

Teaching Approaches and Scientific and Environmental Literacy Outcomes in Green Chemistry Education: A Systematic Review

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Abstract

This systematic review synthesized the teaching approaches and scientific and environmental literacy outcomes reported in Green Chemistry Education (GCE) at the high school level. Guided by four research questions, the review examined (1) the teaching approaches employed and their implementation in chemistry learning contexts, (2) reported scientific literacy outcomes, (3) reported environmental literacy outcomes, and (4) patterns, consistencies, contradictions, methodical limitations, and research gaps. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 framework was used to identify, screen, assess, and synthesize relevant literature according to predefined eligibility criteria. Nineteen studies were included in the final synthesis. The findings showed that GCE was predominantly characterized by experiential, hands-on, laboratory-based, and inquiry-oriented instruction. Hands-on or experimental learning was the most frequently reported approach, followed by inquiry-based learning, while collaborative, problem-based, context-based, and project-based approaches were commonly integrated as complementary strategies. Scientific literacy outcomes were generally reported in terms of conceptual understanding, inquiry reasoning, critical thinking, data interpretation, and application of scientific knowledge. Environmental literacy outcomes were commonly associated with environmental awareness, sustainability-oriented thinking, responsible decision-making, and environmentally responsible practices. However, scientific literacy was more frequently assessed through quantitative measures, whereas environmental literacy was often assessed through qualitative, attitudinal, or self-reported measures. The synthesis further indicated that positive outcomes were mostly consistently associated with integrated instructional designs that connected authentic sustainability problems, inquiry, hands-on experimentation, collaboration, and reflection rather than with a single teaching approach. Important gaps included methodical heterogeneity, limited comparative and longitudinal evidence, inconsistent measurement of literacy outcomes, and limited studies simultaneously examining scientific and environmental literacy.

Keywords: Green Chemistry Education; Teaching Approaches; Scientific Literacy; Environmental Literacy; High School Chemistry; Sustainability Education; Inquiry-Based Learning

1. Introduction

The movement toward “greening” chemistry education has increasingly emphasized laboratory-based and hands-on instruction as core approaches in Green Chemistry Education (Dicks et al., 2019); Karpudewan et al., 2015; Taha et al., 2019). Curriculum integration effort in high school chemistry have also emerged, alongside the development of teaching materials such as modules, experiments, and digital resources (Imai et al., 2022); Santos & Guidote Jr, 2015; Wissinger et al., 2020). Despite these developments, research shows that curriculum revision aligned with green chemistry principles remains limited and unevenly implemented (Barra & Gonzales, 2017; Li & Eilks, 2021), particularly in developing contexts such as the Philippines where empirical evidence on integration is still scarce (Carangue et al., 2021).

Globally, Green Chemistry Education is supported by active learning approaches such as inquiry-based, problem-based, and context-based learning. However, these are often implemented in isolation, resulting in fragmented instructional practices and limited development of higher-order competencies (Koulougliotis et al., 2024). While these approaches improve conceptual understanding and environmental awareness, their impact is constrained by challenges such as lack of teacher training, inadequate laboratory resources, and weak curriculum alignment (Agustian, 2024). In many cases, Green Chemistry is still treated as an “add on” rather than a transformative framework, leading to weak integration between content, pedagogy, and assessment (Marques et al., 2020).

At the pedagogical level, research highlights the promise of inquiry-, problem-, and systems-based learning for developing scientific and environmental literacy. However, implementation lacks structured progressions and coherence across instructional design (Vaz et al., 2025); Sunday et al., 2026). At the curriculum level, insufficient scaffolding and limited alignment between learning objectives, laboratory practice, and assessment further hinder meaningful integration (Agustian, 2024). Additionally, sustainability is often narrowly interpreted as environmental awareness, with limited attention to its social and ethical dimensions (Quiroz-Martinez, 2024).

Assessment practices also remain a key gap. Most studies focus on cognitive achievement and environmental attitudes, while fewer examine real-world application, sustainability competencies, or systems thinking development (Ramirez & Paderna, 2024; Koulougliotis et al., 2024). Although systems thinking has been proposed as a unifying framework for sustainability education, its classroom application remains underdeveloped and weakly supported by empirical evidence (Shidiq et al., 2020; Marques et al., 2020).

Although previous studies have examined various approaches to integrating Green Chemistry into secondary chemistry education, the evidence remains dispersed across different instructional approaches and literacy outcomes. In particular, there is a need to synthesize how teaching approaches are implemented and how they relate to the development of scientific and environmental literacy among high school learners. Accordingly, this systematic review was guided by four research questions: (RD1) What teaching approaches have been employed in Green Chemistry education at the high school level, and how have these approaches been implemented in chemistry learning contexts? (RQ2) What scientific literacy outcomes are reported in high school Green Chemistry education, particularly in relation to conceptual understanding, scientific reasoning, inquiry skills, critical thinking, data interpretation, and application of scientific knowledge? (RQ3) What environmental literacy outcomes are reported in high school Green Chemistry education, particularly in relation to environmental awareness, sustainability-oriented thinking, responsible decision-making, and environmentally responsible practices? (RQ4) What patterns, consistencies, contradictions, methodical limitations, and research gaps emerge regarding the relationship between teaching approaches and scientific and environmental literacy outcomes in high school Green Chemistry education?

