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Reclaiming chemistry as human practice: culture, ethics, and indigenous knowledge in the green chemistry discourse: A systematic review

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ABSTRACT

Chemistry has historically been framed within a technical, value-neutral paradigm that treats matter and its transformations as an isolated object of inquiry, marginalizing the social, ethical, and cultural dimensions increasingly recognized as central to sustainability discourse. This systematic review, conducted in accordance with PRISMA 2020 guidelines, synthesizes evidence from 20 studies published between 2016 and 2025 examining how green chemistry has been reimagined through humanistic, cultural, and digital lenses. Findings reveal a pronounced concentration of scholarship in Southeast Asia, particularly Indonesia, alongside substantial contributions from Europe and North America, reflecting a broader shift toward globalized, culturally responsive engagement with chemical knowledge. Frameworks such as Culturally Responsive Transformative practice and Socio-Scientific Inquiry emerged as prominent vehicles for connecting molecular-level chemistry to social justice and environmental stability, while digital media evolved from basic collaborative platforms toward interactive, culturally mediated resources supporting contextualized engagement. Cultural integration proved highly context-dependent, drawing on indigenous ethnoscience, post-colonial critique, and Eastern philosophical traditions to render chemistry personally and socially meaningful. Across the corpus, humanistic and culturally grounded interventions consistently enhanced both conceptual mastery of green chemistry principles and affective dimensions, including environmental awareness, empathy, and cultural identity, without compromising scientific rigor. This review positions humanistic and cultural integration not as a peripheral enrichment but as a necessary evolution toward Vision III scientific literacy, emphasizing pluralism, ethical reasoning, and emancipatory citizenship. Implications for cultural policy, professional formation, and future inquiry addressing underrepresented regions and long-term behavioral outcomes are discussed.

KEYWORDS: cultural identity, environmental ethics, ethnoscience, indigenous knowledge systems, post-colonial critique, sustainability discourse

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Introduction

Historically, chemistry education has been organized around a disciplinary identity centered on objectivity, systematic experimentation, and technical explanation, with matter and its transformations treated as the core object of study (Rahmawati et al., 2022). Laboratory work has constituted a defining feature of university-level chemistry instruction for roughly two centuries, reinforcing the assumption that competence in chemistry is chiefly a matter of experimental and procedural skill (Agustian et al., 2022). This disciplinary emphasis produced curricula that were heavily fact-based, encyclopedic, and fragmented into discrete topics, particularly at the introductory level (Seery, 2015). Because instruction remained content-driven and lacked an interdisciplinary-systemic orientation, social, ethical, and cultural dimensions of chemistry were consistently marginalized within mainstream teaching and curriculum design (Celestino, 2023; Paristiowati et al., 2022).

This technical, value-neutral paradigm has generated several documented limitations. Teaching chemistry through abstract definitions, symbols, and memorization detached from daily life has been linked to reduced student engagement and motivation (Rahmawati et al., 2023), whereas connecting content to everyday experience and environmental issues improves motivational outcomes (Araripe & Zeidler., 2024; Domenici, 2022; Koulougliotis et al., 2024). The paradigm has also fostered a perceived irrelevance of chemistry to real-world and environmental concerns, with the discipline sometimes viewed publicly as part of the environmental problem rather than a resource for ecological transition (Celestino, 2023; Rahmawati et al., 2023). Finally, because curricula omit social, ethical, and cultural dimensions, students remain underprepared for the interdisciplinary thinking, ethical judgment, and systems understanding that sustainability challenges require (Georgiou & Kyza, 2023; Gomes & Zeidler, 2023; Paristiowati et al., 2022; Sunday et al., 2025).

In response to the limitations of a purely technical paradigm, science education theory has increasingly turned toward humanistic and values-based frameworks that reposition ethical, cultural, and socio-political dimensions as constitutive of scientific literacy rather than peripheral additions. Eco-reflexive approaches extend green chemistry teaching beyond principles and techniques by incorporating worldview perspectives, critical reflection, and ethical knowledge directly into curriculum design (Herranen et al., 2021; Zuin et al., 2021). This shift parallels the broader evolution from content-centered scientific literacy toward Vision III, which foregrounds pluralism, agency, indigenous worldviews, and responsible knowing-in-action as legitimate curricular emphases (Sjöström, 2024; Sjöström & Eilks, 2017). Complementary strands — including socio-scientific inquiry, indigenous knowledge integration, and culturally responsive pedagogy — further operationalize this transition, positioning humanistic grounding as a natural, theory-driven maturation of green chemistry education rather than an external correction (Chen et al., 2020; Zidny & Eilks, 2022).

