Research Journal in Advanced Humanities

https://doi.org/10.58256/7rmwnh05

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REVIEW ARTICLE **Section:** *Philosophy & Religion*

Philosophy and ethics of green chemistry: A systematic review

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ABSTRACT

This systematic review examines the philosophical and ethical foundations of green chemistry, tracing its conceptual evolution from a narrowly technical, pollution-prevention paradigm toward an interdisciplinary framework grounded in moral responsibility, systems thinking, and environmental justice. Conducted in accordance with PRISMA guidelines, the review synthesizes thirty-eight peer-reviewed studies published between 2016 and 2025, drawn from philosophy, bioethics, environmental policy, and chemical education literatures. Findings reveal a persistent tension between the proliferation of quantitative "greenness" metrics and the qualitative ethical commitments—including precaution, virtue, and epistemic justice—that these tools struggle to capture. The analysis further identifies a gap between students' and practitioners' often superficial grasp of green chemistry principles and the deeper systems thinking genuine sustainability demands, alongside institutional pressures that risk reducing "green" terminology to a marketing device shaped by shifting policy priorities. Attention to cultural and epistemic pluralism, including non-Western philosophical traditions such as Hindu metaphysics and Confucian ecological ethics, emerges as a corrective to the anthropocentric assumptions embedded in much Western scientific discourse. By positioning the chemist as a moral agent accountable for the full life cycle of chemical innovation, the review argues that technical optimization alone cannot secure responsible outcomes; ethical reflection, inclusive deliberation, and systems-level education must accompany scientific advancement. The study offers humanities scholars a synthesized map of green chemistry's normative terrain, situating it within broader debates on justice, culture, and knowledge production that resonate across the arts and humanities, and identifies directions for interdisciplinary collaboration among chemists, philosophers, and educators.

KEYWORDS: environmental justice, epistemic pluralism, ethics of science, green chemistry, moral agency, sustainability education, systems thinking

Research Journal in Advanced Humanities

Volume 7, Issue 3, 2026

ISSN: 2708-5945 (Print)

ISSN: 2708-5953 (Online)

ARTICLE HISTORY

Submitted: **22 June 2026**

Accepted: 26 **August 2026**

Published: 07 **September 2026**

HOW TO CITE

Wizrah, M. S. I., Abdellatif, M. S., Ibrahim, A. R., & Nemtallah, M. A. . (2026). Philosophy and ethics of green chemistry: A systematic review. *Research Journal in Advanced Humanities*, 7(3). https://doi.org/10.58256/7rmwnh05

Published in Nairobi, Kenya by Royallite Global, an imprint of Royallite Publishers Limited

Introduction

Green chemistry is a scientific and design philosophy centered on developing chemical products and processes that minimize or eliminate the use and generation of hazardous substances (Abdussalam-Mohammed, 2020; De Marco et al., 2018; Kharissova et al., 2019; Vaccaro, 2016; Zuin et al., 2021). The field emerged in the 1990s out of a broader pollution-prevention policy movement, drawing on precedents such as the Responsible Care® initiative and the Brundtland Report, and was later codified by Anastas and Warner's twelve guiding principles published in 1998 (De Marco et al., 2018; Vaccaro, 2016). These principles—spanning waste prevention, atom economy, safer solvent design, energy efficiency, and the use of renewable feedstocks—gave chemists a practical design vocabulary for reducing the ecological footprint of chemical synthesis from its inception (Abdussalam-Mohammed, 2020; Kharissova et al., 2019).

Over time, however, green chemistry has moved beyond this narrowly technical formulation toward a more expansive integration with sustainability science. Scholars have argued that the twelve principles alone provide limited guidance on the social, ethical, economic, and political dimensions of chemical innovation, prompting calls for systems-based, life-cycle-informed, and interdisciplinary approaches (Amoneit et al., 2024; Constable, 2021). Between 2016 and 2025, this shift has been reinforced by mounting environmental pressures—climate change, biodiversity loss, and resource depletion—that have positioned green chemistry as central to circular economy models and to fourteen of the seventeen UN Sustainable Development Goals (Kumari et al., 2025; Ncube et al., 2023; Venkatesan et al., 2024).

Technical advancement in green chemistry, however sophisticated, is not by itself sufficient to guarantee responsible outcomes. The field's twelve principles offer robust guidance on hazard reduction and pollution prevention but remain largely silent on the social, economic, and political dimensions that shape whether innovations ultimately serve the common good (Amoneit et al., 2024). Chemists' molecular design choices carry direct consequences for environmental justice, climate justice, and equitable land use, even when these connections are not immediately visible to the researchers making them (Mehlich, 2024). Because new technologies such as synthetic biology and AI-driven discovery routinely outpace the field's capacity to anticipate their long-term effects, purely technical optimization must be paired with deliberate ethical reflection (Garcia-Martinez et al., 2026). This gap has driven a moralizing frame that casts chemists as bearing responsibility for the downstream impacts of their designs (Howard-Grenville et al., 2017).