2. Theoretical Framework

This study is grounded in three complementary learning theories that explain how students develop understanding and literacy through Green Chemistry Education.

Experiential Learning Theory (ELT) (Kolb, 1984) explains learning as a cycle of experience and reflection – though concrete experience, reflection, conceptualization, and experimentation. In this study, ELT supports the use of laboratory-based and hands-on Green Chemistry activities, where students actively engage in experiments and reflect on environmental and chemical processes to build understanding. Research shows that experiential laboratory learning improves conceptual understanding, motivation, and achievement in chemistry education (Su & Cheng, 2019; Yao, 2023).

Active Learning Theory emphasizes student-centered engagement through inquiry, collaboration, problem-solving, and hands-on tasks (Dogani, 2023). In the context of this study, it explains how instructional approaches such as inquiry-based and problem-based learning enhance student participation and deepen understanding of green chemistry concepts (Bogart, 2009).

Transformative Learning Theory (TLT) focuses on how learners critically reflect on experiences to reshape their beliefs, values, and behaviors (Wink, 2001). In chemistry education, TLT is particularly relevant because it supports learning that extends beyond conceptual understanding toward personal and social transformation by encouraging students to critically reflect on scientific knowledge in relation to environmental and societal issues, thereby promoting action-oriented learning that responds to real-world problems (Carter et al., 2014; Maneelam et.al., 2022). Furthermore, as a theoretical basis, TLT requires a fundamental shift from traditional content-centered instruction toward reflective, learner-centered, and socially responsive learning environments via pedagogical approaches such as Social Emotional Learning, Dilemmas Stories, Life Cycle Analysis, Socio-Critical Problem-Oriented, Culturally Responsive Teaching, and Science Technology Education Art and Mathematics (STEAM), which help develop students' character, identity, and 21st century competencies (Rahmawati, 2018; Suttiwan et.al., 2026).

3. Methodology

3.1. Research Questions

The systematic review was guided by four research questions that determined the scope of data extraction, categorization, and thematic synthesis. RQ1 examined that teaching approaches employed in high school Green Chemistry education and how these approaches were implemented. RQ2 focused on the scientific literacy outcomes reported across the reviewed studies, including conceptual understanding, scientific reasoning, inquiry skills, critical thinking, data interpretation, and application of scientific knowledge. RQ3 examined reported environmental literacy outcomes, including environmentally awareness, sustainability-oriented thinking, responsible decision-making, and environmentally responsible practices. RQ4 synthesized the patterns, consistencies, contradictions, methodical limitations, and the research gaps concerning the relationship between teaching approaches and scientific and environmental literacy outcomes.

3.2 Selection of Study Sample

Inclusion criteria were scholarly work published within the last decade (2015-2025) in Scopus-indexed journals, Web of Science, ERIC, Google Scholar, or proceedings journal, using keywords related to “Green Chemistry Education”, “12 principles of Green Chemistry”, “teaching approaches to Green Chemistry Education in high school”, and those that directly or indirectly enhance “scientific literacy and environmental literacy.”

Studies that did not meet these criteria were excluded. Data extraction focused on green chemistry integration in high school chemistry, teaching approaches, and learner outcomes in terms of scientific and environmental literacy. Thematic synthesis was used to identify pedagogical patterns and gaps in current Green & Sustainable Chemistry education. Table 1 shows the inclusion criteria used in this paper.

Table 1 Inclusion criteria

Criteria Description
Scopus, Web of Science, ERIC, Google Scholar
Published in ten recent years (2015-2025)
The research is related to GC Education in high school
The research integrates any of the 12 principles of Green Chemistry
The research includes teaching approaches to GC instruction in high school
Directly or indirectly enhance or improve scientific literacy and environmental literacy

3.2. Systematic Review of Literature.

This systematic review employed systematic literature review guided by Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines (Page et al., 2021) to select and organize selected studies from scholarly electronic databases. Figure 1 presents the PRIMSA flow diagram for this paper.