Cultural and ethical grounding matters pedagogically because it renders abstract chemical content personally meaningful, connecting scientific knowledge to students' lived experience, sociocultural identity, and community values rather than isolating it as decontextualized technique (Rahmawati et al., 2023; Reyes, 2025; Zidny & Eilks, 2022). Societally, this grounding matters because sustainability decisions are never purely technical: they require ethical reasoning, systems thinking, and democratic participation, positioning chemistry education as a vehicle for responsible citizenship rather than specialist training alone (Ariza et al., 2021; Georgiou & Kyza, 2023). Integrating diverse knowledge systems, including indigenous and local ways of knowing, further broadens what counts as legitimate chemistry knowledge and strengthens learners' capacity for informed, collaborative decision-making in environmentally consequential contexts (Wheeler & Root-Bernstein, 2020; Zidny & Eilks, 2022).

The COVID-19 pandemic accelerated a global, largely involuntary transition from face-to-face to online and blended instruction, compelling science educators to rapidly adopt digital tools across disciplines (Chiu, 2021; Gamage et al., 2020; Rapanta et al., 2021; Singh et al., 2021). Chemistry departments were among those most affected, requiring urgent adaptation of laboratory and lecture content to virtual formats, with chemical and medical education emerging as the most extensively studied disciplines in pandemic-era online learning research (Reyes et al., 2023; Singh et al., 2021; Zhang et al., 2022). Blended strategies combining asynchronous and synchronous delivery produced positive academic outcomes (Lapitan et al., 2021), and in the post-pandemic period, students and educators have increasingly gravitated toward blended models that balance digital flexibility with in-person interaction, reflecting durable shifts in expectations rather than a temporary emergency response (Ramadhani et al., 2023; Rapanta et al., 2021; Singh et al., 2021).

This broader digitalization trend carries particular relevance for green chemistry education, since digital platforms can support contextualized, real-world learning aligned with Education for Sustainable Development principles while lowering barriers in resource-limited settings (Chiu, 2021; Dewi et al., 2025). Digital worksheets integrating sustainability-oriented, project-based tasks have been shown to strengthen students' creative and contextual engagement with green chemistry content (Dewi et al., 2025), while culturally responsive digital formats, such as podcast-based instruction, enhance both environmental and cultural awareness by connecting learning to students' community and value systems (Widarti et al., 2025). Emerging tools including augmented reality, virtual laboratories, and adaptive AI further extend access to experiential, hazard-reduced learning while promoting inclusive participation regardless of socioeconomic background, positioning digital technology as a conceptual bridge between sustainability competence and culturally grounded chemistry pedagogy (Bankole & Ayanwale, 2025; Czok et al., 2023; Strielkowski et al., 2024).

Despite this growing conceptual convergence, research on humanistic and cultural approaches to green chemistry education remains scattered across education, chemistry, and sustainability journals, preventing a unified understanding of how specific principles translate into pedagogical models and learning outcomes (Puspita et al., 2026; Marques et al., 2020). Bibliometric evidence suggests this concentration may reflect incremental adjustments to laboratory practice rather than substantive pedagogical transformation, with a large share of relevant output confined to a single chemistry-education journal while conceptually richer contributions in other outlets remain unsynthesized (Marques et al., 2020). Cultural and ethnochemistry strands, digital and AI-based tools, and eco-reflexive humanistic frameworks have each developed as largely separate research streams, with no existing review consolidating these dimensions into a coherent, cross-disciplinary account of the field (Herranen et al., 2021; Kusuma et al., 2026; Wardani et al., 2023).

Addressing this fragmentation requires a methodologically rigorous approach capable of mapping a dispersed and multidisciplinary evidence base transparently and reproducibly. A systematic literature review, rather than a narrative or ad hoc synthesis, offers structured coverage of trends across humanistic, cultural, and digital dimensions of green chemistry education (Puspita et al., 2026). Adherence to PRISMA 2020 reporting standards ensures traceability across identification, screening, eligibility, and inclusion stages, thereby enhancing methodological transparency and minimizing selection bias when pre-established criteria are applied across multiple databases (Puspita et al., 2026; Kusuma et al., 2026; Salsabila & Hernani, 2025). Such a structured approach further enables comprehensive, reproducible field mapping that individual, fragmented studies cannot achieve, providing educators and curriculum developers with an empirically grounded roadmap for integrating humanistic and cultural dimensions into green chemistry education (Alberto et al., 2024; Puspita et al., 2026). Given this fragmentation across humanistic, cultural, and digital strands of green chemistry education, the present study undertakes a systematic literature review to consolidate and synthesize existing evidence into a coherent, cross-disciplinary account of the field. The review aims to map the geographic, institutional, and methodological characteristics of research published between 2016 and 2025; to identify the pedagogical frameworks and digital tools through which humanistic and cultural values have been integrated into green chemistry instruction; to examine how specific cultural, ethical, and indigenous knowledge systems have been embedded within curricula across diverse educational contexts; to characterize how core green chemistry principles and evaluative metrics are taught alongside these humanistic dimensions; and to synthesize the cognitive and affective learning outcomes reported across studies. In pursuing these aims, this review seeks to provide educators, curriculum developers, and policymakers with an empirically grounded roadmap for integrating humanistic and cultural perspectives into green chemistry education, while identifying critical gaps to guide future research and pedagogical innovation.

