula, and learning media; and (4) reported learning outcomes.

The frequency of each green chemistry principle's occurrence was calculated to illustrate implementation trends in the analyzed articles. An article could be classified into more than one category if it reported more than one principle, activity, approach, media, or learning outcome. Additionally, the results of the study quality assessment were used as supporting information to interpret the strengths of the reporting in the synthesized articles. Furthermore, a narrative synthesis was used to explain key patterns, implementation trends, and the contributions of green chemistry to chemistry learning. The analysis results were then presented in tables, graphs, and thematic discussions according to the research focus.

Result and Discussion

Overview of the Reviewed Articles

Based on the PRISMA 2020 flowchart, 57 articles meeting the inclusion criteria were identified and further analyzed. These articles were collected between January 2016 and January 2026 and focused on the application of green chemistry in the context of chemistry education, both at the secondary and higher education levels. In general, the reviewed articles indicated that the integration of green chemistry was carried out in various contexts, such as curriculum development, laboratory activities, learning projects, teacher training, media development, and learning assessments.

The classification results also indicated that the implementation of green chemistry principles in chemistry education was not always comprehensive. Some articles explicitly applied all principles, while most others emphasized only one or a few specific principles deemed most appropriate for the learning context, particularly in laboratory activities and context-based learning. These findings demonstrate that the integration of green chemistry in chemistry education is flexible and contextual, depending on the learning objectives, educational level, and type of activity implemented.

Study Quality Assessment

The methodological rigor of the 57 selected articles was evaluated using the structured six-indicator quality assessment rubric tables 4 and 5. The distribution of the quality scores indicates a highly robust evidence base: 53 articles (92.98%) were classified as high quality, while the remaining 4 articles (7.02%) were graded as moderate quality. No articles fell into the low or very low-quality tiers.

The high-scoring papers were characterized by pristine transparency in their research objectives, reproducible methodological frameworks, well-defined educational cohorts, and direct alignment with the core tenants of green chemistry pedagogy. Conversely, the minor score deductions in the moderate-quality papers stemmed from less detailed descriptions of the student demographics a lack of explicit replication protocols for the modified laboratory procedures. Overall, this quality distribution confirms that the empirical baseline of this review is sufficiently sound to generate valid, generalizable thematic conclusions.

Table 4. Study Quality Assessment Rubric

Indicator	Score 2	Score 1	Score 0
Clarity of research objectives	Objectives are clearly stated, specific, and operational	Objectives are present but still general	Objectives are unclear or not stated
Clarity of research method/design	Method/design is described in sufficient detail and is understandable	Method is mentioned but lacks detail	Method is unclear
Clarity of study context/subjects	Context, level, or subjects are clearly described	Context/subjects are only briefly mentioned	Context/subjects are unclear
Clarity of green chemistry implementation	Form of implementation, GC principles, or interventions are clearly described	GC implementation is present but not detailed or still implicit	GC implementation is unclear
Clarity of main results/findings	Findings or outcomes are clearly reported and relevant	Findings are reported but still general	Findings are unclear
Relevance to the research question in the review	Highly relevant to one or more research questions (RQ)	Partially/marginally relevant	Not directly relevant

Table 5. Study Quality Assessment Results

Code	No. Indicator						Total Score	Category
	1	2	3	4	5	6		
A1	2	2	2	2	2	2	12	High
A2	2	2	2	2	2	2	12	High
A3	2	2	2	1	2	1	10	High
A4	2	2	2	2	2	2	12	High
A5	2	2	2	2	2	2	12	High
A6	2	2	2	2	2	2	12	High
A7	2	2	2	2	2	2	12	High
A8	2	2	2	2	2	2	12	High
A9	2	2	2	2	2	2	12	High
A10	2	2	2	2	2	2	12	High
A11	2	2	2	2	2	2	12	High
A12	2	2	2	2	2	2	12	High
A13	2	2	2	2	2	2	12	High
A14	2	2	2	2	2	2	12	High
A15	2	1	1	1	1	1	7	Moderate
A16	2	1	1	1	1	1	7	Moderate
A17	2	2	2	2	2	2	12	High
A18	2	2	2	2	2	2	12	High
A19	2	2	2	2	2	2	12	High
A20	2	2	2	2	2	2	12	High
A21	2	2	2	2	2	2	12	High
A22	2	2	2	2	2	2	12	High
A23	2	2	2	2	2	2	12	High
A24	2	2	2	2	2	2	12	High
A25	2	2	2	2	2	2	12	High
A26	2	2	2	2	2	2	12	High
A27	2	2	2	2	2	2	12	High