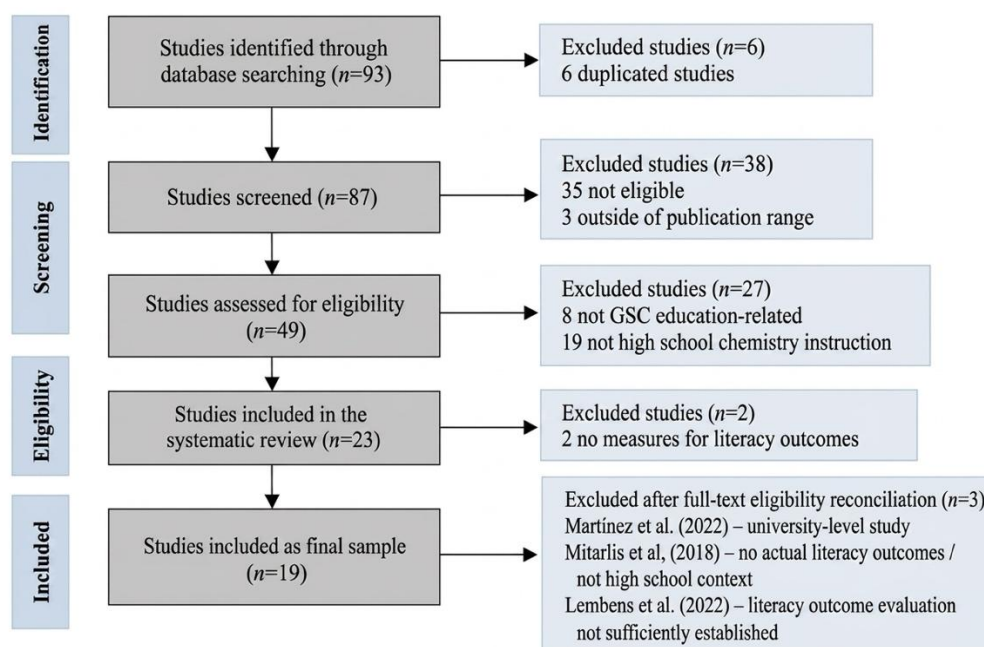


Figure 1. PRISMA flow diagram for the study selection process

Identification. The process began with 93 studies identified through database searching. This number was immediately reduced to 87 after the exclusion of 6 duplicate studies.

Screening. The screening phase involved two distinct layers of evaluation: *Initial Screening*, where out of 87 remaining studies, 38 were excluded. Reasons included 35 studies having been deemed not eligible and 3 studies falling outside the required

publication range. *Eligibility Assessment*, where the remaining 49 studies were assessed for specific fit, leading to 26 more exclusions. These were rejected because 8 were not related to green chemistry education and 18 did not focus on high school chemistry instruction.

Inclusion. In the final stage, 23 studies were initially included in the systematic review. Exclusion of 2 studies was made because they lacked measures for literacy outcomes. This resulted in a sample of 21 studies used for the research. However, after a full-text eligibility reconciliation, another 3 studies were excluded due to several eligibility issues such as: university-level study, absence of actual literacy outcomes, or that no sufficient measures for literacy was found, resulting to 19 final sample studies.

4. Results

4.1. Overview of the Reviewed Studies

Following the systematic screening and subsequent eligibility reconciliation, 19 studies were retained for the final thematic synthesis. The reviewed literature was published within the 2015-2025 period and represented diverse educational contexts in which Green Chemistry concepts related to scientific learning and environmental sustainability. The studies varied considerably in their research designs, instructional contexts, and methods of assessing learning outcomes.

The evidence based included curriculum and instructional-material development studies, classroom-based investigations, qualitative and mixed-methods studies, and quasi-experimental investigations. This methodological diversity is important in interpreting the findings because the studies did not provide equivalent forms of evidence. Some investigations directly measured changes in students' conceptual understanding, scientific reasoning, or environmental awareness, whereas others relied on qualitative observations, student reflections, questionnaires, or evaluations of instructional materials.

The educational contexts were predominantly secondary or high-school settings, although some studies initially considered during screening were excluded during eligibility reconciliation because their participants or evidence based did not satisfy the operational criteria of the present review. Corcoran et al. (2022) was retained because its instructional materials and activities explicitly included middle- and high-school learners and addressed Green Chemistry through biodegradable polymer experiments and the environmental problem of plastic pollution.

The reviewed studies also differed in the extent to which they explicitly identified Green Chemistry principles. Some interventions directly addressed principles such as prevention of waste, safer synthesis, renewable feedstocks, energy efficiency, and design for degradation, whereas others incorporated Green Chemistry more contextually through sustainable materials, resource conservation, waste reduction, or environmentally preferable chemical practices.

Taken as a whole, the literature demonstrates a predominantly experiential orientation. Hands-on or laboratory-based learning was identified in 18 of the 19 studies (94.7%), while inquiry-based learning appeared in 12 studies (63.2%). Other approaches were commonly embedded within these experiential and inquiry-oriented activities rather than implemented as isolated instructional models. This pattern suggests that Green Chemistry education in the reviewed literature is generally characterized by the active engagement with authentic chemical materials, processes, and sustainability problems.

4.2. Teaching Approaches in Green Chemistry

The reviewed literature revealed that Green Chemistry education was most frequently implemented through hands-on experiential learning, often combined with inquiry, contextualization, collaboration, or problem-based learning. Rather than appearing as

discrete and mutually exclusive instructional models, these approaches frequently functioned in combination.

4.2.1 Hands-on and Experimental Learning

Hands-on experimentation was the dominant instructional modality, occurring in 18 of the 19 included studies (94.7%). Laboratory activities enabled learners to directly observe chemical processes, manipulate materials, collect evidence, compare properties, and evaluate the environmental implications of chemical practices.

The experimental activities varied considerably. They included microscale chemistry, synthesis of alternative materials, chemical reaction investigations, waste-derived materials, energy-related investigations, and other Green Chemistry applications. Corcoran et al. (2022), for example, used alginate biopolymer experiments to allow students to investigate polymer formation, cross-linking, and material properties while considering biodegradable alternatives to conventional plastics. Similarly, other studies used hands-on investigations to connect chemical concepts with waste reduction, safer chemical practices, renewable materials, and environmental sustainability.

The predominance of hands-on learning suggests that Green Chemistry education is strongly associated with experiential engagement. Laboratory work provides an opportunity for students to encounter sustainability not merely as an abstract concept but as a characteristic that can be examined through chemical materials, procedures, products, and processes.