Methods

Study Design and Reporting Standards

This systematic review was conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines (Page et al., 2021). The review sought to synthesize evidence on the integration of green chemistry education through humanistic, cultural, and digital lenses, drawing on studies published between 2016 and 2025.

Search Strategy

A comprehensive literature search was conducted across four databases — Scopus, Web of Science, ERIC (Education Resources Information Center), and ScienceDirect — selected to ensure broad coverage across the chemistry, science education, and sustainability literatures relevant to this review. The search combined keywords and Boolean operators related to green chemistry education, humanistic and cultural pedagogy, sustainability, and digital integration, using the following string applied to titles, abstracts, and keywords: ("green chemistry" OR "sustainable chemistry") AND ("education" OR "teaching" OR "pedagogy" OR "curriculum") AND ("humanistic" OR "cultural" OR "ethno*" OR "indigenous" OR "values-based" OR "culturally responsive") AND ("digital" OR "online" OR "blended" OR "e-learning" OR "technology-enhanced"). The search was restricted to publications from 2016 to 2025 to capture the most recent developments in the field, and no language restrictions were applied. In total, the initial search across all databases yielded 815 records.

Eligibility Criteria

Studies were included if they (a) addressed green chemistry education within a humanistic, cultural, or ethical framework; (b) were conducted in formal or informal educational settings (e.g., secondary, undergraduate, or teacher-education contexts); (c) reported empirical, conceptual, or design-based findings relevant to pedagogical practice; and (d) were published in peer-reviewed journals between 2016 and 2025. Studies were excluded if they focused exclusively on technical or laboratory-based green chemistry without an educational or pedagogical dimension, were not available in full text, or did not meet the methodological quality threshold set for inclusion.

Study Selection Process

Following the removal of duplicate records, titles and abstracts were independently screened against the eligibility criteria. Full-text reports of potentially eligible studies were then retrieved and assessed in detail. Discrepancies between reviewers at any stage were resolved through discussion or consultation with a third reviewer. The complete study selection process, including the number of records identified, screened, excluded, and included at each stage, is presented in the PRISMA 2020 flow diagram (Figure 1).