Code	No. Indicator						Total Score	Category
	1	2	3	4	5	6		
A28	2	2	2	2	2	2	12	High
A29	2	2	1	1	2	1	9	Moderate
A30	2	2	2	2	2	2	12	High
A31	2	2	2	2	2	2	12	High
A32	2	2	2	2	2	2	12	High
A33	2	2	2	2	2	2	12	High
A34	2	2	2	2	2	2	12	High
A35	2	2	1	1	1	2	9	Moderate
A36	2	2	2	1	2	2	11	High
A37	2	2	2	2	2	2	12	High
A38	2	2	2	2	2	2	12	High
A39	2	2	2	2	2	2	12	High
A40	2	2	2	2	2	2	12	High
A41	2	2	2	2	2	2	12	High
A42	2	2	2	2	2	2	12	High
A43	2	2	2	2	2	2	12	High
A44	2	2	2	2	2	2	12	High
A45	2	2	2	2	2	2	12	High
A46	2	2	2	2	2	2	12	High
A47	2	2	2	2	2	2	12	High
A48	2	2	2	2	2	2	12	High
A49	2	2	2	2	2	2	12	High
A50	2	2	2	2	2	2	12	High
A51	2	2	2	2	2	2	12	High
A52	2	2	2	2	2	2	12	High
A53	2	2	2	1	2	1	10	High
A54	2	2	2	2	2	2	12	High
A55	2	2	2	2	2	2	12	High
A56	2	2	2	2	2	2	12	High
A57	2	2	2	2	2	2	12	High

Distribution of the Application of the 12 Principles of Green Chemistry

An analysis of 57 articles showed that the application of the 12 principles of green chemistry in chemistry education was not evenly distributed (Table 6 and Table 7). The most dominant principle was waste prevention, which appears in 43 articles, (proximately 75.44% of all articles analyzed). This is closely followed by Principle 5 (Safer Solvents and Auxiliaries) at 57.89%, and Principle 7 (Use of Renewable Feedstocks) at 54.39%. Meanwhile, less frequently applied principles include reducing derivatives, designing for degradation, and real-time analysis for pollution prevention.

The dominance of the waste prevention principle is understandable, as it is the easiest to operationalize in the context of chemistry education, particularly through small-scale laboratory activities, reduced reagent use, more efficient procedures, and the use of safer materials. In laboratory learning, waste prevention is the most concrete and easily observable principle by students, making it a primary entry point for green chemistry integration. In contrast, principles such as design for degradation and real-time analysis for pollution prevention require a higher level of complexity, both conceptually and in terms of facilities, which limits their implementation in educational settings.

These findings indicate that the implementation of green chemistry in chemistry education remains largely oriented toward principles that are practical, direct, and easily applied in laboratory or classroom settings. This also highlights an opportunity to expand the integration of less frequently applied principles, particularly those related to process design, real-time monitoring of pollution, and chemical life-cycle thinking. Given that the majority of the analyzed articles were of high quality, this distribution pattern can be considered sufficiently representative of trends in the implementation of green chemistry in chemistry education within the reviewed literature.