4.2.2 Inquiry-Based Learning

Inquiry-based learning was the second most frequently identified pedagogical approach, appearing in 12 of the 19 studies (63.2%). Inquiry activities generally required students to formulate questions, investigate chemical phenomena, collect and interpret evidence, compare alternatives, and develop explanations based on observations.

The approach was particularly evident in studies in which students were given authentic Green Chemistry problems and encouraged to investigate possible solutions. In several studies, inquiry was integrated with laboratory experimentation, allowing students to move from sustainability-related question to experimental investigation and interpretation.

The evidence indicates that inquiry served as an important mechanism for connecting Green Chemistry content with scientific reasoning. Rather than simply receiving information about sustainability, students were often required to generate or interpret evidence to explain chemical phenomena or evaluate environmentally preferable alternatives.

4.2.3 Collaborative Learning

Collaborative learning was reported in several studies, particularly those involving group investigations, student-designed experiments, or sustainability-oriented problem solving. Collaborative structures enabled students to discuss observations, divide investigative tasks, interpret evidence, and communicate conclusions.

Cocoran et al. (2022), for example, incorporated collaborative inquiry in which students designed and investigated experiments involving alginate materials. López-Fernández and Franco-Mariscal (2025) likewise used collaborative inquiry and extended investigation to support students' development of explanatory models related to sustainability.

Collaborative learning therefore appeared less often as an independent pedagogical model and more frequently as a complementary structure supporting inquiry and hands-on investigation.

4.2.4 Problem-Based and Project-Oriented Learning

Problem-based learning was identified in four studies (21.1%). These approaches generally situated chemistry learning within an authentic environmental or sustainability problem and required students to investigate or propose solutions.

The problem contexts included environmental pollution, sustainable materials, resource use, and other real-world chemical problems. STEM-integrated problem-based learning also appeared in the reviewed literature, demonstrating how Green Chemistry can be integrated with engineering and design-oriented learning.

Project-based learning was less frequently represented than inquiry, hands-on, or problem-based approaches. This suggests that although extended project work is potentially well suited to Green Chemistry, the available literature has more frequently emphasized shorter inquiry and laboratory experiences.

4.2.5 Contextual, Systems-Oriented, and Other Approaches

Contextual learning connected chemical concepts to familiar environmental and societal issues and were found in studies involving sustainable materials, energy, waste, consumer practices and environmental problems. Systems thinking appeared less frequently but provided important conceptual orientation by linking chemical processes, resources, products, environmental impacts, and human decisions. Microscale chemistry identified in at least two samples provided laboratory strategy rather than a standalone pedagogical framework.

4.3. Scientific Literacy Outcomes in Green Chemistry Education

Several dimensions of scientific literacy outcomes in Green Chemistry instruction were reported in the sampled literatures. These included conceptual understanding, scientific reasoning, inquiry skills, critical thinking, interpretation of evidence, problem solving, and application of scientific knowledge to authentic contexts.

4.3.1. Conceptual Understanding

Quantitative evidence was particularly evident in intervention studies supporting the frequently reported outcome. For instance, Jarujamrus et al. (2024) reported substantial improvement in students' conceptual understanding following a 5E inquiry-based Green Chemistry intervention. Karpudewan et al. (2015) likewise reported significant differences in chemistry understanding following implementation of a Green Chemistry curriculum.

4.3.2. Scientific Reasoning and Inquiry Skills

Several studies associated inquiry-oriented Green Chemistry instruction with scientific reasoning and investigative skills. Students were required to formulate questions, design investigations, interpret observations, compare experimental conditions, and develop explanations such as in the work of Corcoran et al. (2022); Kohn (2018); Jarujamrus et al. (2024); Lingkwitz & Eilks (2022) and McCance et al. (2021).

4.3.3 Critical Thinking, Data Interpretation, and Problem Solving

Critical thinking and problem solving were particularly evident in studies involving student-designed experiments and authentic environmental problems. Virginia (2025), for example, reported improvement in critical-thinking performance following a problem-based Green Chemistry intervention.

Similarly, inquiry and collaborative investigations required students to interpret experimental evidence and use scientific knowledge to evaluate possible solutions. These findings indicate that Green Chemistry contexts can support the application of scientific knowledge rather than limiting learning to the recall of Green Chemistry principles.

4.3.4 Application of Scientific Knowledge

A recurring feature across the literature was the use of authentic environmental or sustainability problems as contexts for chemistry learning. Students were expected to apply chemical concepts to issues such as plastic pollution, waste, energy use, sustainable materials, and environmentally preferable chemical practices.

This contextual application is important because it links scientific knowledge to decisions and problems encountered beyond the classroom.

4.4. Environmental Literacy Outcomes in Green Chemistry Education

Environmental literacy outcomes were evident across the reviewed literature, although they were measured less consistently than conventional chemistry learning outcomes. Reported outcomes included environmental awareness, sustainability-oriented thinking, responsible decision-making, and environmentally responsible practices.

4.4.1 Environmental Awareness

Environmental awareness was a recurring outcome, particularly in studies that explicitly connected chemistry instruction with environmental problems. Plastic pollution, chemical waste, resource consumption, energy use, and sustainable materials were used as contexts through which students could examine the environmental consequences of chemical practices.