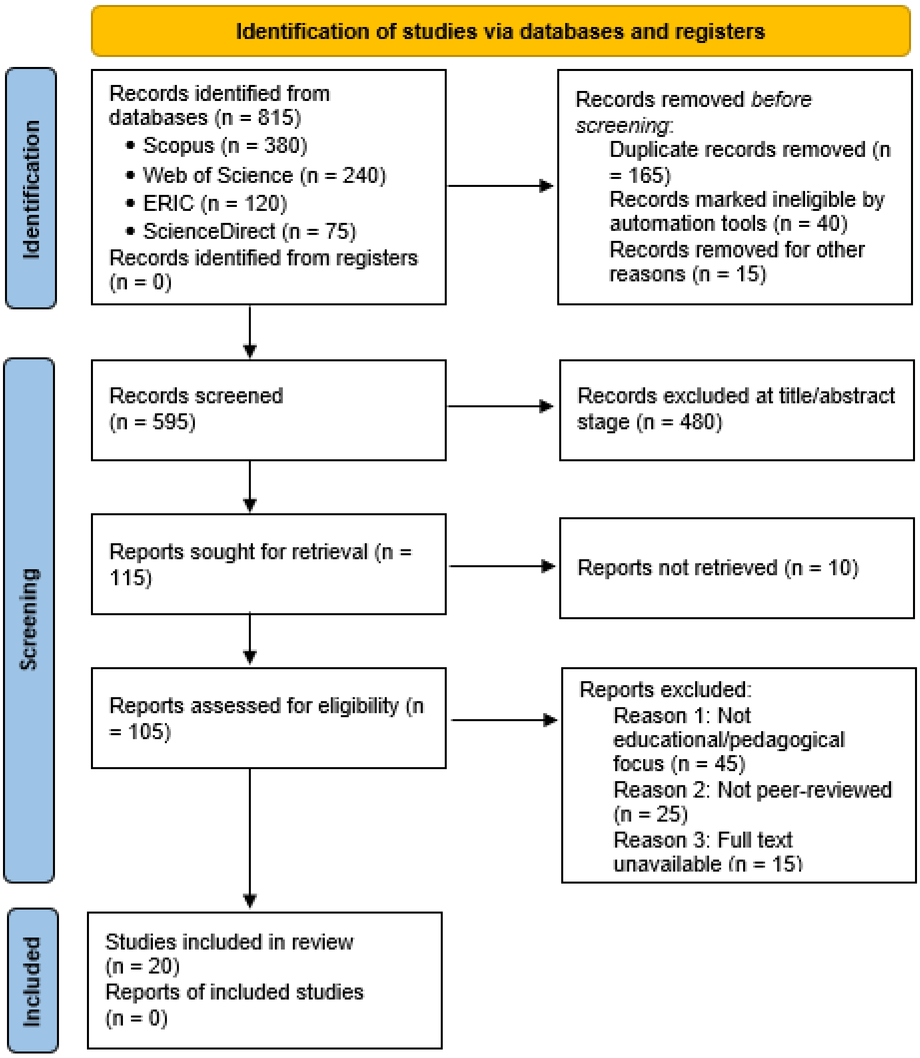

Figure 1. PRISMA 2020 flow diagram of the study selection process.

Data Extraction and Synthesis

Data from the included studies were extracted using a standardized coding framework capturing author(s), year, country, educational level, methodology, pedagogical framework, digital tools, humanistic/cultural dimensions, and reported learning outcomes. Extracted data were synthesized narratively and organized thematically across the five domains reported in the Results section (study characteristics, pedagogical frameworks, cultural values integration, green chemistry content/metrics, and learning outcomes).

Results

This section synthesizes findings from 20 studies examining the integration of green chemistry education through humanistic, cultural, and digital perspectives. The geographic distribution of the sample reveals a pronounced research interest in Southeast Asia, particularly Indonesia, alongside substantial contributions from Europe and North America. This pattern points to a broader disciplinary shift away from a predominantly Western, technically oriented paradigm toward a more globalized and culturally responsive framework. A recurring emphasis across the literature is the positioning of pre-service teachers and secondary students as central agents of change in sustainability education. Table 1 presents the descriptive and contextual characteristics of the included studies.

Table 1. Overview of Included Studies: Geographic, Institutional, and Methodological Profile

#	Author(s)	Year	Country	Educational Level	Sample Context	Methodology
1	Kennedy	2016	USA	Undergraduate	Chemistry Majors	Curriculum Design/ Survey
2	Sjöström et al.	2016	Global	Higher Ed	Science Education	Philosophical Reflection
3	Płotka-Wasylka	2018	Poland	Higher Ed	Analytical Chemistry	Systematic Review
4	Armstrong et al.	2018	USA	Higher Ed	Organic/General	Evaluative Review
5	Rahmawati et al.	2022	Indonesia	Secondary	Ethical Dilemma-STEAM	Case Study (Qualitative)
6	Zidny & Eilks	2022	Indonesia	Pre-service	Ethnochemistry Lab	R&D / Case Study
7	Hoffman	2023	Global	Secondary	High School Curricula	Perspective Analysis
8	Celestino	2023	Italy	Secondary	Environmental History	Epistemological Analysis
9	Gomes & Zeidler	2023	Brazil	Pre-service	Liberatory Pedagogy	Discourse Analysis
10	Rahmawati et al.	2023	Indonesia	Secondary	CRTT Framework	Mini-ethnography
11	Tveit & Faegri	2023	Europe	Professional	Teachers/Technicians	Developmental Review
12	Wardani et al.	2023	Indonesia	Secondary	Ethnochemistry-PBL	Quasi-experimental
13	Araripe & Zeidler	2024	Germany	Undergrad	Systems Thinking	Lesson Observation
14	Li & Eilks	2024	China	Secondary	Confucian Ethics	Good Practice Report
15	Mamluaturrahmatika	2024	Indonesia	Pre-service	Ethics Habituation	Descriptive Statistical
16	Okonkwo et al.	2024	Nigeria	Secondary	Renewable Energy	STEM Perspective
17	Dewi et al.	2025	Indonesia	Secondary	TPACK-ESD	Quasi-experimental
18	Nikolovski & Stojanovska	2025	Macedonia	Primary/Sec	Student Interventions	Mixed Methods
19	Quiroz-Martinez & Rushton	2025	Chile	Secondary	Action Inquiry	Collaborative Case Study
20	Teplá et al.	2025	Austria	Secondary	Wood Biorefinery	TLS Design/Evaluation