Table 6. Data Extraction Matrix from 57 Included Articles

Code	Learning Activity	Approach/Model/Media	GC Principles	Main Findings
A1	Project-based classroom Learning	LUNTIAN Project	All	Enhancing Students' sustainability understanding and practice

Code	Learning Activity	Approach/Model/Media	GC Principles	Main Findings
A2	Questionnaire/needs assessment	Curriculum integration	All	Enhancing teacher awareness and informing curriculum development
A3	Learning Modules	Scrum, context-based approach	All	Supports learning outcomes achievement and the development of metacognitive dimensions.
A4	Assesment	GC² Prompt	All	Evaluates the level of understanding of the "greenness" of chemical reactions.
A5	Practicum	Hands-on learning	All	Connects learning with the SDGs and sustainability principles.
A6	Laboratory curriculum	GC2 curriculum	All	Enhances students' understanding and perceptions.
A7	Digital game	Educational escape room	All	Increases motivation,collaboration, and understanding of GC
A8	Proposal Assigment	Critical use of AI	All	Develops critical thinking and methodological evaluation skills.
A9	Laboratory culture	Systems thinking, safety integration	All	Strengthens safety culture and experimental evaluation practices.
A10	Teacher workshop	Hands-on professional development	All	Builds teachers' capacity for implementing GC
A11	Teacher workshop	Case-based learning	All	Reinforces critical thinking and pedagogical competence.
A12	ELN-based practicum	AI4Green digital ELN	All	Enhances student engagement and the application of green metrics.
A13	Green chemistry materials	Scrum, ethnochemistry	All	Promotes creative thinking and entrepreneurial attitudes.
A14	Assessment	ASK-GCP	All	Measures knowledge of GC Principles
A15	Interdisciplinary teaching	MITT	All	Link chemistry to sustainable issues.
A16	Laboratory safety	RAMP Program	All	Integrates safety practices with GC Principles
A17	Authentic module	Authentic learning	All	Fosters systems thinking
A18	Seminar and laboratory	Safety and green chemistry integration	2, 5, 6	Improves understanding of risk, waste management, and environmental impacts.
A19	Electrolysis learning media	Microscale kit, STEM	1	Develops HOTS while reducing waste
A20	Practicum module	Hands-on learning	1	Cultivates awareness of recycling and the circular economy
A21	Analytical practicum	Hands-on learning	1	Teaches quantitative analysis with minimal waste generation
A22	Research based practicum	CURE, IBL	1	Develops critical thinking and research readiness.
A23	Card game	Systems thinking game	1	Promotes systems thinking skills
A24	Miniaturized practicum	3R program	1	Enhances critical thinking skills
A25	Computational media	rxnSMILES4AtomEco	2	Strengthens understanding of atom economy
A26	Organic practicum	Hands-on learning	4	Improves understanding of reaction concepts and laboratory skills
A27	Synthesis practicum	Water-based experiment	5	Fosters sustainability awareness
A28	Project	Project-based learning	5	Enhances problem-solving skills
A29	Course module	Integrated Course Design	11	Develops reflective and critical thinking
A30	Assessment/LCA	Impact-based metrics, problem-based learning	1, 12	Reinforces system thinking and sustainability evaluation
A31	Learning module	POGIL	1, 2	Enhances communication skills and awareness of environmental issues.
A32	Organic practicum	Laboratory experiment	1, 2, 3, 4, 5, 6, 11, 12	Strengthens understanding of GC Principles and spectroscopy interpretation
A33	Practicum	Laboratory experiment	1, 2, 3, 5, 7, 9	Enhances the evaluation of reaction sustainability
A34	Practicum	Systems thinking	1, 2, 3, 5, 7, 9, 12	Introduces green metrics and systemic evaluation
A35	Resource/web learning	Temporal systems thinking	1, 2, 3, 6, 7, 12	Improves understanding of biorefineries as integrated systems