Corcoran et al. (2022) is particularly illustrative because students investigated biodegradable alginate materials while considering plastic pollution and sustainable materials design. The chemistry activity therefore served simultaneously as a scientific investigation and as an environmental problem-solving context.

4.4.2 Sustainability-Oriented Thinking

Several studies encouraged students to evaluate chemical processes according to their environmental consequences. Rather than considering chemical reactions solely in terms of yield or product formation, students were encouraged to consider waste generation, resource use, safety, renewable materials, energy consumption, and environmental impact.

This represents an important shift from conventional chemistry learning toward sustainability-oriented scientific thinking.

4.4.3 Environmental Responsibility and Decision-Making

Some studies reported outcomes involving responsible chemical practices, sustainable choices, or environmentally responsible decision-making. Taha et al. (2019), for example, provides evidence that student-initiated Green Chemistry activities can improve environmental awareness and sustainable practices even when conventional academic achievement does not necessarily improve to the same extent.

This finding is important because it demonstrates that environmental literacy and academic chemistry achievement should not be treated as interchangeable outcomes.

4.5 Relationship Between Teaching Approaches and Literacy Outcomes

The cross-study synthesis indicates a recurring relationship between integrated active-learning approaches and the development of scientific and environmental literacy. The strongest pattern was not associated with one isolated pedagogical approach but with the combination of authentic sustainability contexts, inquiry, hands-on investigation, and reflection or application.

Across reviewed studies, the following instructional sequence emerged:

Authentic sustainability problem → inquiry/questioning → hands-on investigation → evidence interpretation → reflection/conceptualization → scientific understanding and environmental decision-making.

Hands-on learning provided the experiential foundation for chemical investigation, while inquiry processes encouraged students to formulate questions, gather evidence, and construct explanations. Contextual and problem-based elements connected these investigations to environmental and societal concerns. Collaborative learning further supported discussion and interpretation of evidence.

This integrated structure appears particularly relevant to the simultaneous development of scientific and environmental literacy. Scientific literacy was most visible when students were required to understand chemical concepts, investigate phenomena, interpret evidence, and solve problems. Environmental literacy became more prominent when the same investigations required students to evaluate waste, resource use, pollution, sustainability, or safer alternatives.

However, the evidence does not demonstrate uniformly that every approach produces superior academic outcomes. Some studies reported substantial gains in conceptual understanding or critical thinking, whereas others showed stronger changes in environmental awareness, attitudes, or practices. Taha et al. (2019), for instance, illustrates this distinction: environmental awareness and sustainable practices improved even though academic achievement did not show a comparable significant improvement.

Therefore, the evidence supports the potential of integrated Green Chemistry pedagogy to promote multiple literacy dimensions, but it does not justify ranking a single teaching approach as universally most effective. The outcomes appear to depend partly on the learning objectives, instructional design, duration of the intervention, and type of assessment employed

Table 2 Synthesis of Teaching Approaches and Reported Literacy Outcomes in Green Chemistry Education

Reviewed Study	Teaching approach(es)	Scientific Literacy Outcomes	Environmental Literacy Outcomes	Overall Evidence Pattern
1. Corcoran et al. (2022)	Hands-on laboratory learning; inquiry-based learning; collaborative group work; student-designed experiments	Understanding of polymer formation, cross-linking, material properties; scientific inquiry and critical-thinking skills	Awareness of plastic pollution; sustainability; biodegradable-material alternatives	Particularly strong example of connecting chemistry concepts, inquiry, and environmental problem solving through biodegradable-material experiments.
2. du Toit & du Toit (2024)	Microscale/small scale chemistry; hands-on laboratory learning	Improved conceptual understanding; reduced misconceptions; practical chemistry skills	Awareness of resource efficiency, reduced waste, safer and more sustainable laboratory practice	Microscale experimentation makes practical chemistry more accessible while reducing material use and laboratory constraints.
3. Garner, Siol, & Eilks (2015)	Inquiry-based learning; collaborative/ group laboratory work; non-formal learning	Improved understanding of chemistry concepts; practical scientific investigations; independent experimentation	Sustainability awareness and connection between chemistry and real-world environmental issues	Non-formal laboratory experiences supported engagement, conceptual learning, and sustainability education.
4. Imai et al. (2022)	Contextual learning; teaching-material-based learning; real-life connections	Improved understanding and interest in Green and Sustainable Chemistry	Recognition of links among chemistry, daily life, and environmental sustainability	Contextual instructional materials increased relevance and learner interest, although the evidence