The data presented in Table 1 indicate a discernible shift toward interdisciplinary case studies and quasi-experimental designs in more recent publications (Dewi et al., 2025; Nikolovski & Stojanovska, 2025), in contrast to earlier work by Kennedy (2016) and Sjöström et al. (2016), which prioritized curriculum design and philosophical grounding. This progression toward empirical evaluation in secondary-school settings (Rahmawati et al., 2023; Wardani et al., 2023) reflects a growing effort to assess the tangible impact of green values on student identity and environmental awareness within distinct cultural contexts, such as the Baduy tribal community in Indonesia (Zidny & Eilks, 2022) and post-colonial settings in Chile (Quiroz-Martinez & Rushton, 2025).

Pedagogical innovation in green chemistry education has increasingly drawn on active-learning models that connect scientific content to social dilemmas. Frameworks such as Culturally Responsive Transformative Teaching (CRTT) and Socio-Scientific Issues (SSI) are especially prominent, aiming to dismantle the disciplinary insularity of chemistry by illustrating how molecular-level decisions bear on social justice and environmental stability (Celestino, 2023; Gomes & Zeidler, 2023). Table 2 synthesizes the pedagogical frameworks and digital integration strategies identified across the corpus.

Table 2. Pedagogical Frameworks and Digital Tools Employed in Green Chemistry Instruction

#	Study	Pedagogical Framework	Primary Strategy	Digital Medium/Tool	Tech Application
1	Kennedy (2016)	Historical Imperative	Service Learning	Google Docs	Collaborative Editing
2	Armstrong et al. (2018)	Complexity Progression	Decision Mapping	Not specified	Communication with Public
3	Rahmawati et al. (2022)	Dilemma-STEAM	Values-based Projects	PowerPoint/Videos	Narrative Delivery
4	Zidny & Eilks (2022)	MER Framework	Ethnochemistry Lab	SPADA/Google Meet	Online Collaborative Inquiry
5	Tveit & Faegri (2023)	HSE-Safety Model	Practical Training	chesse.org	Online Interactive Resource
6	Wardani et al. (2023)	CRT-integrated PBL	Contextual Learning	Not specified	Knowledge Construction
7	Araripe & Zeidler (2024)	Systems Thinking	Real-world Cases	PPT/Mandatory Literature	Critical Reflection
8	Li & Eilks (2024)	Confucian Ethics	Online Inquiry	Padlet/Tencent Docs	Collaborative Knowledge Display
9	Dewi et al. (2025)	TPACK-ESD	PjBL	Liveworksheets.com	Interactive Digital Worksheets
10	Teplá et al. (2025)	TLS Sequence	Industrial Context	SpottingScience	Interactive QR Learning

As shown in Table 2, digital pedagogy has evolved from basic collaborative tools such as Google Docs (Kennedy, 2016) toward more sophisticated interactive platforms, including SpottingScience and purpose-built resources such as chesse.org (Tveit & Faegri, 2023; Teplá et al., 2025). Digital worksheets (Dewi et al., 2025) and online inquiry platforms (Li & Eilks, 2024) enable contextualized learning even in the absence of physical laboratory access. This technological integration is frequently paired with a human-centered orientation, positioning digital tools as cultural mediators rather than mere delivery mechanisms (Rahmawati et al., 2023).

The humanistic dimension of this review illustrates how green chemistry education is mobilized to instill ethical and cultural values. A substantial body of research draws on the concept of eco-reflexive Bildung to cultivate responsible citizenship among students (Sjöström et al., 2016), integrating environmental history, indigenous knowledge systems, and Eastern philosophical traditions to construct a holistic worldview in which chemistry is understood as inseparable from human experience (Li & Eilks, 2024). Table 3 examines the specific humanistic and cultural dimensions embedded within the chemistry curriculum.