Code	Learning Activity	Approach/Model/Media	GC Principles	Main Findings
A36	Instructional techniques	SSC, IBL, STEM	1, 2, 4	Promotes critical awareness of sustainability
A37	Practicum	Hands-on learning	1, 2, 5, 6, 8	Introduces solvent-free mechanochemistry
A38	Practicum module	IBL, continuous flow	1, 2, 6, 11	Strengthens understanding of GC and chemical engineering principles.
A39	Practicum	Hands-on learning	1, 3	Reduces the use of hazardous materials and waste generation
A40	Practicum	IBL	1, 3, 7, 10, 11	Integrates sustainability concepts and material degradation processes
A41	Laboratory	Experimental learning	1, 4, 7, 10	Enhances critical thinking and understanding of natural surfactants
A42	Mini-project	IBL, student-led inquiry	1, 5	Develops HOTS and sustainability evaluation
A43	Practicum	Demonstration/lab activity	1, 5	Integrates colligative property concepts using safer materials
A44	Green analytical chemistry lab	GAC	1, 5	Improves understanding of sustainability and student learning interest
A45	Practicum	ESD	1, 5, 7	Utilizes safer and renewable natural indicators
A46	Practicum /LCA	Hands-on learning	1, 7, 10	Enhances critical perspective on the plastic life cycle
A47	Practicum	Hands-on learning	1, 9, 12	Develops problem-solving skills and awareness of environmental remediation
A48	Practicum	Laboratory experiment	4, 5, 12	Strengthens safer synthesis practices in the laboratory
A49	Practicum/comparative synthesis routes	Comparative route analysis	1–3, 5–10, 12	Expands understanding of GC principles through route comparison
A50	Practicum	Guided inquiry	2, 6, 12	Develops critical thinking and problem-solving skills
A51	Undergraduate teaching	Project-based learning	2, 6, 7, 9	Promotes the development of greener chemistry through student-driven approaches
A52	Hybrid/remote Synthesis	Hands-on learning	3, 4, 5, 6, 7, 10, 11, 12	Strengthens laboratory skills and sustainability competencies
A53	Group project	Project/group role-play	4, 10	Develops decision-making skills in the context of climate-related issues
A54	Practicum	Laboratory improvement	4, 5, 6, 7	Enhances the use of safer solvents and process efficiency
A55	Experimental module	Enquiry-based experimental	5, 9	Develops laboratory skills grounded in green nanochemistry
A56	Practicum	Inquiry-based learning	7, 10	Links polymer science with green chemistry principles
A57	Practicum	Continuous flow	7, 9	Strengthens understanding of flow chemistry and sustainability

Table 7. Frequency of Application of the 12 Principles of Green Chemistry in 57 Articles

GC Principles	Frequency
P1. Prevention	43
P2. Atom Economy	30
P3. Less Hazardous Chemical Syntheses	26
P4. Designing Safer Chemicals	26
P5. Safer Solvents and Auxiliaries	33
P6. Design for Energy Efficiency	27
P7. Use of Renewable Feedstocks	31
P8. Reduce Derivatives	20
P9. Catalysis	25
P10. Design for Degradation	25
P11. Real-time Analysis for Pollution Prevention	23
P12. Inherently Safer Chemistry for Accident Prevention	27

Learning Activities to Integrate Green Chemistry Principles

The analysis showed that green chemistry was implemented through various learning activities, with laboratory activities (80.70%) being the most dominant. Laboratory experiment served as the primary means of implementation, as they allowed students to directly engage with safer materials, waste reduction, material efficiency, and the modification of experimental procedures to be more environmentally friendly. In addition to laboratory activities, implementation also occurred through workshops, seminars, group projects, classroom teaching and learning (classroom interaction), and assessment activities.

The dominance of laboratory activities indicates that the integration of green chemistry in chemistry education remains closely aligned with the experimental nature of the discipline. Through lab work, students not only learn chemical concepts but are also trained to consider safety, efficiency, and environmental impacts in every procedure they perform (Lee et al., 2024; Sheppard, 2021). In this context, green chemistry functions not merely as supplementary content but as a foundational framework for designing and evaluating laboratory activities. Beyond the bench, collaborative group projects and problem-based learning play a crucial role in connecting green chemistry to socio-environmental crises, such as waste management, global pollution, resource depletion, and industrial sustainability. These activities effectively broaden the scope of green chemistry from simple "greener labs" into a holistic pedagogical approach that encourages critical thinking and sustainability-oriented decision-making. Concurrently, tracking current testing and assessment activities indicates that integration is increasingly focused on evaluating both students' deep conceptual understanding and their practical ability to systematically assess the "greenness" of chemical reactions or procedures.

These results should also be interpreted in light of the generally high quality of the studies. This suggests that the dominance of laboratory activities is not merely a result of reporting bias but reflects a consistent implementation trend across the analyzed articles.