5. Jarujamrus, Chairam, & Supasorn (2024)	5E inquiry-based learning; hands-on experimentation; demonstration	Significant improvement in reaction-rate understanding; pretest 33.94% → posttest 78.03%; normalized gain 0.63-0.71	Indirect environmental awareness through safe, low-waste experimental design	was largely evaluative/perceptual. One of the clearer quantitative examples of inquiry-based laboratory instruction improving conceptual scientific learning.
6. Jusniar, Syamsidah, & Auliah (2023)	Problem-based learning; project-oriented activities; group discussion; hands-on experiments/ modeling	Conceptual understanding and sustainability-oriented scientific understanding	Environmental awareness and responsibility	Green Chemistry can be embedded systematically in secondary chemistry, but teacher/student understanding of individual principles remains uneven.
7. Karpudewan, Roth, & Ismail (2015)	Green Chemistry curriculum; contextualized instruction; inquiry-oriented activities	Strong improvement in chemistry understanding; ANCOVA $F = 1018.26$, $p < .0001$	Increased motivation and environmental awareness	Strong quasi-experimental evidence supporting Green Chemistry curriculum reform for conceptual learning and affective outcomes.
8. Kohn (2018)	Inquiry-based learning; investigation-driven laboratory work; real-world problem solving; collaboration	Scientific inquiry, problem solving, authentic scientific practices	Understanding of sustainable energy systems and sustainability	Authentic bioenergy investigations provide a strong context for linking scientific practices with sustainability.
9. Linkwitz & Eilks (2022)	Hands-on laboratory learning; comparative inquiry	Scientific reasoning, comparison, interpretation of experimental results	Understanding sustainability implications of enzymatic versus conventional synthesis	Comparative laboratory inquiry makes Green Chemistry principles visible through direct comparison of chemical processes.
10. Likwitz et al. (2022) – microwave experiments	Demonstration-based learning; student laboratory work; hands-on learning	Understanding of alternative synthesis methods; conceptual understanding of reaction processes	Awareness of energy efficiency, reduced reaction time, and environmentally preferable synthesis	Everyday technology helped make Green Chemistry principles concrete and relevant to students.
11. Listyarini et al. (2019)	Small-scale chemistry; hands-on practical work; contextual laboratory activities	Improved understanding of chemistry concepts; practical skills	Environmental awareness; waste reduction; safer laboratory practices	Small-scale chemistry provides a feasible route for integrating Green Chemistry into ordinary high-school laboratory topics, although evidence relied substantially on student perceptions.
12. López-Fernández and Franco-Mariscal (2025)	Long-term inquiry; collaborative laboratory activities	Inquiry reasoning; data interpretations; scientific explanation/ modelling	Sustainability thinking; responsible consumption; understanding degradation and	Extended authentic inquiry supported both scientific reasoning and sustainability-oriented thinking.

13. McCance et al. (2021)	Inquiry-based learning; hands-on laboratory activity; collaborative learning; interdisciplinary learning	Data interpretation; experimental reasoning; understanding biorefinery concepts	environmental systems Sustainable resource use; waste valorization; circular bioeconomy thinking	A strong example of combining chemistry, biology, engineering, and sustainability through authentic laboratory problem solving.
14. Murphy et al. (2019)	Systems thinking; laboratory investigation; outreach/ informal learning; real-world contextual learning	Scientific investigation, laboratory skills, data analysis, evidence-based decision making	Understanding environmental impacts of consumer products; sustainable purchasing decisions	Systems thinking extended chemistry learning from laboratory phenomena to whole-product life-cycle and consumer decisions.
15. Santos & Guidote Jr. (2015)	Contextualized hands-on learning; practical laboratory work; culturally responsive/ contextual instruction	Improved conceptual understanding and meaningful application of chemistry	Responsible chemical use and environmental awareness	Combining cultural context, sustainability, and practical chemistry increased relevance and engagement.
16. Taha et al. (2019)	Student-initiated hands-on experiments; inquiry through experimental design	Application of chemistry concepts; academic achievement showed no significant improvement	Significant increase in environmental awareness and sustainable practices	Important contrasting evidence: environmental outcomes improved despite no corresponding significant gain in conventional academic achievement.
17. Taha et al. (2021)	Student-initiated experiments; hands-on learning; inquiry-oriented investigation	Chemistry understanding/ achievement; application of chemistry concepts	Higher environmental awareness and sustainability practices	Student participation improved sustainability awareness and practices, while academic achievement effects were less consistent.
18. Tairas et al. (2025)	STEM-integrated problem-based learning; contextual learning; inquiry; collaboration	Moderate chemical-literacy gain (N-gain = 0.54); improved scientific attitudes; critical thinking/ problem solving	Engagement with sustainability issues and contextual environmental problems	PBL showed stronger evidence for scientific attitudes than for chemical-literacy differences, suggesting that conceptual gains may require deeper scaffolding.
19. Virginia (2025)	Problem-based learning; experimental activities; structured worksheets; instructional design	Strong improvement in critical thinking; pretest 70.98 → posttest 86.26; N-gain = 0.58	Increased environmental awareness and engagement with sustainability issues	PBL integrated with authentic Green Chemistry experiments produced measurable critical-thinking gains and environmental awareness.

Note. The table synthesizes the evidence reported in the reviewed studies. Teaching approaches were frequently combined within the same intervention; therefore, categories should not be interpreted as mutually exclusive. Scientific and environmental literacy outcomes also varied in the type and strength of evidence, ranging from quantitative pretest-posttest measures to questionnaires, observations, reflections, and qualitative assessments.

5. Discussion

The findings of this systematic review indicate that Green Chemistry Education (GCE) at the high school level is characterized primarily by experiential, inquiry-oriented, and student-centered instruction. Across 19 included studies, hands-on or experimental learning was the most frequently reported approach (18 studies, 94.7%), followed by inquiry-based learning (12, 63.2%). Collaborative learning was reported in seven studies (36.8%), while problem-based learning (PBL), context-based learning, project-based instructional, and informal or non-formal learning appeared less frequently. Because several studies combined multiple instructional approaches, these categories are overlapping rather than mutually exclusive.