Table 3. Humanistic and Cultural Values Embedded in Green Chemistry Curricula

#	Author	Humanistic Lens	Ethical/Social Value	Cultural Integration	Cultural Context
1	Kennedy (2016)	Industrial History	Obligation in Decisions	Historical Missteps	US Chemical Industry
2	Płotka-Wasylka (2018)	Humanities Awareness	Eco-Citizenship	Social Impact	Global/European
3	Rahmawati et al. (2022)	Affective Domain	Empathy/Values	Ethical Stories	Local Indonesian Projects
4	Zidny & Eilks (2022)	Indigenous Science	Sustainable Wisdom	Ethnoscience	Baduy Tribe (Indonesia)
5	Hoffman (2023)	Human-centered	Hope vs Despair	Mental Health/SDGs	International Baccalaureate

#	Author	Humanistic Lens	Ethical/Social Value	Cultural Integration	Cultural Context
6	Celestino (2023)	Environmental History	Social Responsibility	History of Science	Rachel Carson (Italy/Global)
7	Gomes & Zeidler (2023)	Liberatory Pedagogy	Social Justice	Just Realities	Brazilian University
8	Rahmawati et al. (2023)	Cultural Identity	Heritage Preservation	CRTT Narratives	Multi-province Indonesia
9	Li & Eilks (2024)	Eastern Philosophy	Harmony/Responsibility	Confucian Ethics	Secondary School (China)
10	Quiroz-Martinez & Rushton (2025)	Post-Colonial	Environmental Injustice	Action Inquiry	Copper Mining (Chile)

Table 3 demonstrates that the integration of values is highly context-dependent. Quiroz-Martinez and Rushton (2025), for example, address the ethics of copper mining in Chile through a post-colonial lens, while Zidny and Eilks (2022) explore traditional pesticide knowledge systems. Collectively, these studies move beyond the "Vision I" (technical) and "Vision II" (contextually meaningful) models of scientific literacy toward "Vision III," which foregrounds transformation and emancipation (Sjöström et al., 2016; Marcelino et al., 2019). By linking environmental responsibility to religious teaching and moral obligation (Li & Eilks, 2024), these interventions render chemistry more personally relevant to students.

A core technical component of green chemistry education is the application of green metrics and the Twelve Principles of Green Chemistry, which serve as evaluative tools enabling students to objectively assess the "greenness" of chemical processes. This technical rigor ensures that the humanistic orientation does not compromise scientific accuracy but instead strengthens it by providing a structured framework for critical reasoning (Mamluaturrahmatika, 2024). Table 4 summarizes the core content and specific metrics employed across the reviewed studies.

Table 4. Core Content, Guiding Principles, and Evaluative Metrics in Green Chemistry Education

#	Study	Core GC Principles	Green Metrics Tool	Specific Topic	Application
1	Płotka-Wasylka (2018)	Principles 1, 2, 6, 7	Green Matrix/Circle	Analytical Metrics	Higher Ed Labs
2	Zidny & Eilks (2022)	Principles 1, 7, 12	Green Star Metric	Botanical Pesticides	Phytochemical Extraction
3	Tveit & Faegri (2023)	Principles 1, 3, 5, 12	Green Star / Tick	Chemical Safety	Lab Management
4	Araripe & Zeidler (2024)	Systems Thinking	Life-cycle Analysis	Toys/Burgers	Plastic Sustainability
5	Mamluaturrahmatika	All 12 Principles	Ethics Questionnaire	General Chemistry	Ethics Habituation
6	Okonkwo et al. (2024)	Principle 6	Efficiency Ratios	Renewable Energy	High School STEM
7	Dewi et al. (2025)	Principles 1, 2, 7	Stoichiometry	Aromatherapy Candles	Cooking Oil Recycling
8	Vaz et al. (2025)	Principles 1-12	ASK-GCP Tool	Industrial Reformulation	Industrial Case Studies
9	Teplá et al. (2025)	Principle 7	Sustainability Comp.	Wood Biorefinery	Acetic Acid Production

The analysis in Table 4 indicates that Prevention (Principle 1) and Renewable Feedstocks (Principle 7) are the most frequently taught principles (Dewi et al., 2025; Teplá et al., 2025). The introduction of systems thinking

(Araripe & Zeidler, 2024) represents a notable pedagogical development, enabling students to visualize the interdependence of chemical cycles and their implications for the Anthropocene (Celestino, 2023). Quantitative tools such as the Green Star Metric (Zidny & Eilks, 2022) and the Green Matrix further support students in making evidence-based ethical judgments within laboratory contexts.

The overarching objective of integrating green values is the enhancement of both cognitive and affective learning outcomes. The majority of reviewed studies report significant gains in environmental awareness and creative thinking, with several also noting that gender and digital literacy moderate these outcomes—female students, in particular, tend to demonstrate deeper affective engagement with cultural sustainability content (Widarti et al., 2025). Table 5 summarizes the reported outcomes and corresponding assessment methods.