Pedagogical Approaches, Models, Curricula, and Learning Media

The implementation of green chemistry in chemistry education was carried out through various approaches, models, curricula, and learning media. In terms of approaches, prominent strategies include small-scale chemistry, hands-on learning, student-centered learning, context-based approaches, and approaches oriented toward Education for Sustainable Development (ESD). Regarding learning models, the application of green chemistry was commonly associated with inquiry-based learning, guided inquiry, project-based learning, problem-based learning, and Process-Oriented Guided Inquiry Learning (POGIL). Several studies also demonstrated the integration of green chemistry into curriculum development, such as the General Chemistry Green Curriculum (GC^2).

Table 8. Curriculum

Type	Article Codes
General Chemistry Green Curriculum (GC^2)	A6

The trend toward using mall-scale chemistry is closely related to the dominance of the waste prevention principle. Small-scale laboratory activities enable reductions in reagent use, waste generation, and exposure to hazardous materials, without compromising the core objectives of experimental learning (Tantayanon et al., 2025). Meanwhile, inquiry-based and project-based learning approaches provide opportunities for students to explore safer and more sustainable alternative procedures, positioning green chemistry not only as a set of principles but also as a basis for scientific decision-making.

Table 9. Learning Media

Type	Article Codes
Laboratory Manual or practicum module	A9, A20, A38
Learning module	A3, A17, A25, A31, A55
Game	A7, A23
Website	A8, A12, A35
Laboratory Equipment	A9, A19

In terms of media, the implementation of green chemistry was supported by the use of learning modules, laboratory manuals, educational games, websites, and laboratory equipment. The use of modules reflects efforts to systematically integrate green chemistry principles into learning materials, while games and websites offer more interactive and contextual learning experience. Digital media, including AI-based technologies and electronic laboratory notebooks, further indicate that green chemistry education is beginning to adapt to advancements in modern educational technology.

Overall, the diversity of approaches, models, curricula, and media suggests that green chemistry can be integrated through a wide range of pedagogical strategies. However, emerging patterns indicate that the most effective strategies tend to be contextual, participatory, and provide opportunities for students to directly experience, evaluate, and reflect on the environmental impacts of chemistry. Given that most studies were high-quality, this diversity can be considered representative of well-established practices in the literature.

Table 10. Learning Activities

Type	Article Codes
Workshop	A10, A11
Laboratory	A5, A9, A20–A24, A26–A28, A32–A34, A37–A43, A45–A52, A54–A57
Group Project	A1, A13, A19, A53
RAMP Program	A16
Biorefinery Experience	A35
Seminar	A18
Teaching and Learning	A1, A2, A7, A10, A12, A15, A25, A29–A31, A36, A44
Testing and assessment	A4, A14, A18, A29

Table 11. Approach

Type	Article Codes
Small Scale Chemistry (SSC)	A36
Real-World Context Approach	A44
Enquiry-Based Experimental	A55
Authentic Learning	A17
Hands-on Learning	A1, A2, A5, A6, A10, A20, A21, A24, A26, A34, A37, A39, A41, A43, A47–A49, A52, A57
Student-Centered Learning	A8
Context-Based Approach	A3
STEM	A19, A36
Education for Sustainable Development (ESD)	A45
MITT	A15
Guided Inquiry	A50

Table 12. Model

Type	Article Codes
Case-Based Learning	A11
Inquiry Based Learning	A36, A38, A40, A42, A56
Project Based Learning	A28, A51
Problem Based Learning	A30
Process-Oriented Guided Inquiry Learning (POGIL)	A31

Reported Learning Outcomes

Analysis of the reviewed articles indicates that the implementation of green chemistry had a positive impact on range of learning outcomes. These included improvements in critical thinking, higher-order thinking skills (HOTS), systems thinking, creative thinking, problem-solving, laboratory skills, computational analysis skills, as well as enhanced understanding of green chemistry principles and increased awareness of sustainability issues.

Improvements in critical thinking and problem-solving were particularly evident in learning activities involving lab work, inquiry-based approaches, and project-based tasks, where students were required to evaluate procedural choices, compare the "greenness" of processes, and consider the efficiency and safety of experiments. These findings suggest that green chemistry can serve as an authentic context for developing higher-order thinking skills, rather than functioning merely as supplementary content in chemistry education.