5.1 Teaching Approaches in Green Chemistry Education

The predominance of hands-on and experimental learning suggests that practical engagement is a central mechanisms through which Green Chemistry concepts are introduced and experienced by high school learners. Students were exposed to authentic chemical processes and sustainability-related applications, including biopolymer synthesis, enzymatic catalysis, microwave-assisted synthesis, reaction kinetics, and bioenergy-related investigations (Corcoran et al., 2022; Linkwitz & Eilks, 2022; Linkwitz et al., 2022; McCance et al., 2021). These activities allow learners to observe chemical phenomena directly while simultaneously considering issues such as resource use, waste generation, safety, and sustainability. The reviewed evidence therefore supports the view that laboratory experiences are particularly compatible with Green Chemistry because they connect chemical knowledge with observable processes and real-world applications.

Inquiry-based learning emerged as the second most frequently represented approach and was commonly integrated with laboratory activities rather than implemented independently. For example, López-Fernández and Franco-Mariscal (2025) used extended investigation of environmental degradation, while other studies engaged learners in prediction, experimentation, observation, and interpretation of evidence. Cocoran et al. (2022) similarly incorporated student-designed experiments in which learners investigated the properties of alginate-based materials. Such applications suggest that inquiry provides the cognitive structure through which students move beyond simply performing experiments toward asking questions, generating explanations, interpreting evidence, and applying findings to sustainability problems.

Collaborative learning was also evident across several studies, particularly where learners worked in groups to conduct experiments, solve sustainability problems, or develop projects. PBL appeared less frequently than hands-on and inquiry approaches and generally functioned as a contextual mechanism for introducing authentic problems, such as waste management, pollution, and sustainable chemical production. Project-based learning similarly provided opportunities for learners to develop solutions through experimentation, modeling, and authentic research experiences (Jusniar et al., 2023; Kohn, 2018). Rather than replacing laboratory or inquiry-based instruction, these approaches frequently complemented them by providing a meaningful problem or product around which learning activities could be organized.

Less frequently represented approaches included microscale or small-scale chemistry, systems thinking, demonstration-based learning, context-based instruction, and informal or non-formal learning environments. Microscale approaches emphasized reduced chemical consumption, waste minimization, safety, and accessibility, as demonstrated by du Toit and du Toit (2024) and Listyarani et al. (2019). Systems-oriented approaches, such as those reported by Murphy et al. (2019) and Garner et al. (2015), extended chemistry learning toward broader relationships among chemical products, environmental consequences, sustainability, and societal decision-making. These

approaches, although less frequently reported, demonstrate that GCE is not restricted to laboratory experimentation but can incorporate broader sustainability perspectives.

A recurring instructional pattern emerged from these literature review: authentic sustainability contexts provide the initial problem or motivation, inquiry provides the process for investigation, hands-on experimentation generates evidence, and reflection or discussion supports conceptual and sustainability-oriented understanding. This pattern is consistent with experiential learning, in which concrete experience is followed by reflection, conceptualization, and further experimentation (Kolb, 1984). The convergence of these approaches suggests that the strength of GCE may lie less in the use of a single pedagogy and more in the integration of complementary approaches within a coherent learning sequence.

5.2. Scientific Literacy Outcomes in Green Chemistry Education

The reviewed studies provide evidence that GCE can support several dimensions of scientific literacy, particularly conceptual understanding, inquiry reasoning, critical thinking, data interpretation, and application of scientific knowledge. However, the strength of evidence was particularly evident in studies using pretest-posttest or comparative assessments. Karpudewan et al. (2015), for example, reported a substantial improvement in students' conceptual understanding following Green Chemistry curriculum implementation. Similarly, Jarujamrus et al. (2024) reported improvement in students' understanding of reaction kinetics, with normalized gains ranging from 0.63 to 0.71. Virginia (2025) also reported an increase in critical thinking performance from a pretest mean of 70.98 to a posttest mean of 86.26, with an N-gain of 0.58.

Other studies provide evidence for scientific literacy through inquiry and authentic scientific practices rather than conventional achievement measures. López-Fernández and Franco-Mariscal (2025) reported enhanced inquiry reasoning and scientific modeling, while McCance et al. (2021) emphasized data interpretation and experimental reasoning. Murphy et al. (2019) similarly incorporated systems thinking and analytical reasoning into learning activities. Corcoran et al. (2022) demonstrated how students could develop hands-on and student-designed experiments. These findings indicate that GCE can extend scientific literacy beyond factual knowledge toward the interpretation of evidence, investigation, explanation, and application of chemistry to authentic problems.

Nevertheless, the evidence should not be interpreted as demonstrating uniformly strong academic gains across all studies. Taha et al. (2019, 2021), for example, reported no significant improvement in conventional academic test performance in some outcomes, despite substantial gains in environmental awareness and sustainable practices. Likewise, Tairas et al. (2025) reported a moderate gain in chemical literacy (N-gain = 0.54; $p = 0.205$), while the improvement in scientific attitudes was statistically significant (N-gain = 0.46; $p = 0.003$). These findings suggest that the effects of GCE may differ according to the particular dimension of scientific literacy being assessed and that improvements in affective or sustainability-related outcomes do not necessarily translate directly into gains in conventional academic achievement.