Table 5. Cognitive and Affective Learning Outcomes Reported Across Studies

#	Author	Cognitive Outcome	Affective/Values Outcome	Assessment Method	Result/Significance
1	Kennedy (2016)	Knowledge of 12 Principles	Sense of Social Power	Pre-Post Survey	Increased Awareness
2	Zidny & Eilks (2022)	Phytochemical Analysis	Value for Indigenous Sci	5-step Likert Scale	97.5% Realized need for GC
3	Rahmawati et al. (2023)	Understanding Heritage	Cultural Identity	Reflective Journals	Support Cultural Sustainability
4	Wardani et al. (2023)	High Cognitive Gains	Cultural Respect	Kruskal-Wallis Test	Exp (78.89) > Control (70.56)
5	Mamluaturrahmatika	Awareness of Impact	Ethical Behavior	TCR Questionnaire	77% Showed Good Ethics
6	Dewi et al. (2025)	Creativity/Stoichiometry	Environmental Literacy	Two-tiered Test	Flexibility Gain = 0.72
7	Nikolovski & Stojanovska (2025)	Academic Performance	Sustainability Motivation	CKT / APQ	Significant Grade Improvement
8	Quiroz-Martinez & Rushton	Action Competence	Social Responsibility	Reflexive Thematic	Empowerment as Citizens
9	Teplá et al. (2025)	Conceptual Knowledge	Consistent Interest	Association Mapping	High Situational Interest

As shown in Table 5, findings are consistently positive across diverse educational contexts. Wardani et al. (2023) and Nikolovski and Stojanovska (2025) provide statistical evidence of improved academic performance when chemistry instruction is culturally contextualized. Additionally, the development of soft skills—including creative thinking and empathy—emerges as a primary outcome of values-based green chemistry education (Rahmawati et al., 2022; Dewi et al., 2025). Taken together, these findings suggest that a humanistic and cultural lens not only preserves scientific rigor but also cultivates the emotional and ethical maturity necessary for global environmental stewardship.

Discussion

The synthesis of literature from 2016 to 2025 reveals a transformative global landscape in green chemistry education. Research has transitioned from technical instruction toward interdisciplinary models that integrate humanistic values and digital pedagogy. Findings highlight a strong emphasis on secondary and pre-service teacher contexts, particularly in Southeast Asia and Europe. Pedagogical strategies have evolved from simple collaborative tools to immersive digital platforms and culturally responsive frameworks. By merging indigenous wisdom and philosophical ethics with quantitative green metrics, these interventions significantly enhance cognitive mastery and affective engagement. Overall, the studies demonstrate that contextualizing chemistry through cultural and digital lenses fosters environmental stewardship and creative problem-solving skills across diverse student populations.

Interpreting these findings through the lens of scientific literacy reveals a distinct shift toward Vision III, which emphasizes emancipation and social transformation. Early curricula within the study range focused on building dynamic undergraduate courses to demonstrate the historical necessity of green principles (Kennedy, 2016). However, recent research aligns more closely with “eco-reflexive Bildung” by encouraging students to challenge unsustainable industrial practices (Sjöström et al., 2016). For instance, the transition toward Vision III critical citizenship is evident in Chilean secondary contexts where students analyze environmental injustices (Quiroz-Martinez & Rushton, 2025). This theoretical progression suggests that green chemistry is now a foundational philosophy for cultivating “eco-reflexive” chemical thinking and action (Marcelino et al., 2019).

Comparative analysis of cultural integration strategies highlights how different philosophical groundings achieve similar affective outcomes. Zidny and Eilks (2022) successfully utilized indigenous ethnoscience from the Baduy tribe to ground green principles in local wisdom. Conversely, Li and Eilks (2024) employed Confucian ecological ethics to foster social responsibility among Chinese students. Both studies demonstrate that culturally responsive transformative teaching (CRTT) increases personal relevance, yet they differ in their specific cultural mediators. While the Indonesian context emphasizes heritage preservation (Rahmawati et al., 2023), the Chinese model focuses on individual cultivation and harmony. These divergent approaches suggest that cultural pedagogy is most effective when it resonates with students’ specific ethical frameworks and lived realities.

The role of digital pedagogy has transitioned from a delivery mechanism to a critical cultural mediator. Recent interventions, such as the use of digital green chemistry worksheets, show significant gains in student creativity by facilitating contextual learning (Dewi et al., 2025). However, Widarti et al. (2025) reveal that the effectiveness of digital tools, like podcasts, is moderated by students’ existing digital literacy and gender-based reflective patterns. This tension suggests that while technology enhances accessibility, it may also exacerbate educational inequities if digital literacy is not explicitly addressed. Furthermore, the integration of interactive platforms like SpottingScience demonstrates that digital environments can maintain high situational interest while delivering complex sustainability content in secondary education (Teplá et al., 2025).