Furthermore, the integration of green chemistry was closely associated with the development of systems thinking. This was reflected in studies that linked chemical processes to broader issues such as waste, energy use, raw materials, safety, and environmental impacts. As a result, students were not only able to understand reactions or procedures in isolation but also recognize the interconnections between chemical practices, production systems, and sustainability. At the same time, context-based and project-based learning contributed to the development of creative thinking, as students were more environmentally friendly and relevant to real-world problems.

In addition to cognitive outcomes, the analyzed articles consistently reported increased awareness of sustainability issues and a deeper understanding of green chemistry principles. These finding are significant, as they indicate that the integrating green chemistry into chemistry education not only supports conceptual mastery but also shapes students' values, attitudes, and environmental responsibility. In the context of 21st-century chemistry education, such outcomes represent an important contribution, as the focus extends beyond conceptual knowledge and laboratory skills to include sustainability-oriented ways of thinking and acting.

Although the majority of included studies were of high quality, the reported learning outcomes should be interpreted with caution. Some studies presented outcomes in general descriptive terms, and thus the strength of evidence regarding the effectiveness of green chemistry on specific learning outcomes was not fully consistent across studies. Nevertheless, the overall quality of reporting provides a sufficiently foundation for the thematic synthesis presented in this review.

Table 13. Learning Outcomes

Type	Article Codes
Critical Thinking	A24, A32, A41, A46, A50
HOTS	A19, A42
Systems Thinking	A9, A17, A23, A34, A35
Creative Thinking	A13, A40
Laboratory Skills	A24, A26, A38, A43, A44, A52, A55, A56
Computational Analysis Skills	A25, A39
Problem Solving	A28, A32, A47, A50
Awareness of sustainability issues and understanding of green chemistry principles	A1–A57

Implications and Geographic/Educational Research Gaps

A critical cross-tabulation of the 57 reviewed articles reveals significant, empirical gaps across both geographic distribution and educational cohorts, as structured in Table 14.

The consolidated data uncovers a severe geographical imbalance within the green chemistry education literature. Developed countries in the Global North overwhelmingly dominate the research landscape, accounting for 80.70% (46 articles) of the total publications, with the United States alone contributing nearly half of the entire database. In stark contrast, the Global South where environmental and waste management crises are often more acute remains severely underrepresented with only 19.30% of the literature. Furthermore, a systemic gap is evident across educational levels; 71.93% (41 articles) of the studies are clustered exclusively within higher education, predominantly targeting advanced undergraduate laboratory courses such as organic and analytical chemistry. Meanwhile, foundational high school environments (19.30%) and teacher professional development frameworks (8.77%) receive minimal scholarly attention.

Table 14. Empirical Distribution of Reviewed Literature by Region and Education Level (N=57)

Geographic Region	Secondary/High School	Undergraduate/Graduate	Teacher Training	Total Articles (%)
Global North (e.g., USA, UK, Germany, Canada, Spain)	6	37	3	46 (80.70%)
Global South (e.g., Indonesia, Philippines, Thailand, India, Brazil)	5	4	2	11 (19.30%)
Total (N=57)	11 (19.30%)	41 (71.93%)	5 (8.77%)	57

A deeper contextual divergence emerges when analyzing how green chemistry is operationalized across these borders. In the Global North, higher education studies frequently leverage sophisticated digital technologies, continuous-flow synthesis, mechanochemistry, and Al-driven platforms (e.g., ChatGPT or Electronic Lab Notebooks) to teach advanced metrics. Conversely, in the Global South, research is compelled to focus on high school settings or resource-optimized pedagogical strategies. Due to institutional budgetary constraints, authors in developing nations primarily focus on low-cost, localized green substitutions, such as converting local agricultural waste (e.g., jambolan fruit peels or coconut water) into natural indicator reagents or relying on microscale kits to circumvent underfunded laboratory infrastructure.