5.3. Environmental Literacy Outcomes in Green Chemistry Education

Environmental literacy outcomes were also consistently reported, particularly in relation to environmental awareness, sustainability-oriented thinking, responsible decision-making, and environmentally responsible practices. Corcoran et al. (2022), for example, connected chemistry learning with plastic pollution and biodegradable-material alternatives, allowing students to consider chemical solutions to a widely recognized environmental problem. Karpudewan et al. (2015) likewise reported increased environmental awareness and motivation following Green Chemistry instruction.

Several studies demonstrated that environmental literacy can develop when chemistry learning is explicitly connected to real-world sustainability decisions. McCance et al. (2021) reported improvements in sustainable consumer decision-making, while Murphy et al., (2019) connected chemistry learning with the environmental impacts of consumer products and sustainable choices. Taha et al. (2019, 2021) similarly reported substantial increase in environmental awareness and sustainable practices. These findings suggest that GCE can provide opportunities for learners to move from understanding chemical processes toward evaluating the environmental consequences of chemical products and practices

An important distinction emerged between the measurement of scientific and environmental literacy. Scientific literacy was more often assessed through quantitative achievement measures, normalized gains, or assessments of conceptual and reasoning skills. Environmental literacy, in contrast, was more frequently examined through attitudes, reflections, perceptions, awareness, and reported practices. Consequently, the evidence for environmental literacy is generally favorable but should be interpreted with greater caution because several outcomes relied on qualitative or self-reported measures.

5.4. Relationship Between Teaching Approaches and Literacy Outcomes

The synthesis indicates that positive literacy outcomes were most evident when teaching approaches were integrated rather than implemented in isolation. Hands-on experimentation provided opportunities to observe and manipulate chemical phenomena; inquiry-based learning structured questioning, investigation, and evidence interpretation; collaborative learning facilitated discussion and explanation; and problem- or context-based approaches connected chemical concepts to authentic sustainability issues. The reviewed studies therefore suggest a complementary relationship among pedagogies rather than a clear hierarchy in which one approach is universally superior.

This integrated pattern appears particularly relevant to the simultaneous development of scientific and environmental literacy. For example, students investigating biodegradable alginate materials could develop scientific understanding of polymers and material properties while considering plastic pollution and sustainability (Corcoran et al. 2022). Similarly, bioenergy investigations combined scientific inquiry and problem solving with understanding of sustainable energy systems (Kohn, 2018), while consumer-product investigations connected analytical and systems thinking with sustainable decision (Murphy et al., 2019). These demonstrate how a single learning experience can address both scientific reasoning and environmental decision-making. Furthermore, these findings point to coherent combinations of authentic sustainability contexts, inquiry, hands-on investigation, collaboration, and reflection approaches to make Green Chemistry instruction address literacy outcomes.

5.5 Gaps and Implications for Future Research

Several gaps emerged from the reviewed literature. First, the studies used diverse research designs, ranging from quasi-experimental and classroom-based investigations to qualitative, descriptive, and instructional-development studies. This methodical variation limits direct comparison of findings and makes it difficult to determine the relative effectiveness of individual teaching approaches. Moreover, many studies examined combinations of approaches rather than isolated instructional models.

Second, scientific literacy outcomes were generally measured more explicitly than environmental literacy outcomes. Scientific outcomes commonly included conceptual understanding, critical thinking, inquiry skills, and data interpretation, whereas environmental literacy was more often assessed through awareness, attitudes, reflections, and reported practices. Only a limited number of studies examined both literacy dimensions simultaneously using clearly defined outcome measures. Longitudinal and

comparative studies are therefore needed to determine whether observed changes in literacy are sustained and how different instructional approaches contribute to both dimensions.

These gaps have implications for curriculum development, teacher education, and future research. Green Chemistry instruction may benefit from integrating authentic sustainability problems with inquiry, hands-on investigation, and reflection. Teachers also need appropriate preparation in both Green Chemistry content and literacy-oriented pedagogy. Future studies should employ stronger comparative and longitudinal designs and use validated measures that capture both scientific and environmental literacy to strengthen the evidence base.

6. Conclusion

The findings of this systematic review demonstrate that Green Chemistry Education at the high school level is predominantly characterized by experiential, hands-on, inquiry-oriented, and student-centered instruction. Among 19 included studies, hands-on or laboratory-based learning was the most frequently reported approach, followed by inquiry-based learning, with collaborative, problem-based, context-based, and project-based approaches frequently serving complementary roles. Less frequently reported approaches, including microscale chemistry, systems thinking, demonstration-based instruction, and informal or non-formal learning, further illustrate the diversity of pedagogical strategies used in GCE.

The review further indicates that generally favorable outcomes for both scientific and environmental literacy, although the strength and nature of evidence varied across studies. Scientific literacy outcomes included improved conceptual understanding, inquiry reasoning, critical thinking, data interpretation, and application of scientific knowledge. Environmental literacy outcomes were particularly evident in environmental awareness, sustainability-oriented thinking, responsible decision-making, and environmentally responsible practices. However, environmental literacy was more frequently assessed through qualitative and self-reported measures, while scientific literacy was more commonly assessed quantitatively.

Consequently, future Green Chemistry instruction should move beyond treating Green Chemistry as an additional set of laboratory activities and instead integrate its principles, pedagogies, and literacy outcomes within a coherent curriculum designs.

7. References

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