A critical pattern in the literature is the increasing reliance on systems thinking to bridge the gap between technical metrics and humanistic values. Araripe and Zeidler (2024) illustrate that case studies on plastic sustainability encourage students to visualize chemical life cycles as interconnected social and ecological systems. This approach complements the use of quantitative green metrics, such as the Green Star, which provides an objective framework for ethical decision-making (Zidny & Eilks, 2022). Nevertheless, a gap remains in how students internalize these metrics as long-term habits. While Mamluaturrahmatika (2024) reports high levels of ethical awareness, the transition from cognitive mastery of principles to sustained pro-environmental behavior remains an unresolved debate within the field.

Evaluative evidence across the 20 studies consistently reports positive learning outcomes, though significant variations exist between cognitive and affective domains. Wardani et al. (2023) and Nikolovski and Stojanovska (2025) provide strong statistical support for improved academic performance when chemistry is culturally contextualized. However, qualitative insights suggest that affective engagement is often deeper among female students, who more frequently connect sustainability concepts to familial and social values (Widarti et al., 2025). This gendered pattern highlights a potential limitation in standardized assessments that may overlook “relational knowing” (Rahmawati et al., 2022). Consequently, the success of green chemistry interventions appears contingent upon pedagogical designs that embrace diverse ways of knowing and emotional engagement alongside scientific rigor.

Based on these synthesized findings, curriculum designers should prioritize the integration of culturally responsive transformative teaching (CRTT) to ensure science is locally relevant. Teacher educators must move beyond technical training to equip pre-service teachers with “eco-reflexive” competencies and Technological Pedagogical Content Knowledge (TPACK) (Dewi et al., 2025; Gomes & Zeidler, 2023). Policymakers are encouraged to support collaborative, place-responsive initiatives that link industrial contexts, such as biorefineries, with classroom instruction (Teplá et al., 2025; Quiroz-Martinez & Rushton, 2025). Furthermore, digital resources should be developed as interactive, multi-modal platforms that support collaborative inquiry. Finally, assessment frameworks must be reformed to include affective dimensions, measuring students’ empathy and ethical reasoning alongside their conceptual understanding.

Several limitations should be acknowledged when interpreting the findings of this review. First, the evidence base is relatively small, comprising only 20 studies, which constrains the generalizability of the patterns identified and limits the ability to draw robust conclusions across educational levels, cultural contexts, and pedagogical models. Second, the sample is geographically and authorially concentrated: a substantial proportion of the included studies originate from Indonesia, with the work of Rahmawati and colleagues and Zidny and Eilks recurring across multiple analytic dimensions of this review. This concentration raises the possibility that the synthesized patterns reflect the theoretical orientations and institutional contexts of a small number of research groups rather than broader, generalizable trends in green chemistry education. Third, this review relies exclusively on narrative synthesis; no quantitative or meta-analytic techniques were applied to pool effect sizes or assess the magnitude and consistency of reported outcomes across studies, limiting the strength of causal or comparative claims that can be drawn. Finally, methodological heterogeneity across the included studies — spanning qualitative case studies, quasi-experimental designs, and conceptual or philosophical analyses — complicates direct comparison of findings and may obscure meaningful differences in the quality and rigor of the underlying evidence.

Future research should address current geographic gaps by investigating green chemistry education in underrepresented regions like Africa and South America through longitudinal designs. While current studies provide snapshots of intervention success, tracking the long-term impact on students' professional identities and environmental behaviors is essential. Additionally, more research is needed to validate assessment tools that measure "eco-reflexive" thinking and systems-oriented competencies (Tveit & Faegri, 2023). Investigating digital equity is also crucial to ensure that podcast-based or platform-driven pedagogies do not exclude students with limited technological access (Widarti et al., 2025). Ultimately, future inquiries should explore the synergy between various cultural philosophies to develop a truly globalized, pluralistic framework for sustainable chemistry education.

Conclusion

This systematic review demonstrates that the future of green chemistry education lies at the intersection of scientific rigor, humanistic values, and digital innovation. By synthesizing a decade of research, the review highlights that integrating cultural contexts and ethical frameworks is not merely a pedagogical preference but a necessity for fostering transformative scientific literacy. The contribution of this work lies in identifying technology and culture as dual mediators that amplify student engagement and social responsibility. As the world faces intensifying environmental crises, the transition toward "eco-reflexive Bildung" provides a robust pathway for educating citizens who can navigate the complex socio-political dimensions of chemistry. Ultimately, these findings underscore the strategic importance of values-based science education in achieving a more just and sustainable global future.

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this review.

Data Availability Statement
The data extracted and synthesized in this review are derived from the included studies, which are publicly available through their respective publishers and are cited in the reference list.

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