Consequently, this mapped fragmentation offers vital directions for future empirical research:

a) There is an urgent need to expand green chemistry education research in the Global South. Future studies must move beyond isolated asset-substitution projects toward building scalable, low-cost green curricula tailored to resource-constrained institutions.
b) Scholars should design structured educational tracks that introduce green chemistry principles early in secondary school (K-12) through inquiry-based modules. This ensures that environmental values and foundational systems thinking are well-established before students enter university-level laboratories.
c) Since teacher training accounts for less than 9% of the literature, more research must focus on longitudinal teacher professional development. Empowering

chemistry teachers is the most strategic lever to ensure sustainable classroom integration.

d) Future research must transition from purely descriptive or self-reported affective evaluations toward rigorous mixed-methods or longitudinal experimental designs. Utilizing validated psychometric. rubrics is necessary to definitively measure the long-term cognitive and behavioral efficacy of green chemistry education.

The results of this review indicate that the integration of green chemistry into chemistry education has progressed in a positive direction, but its implementation still relies heavily on practical and easily applicable principles, particularly waste prevention, the use of safer solvents and auxiliaries, and the utilization of renewable feedstocks. Several other principles remain relatively unexplored. This suggests that future developments in green chemistry education should focus not only on safer and more efficient laboratory practices but also on expanding conceptual dimensions, such as systems thinking, life-cycle assessment, and more comprehensive analyses of the impacts of chemical processes.

Furthermore, the available evidence is still dominated by reports of generally positive outcomes. Therefore, future research should provide stronger empirical evidence on the effectiveness of green chemistry education, for example through more rigorous experimental designs, the use of validated assessment instruments, and clearer reporting of specific outcome. Future studies should not only map implementation approaches but also strengthen the empirical basis for understanding how and to what extent green chemistry enhances the quality of chemistry education.

Although most of the included studies demonstrate high reporting quality, there is still variation in the clarity of study contexts, implementation details, and the robustness of reported results. Therefore, interpretations of the effectiveness of green chemistry implementations should be made with caution. Nevertheless, considering the overall quality of the studies and the emerging patterns of findings, this review provides a sufficiently strong basis to conclude that green chemistry is a promising approach for supporting safer, more contextual, and sustainability-oriented chemistry learning.

Conclusion

Based on this Systematic Literature Review of 57 high-quality articles published from January 2016 up to January 2026, several definitive conclusions can be drawn regarding the integration of green chemistry in chemistry education. First, the mapping of the twelve principles reveals a highly uneven distribution; implementation is heavily dominated by easily operationalized principles specifically waste prevention (75.44%), safer solvents, and renewable feedstocks while advanced lifecycle and process-design principles remain severely underrepresented. Second, this integration is primarily actualized through experiential laboratory experiments, which are increasingly balanced by collaborative group projects, lecture-based theoretical instruction, and specialized assessment practices to bridge the gap between classroom practice and real-world issues. Third, these activities are effectively operationalized through a diverse suite of pedagogical frameworks such as small-scale chemistry, Process-Oriented Guided Inquiry Learning (POGIL), and Project-Based Learning (PjBL) and are increasingly supported by interactive digital media, AI-driven technologies, and sustainability-oriented curricula. Fourth, these comprehensive implementations generate consistently positive multi-dimensional learning outcomes, significantly enhancing students' critical thinking, higher-order thinking skills (HOTS), laboratory precision, sustainability awareness, and transformative systems thinking. Despite database coverage limitations and English-language bias, this robust evidence base underscores an urgent need for practitioners to shift from bench-level "small-scale lab work" toward macro-level chemical lifecycle analysis. Consequently, future research must urgently decentralize toward the resource-constrained contexts of the Global South, utilize rigorous longitudinal experimental designs with validated psychometric instruments, and prioritize underutilized principles alongside systematic teacher professional development to cultivate genuinely environmentally responsible scientific citizens. Overall, this review confirms that integration green chemistry into chemistry education holds substantial potential for supporting safer, more contextual, and sustainability-oriented learning. Given the generally adequate quality of the included studies, these findings provide a strong foundation for advancing chemistry education that emphasizes not only conceptual understanding but also the development of environmentally responsible thinking and behavior

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