In response, a range of philosophical and ethical frameworks has emerged to guide decision-makers toward moral responsibility. The precautionary principle emphasizes preventing harm before it manifests, favoring smarter design over reactive correction (Maertens et al., 2024). Virtue ethics reframes chemical practice as a pursuit of "doing good," mapping the twelve principles onto the criteria of maximizing benefit and minimizing harm (Mammino, 2024). Epistemic justice calls for inclusive, non-hierarchical deliberation that incorporates diverse and non-Western perspectives (Garcia-Martinez et al., 2026; Mehlich, 2024; Sovacool et al., 2016). Together, these frameworks converge on the concept of the chemist as a moral agent, ethically accountable for the human and ecological consequences of chemical design (Celestino, 2023; Howard-Grenville et al., 2017).

A persistent tension in the literature separates the proliferation of quantitative "greenness" metrics from the qualitative ethical dimensions of sustainable chemistry that resist easy measurement. Tools such as DOZN, GEMAM, AGREE, and NEMI score chemical processes on numerical or pictographic scales, yet no single metric captures a process's full sustainability profile, and combining complementary parameters is necessary to approximate its true complexity (Fantozzi et al., 2023; O'Neil et al., 2021; Xin et al., 2025; Yin et al., 2024). Many traditional metrics remain poorly suited to analytical procedures because they reference product mass rather than genuine environmental impact (Tobiszewski, 2016), and rigorous evaluation has shown that some sustainability claims exceed what the underlying data actually support (Quintavalla et al., 2024). Meanwhile, the ethical considerations central to sustainability—fairness, responsibility, and intergenerational justice—remain largely outside what these metrics are designed to measure (Celestino, 2023; Chen et al., 2020).

A parallel gap separates students' and practitioners' often shallow conceptual grasp of green chemistry from the deeper systems thinking that genuine integration demands. Even after targeted instruction, learners struggle to connect core concepts, such as atom economy, to holistic assessments of a process's greenness, and teacher-education students frequently find it difficult to link chemistry content to broader socio-scientific issues (Gomes & Zeidler, 2023; Vaz et al., 2025). Most green chemistry teaching remains occasional and poorly evaluated rather than systematically embedded in curricula (Celestino, 2023), and systems thinking appears as a learning outcome in only a minority of reviewed educational studies (Chen et al., 2020; Hurst et al., 2019). This leaves a wide divide between aspirational calls for mainstreamed education and scalable, evaluated practice (Celestino, 2023; Zuin et al., 2021).

A systematic, interdisciplinary synthesis is particularly needed at this point because relevant discussion of green chemistry's normative dimensions is dispersed across domains that frame the field in fundamentally different terms. Green chemistry is increasingly described as inherently interdisciplinary, requiring input from toxicology, public health, policy, and social science to address life-cycle impacts and sustainability trade-offs (Constable, 2021; Venkatesan et al., 2024). The educational literature contributes a further strand by situating green chemistry within citizenship formation and ethical decision-making, while historical-epistemological work frames it in terms of values and the common good (Celestino, 2023; Chen et al., 2020; Koulougliotis et al., 2024). Other work bridges the field to circular economy and responsible research and innovation, illustrating how its normative content is being developed across separate, largely disconnected bodies of scholarship (Amoneit et al., 2024; Mammino, 2024).

This fragmentation is compounded by a further problem: existing reviews have concentrated overwhelmingly on technical, pedagogical, and implementation-focused questions rather than on green chemistry's philosophical or ethical foundations. Recent syntheses address multidimensional industrial impacts, analytical methods, laboratory pedagogy, and the transition toward circular chemistry, but rarely engage ethics as a central concern (De Marco et al., 2018; Savec & Mlinarec, 2021; Venkatesan et al., 2024). Where social or ethical issues do surface, they are typically identified as underdeveloped extensions of a predominantly technical framework, receiving limited sustained attention (Amoneit et al., 2024; Nowak et al., 2021). This persistent conceptual pluralism further underscores the case for a review that clarifies the field's philosophical and ethical terrain rather than adding another technical overview (Howard-Grenville et al., 2017; Savec & Mlinarec, 2021). Given this fragmented landscape, the present review aims to systematically map and synthesize the philosophical, ethical, and justice-oriented dimensions of green chemistry as they have developed across the peer-reviewed literature. It seeks to trace how the field's conceptual foundations have shifted from a narrowly technical, pollution-prevention paradigm toward an interdisciplinary framework grounded in moral responsibility, systems thinking, and social and environmental justice. In doing so, the review examines the tension between quantitative greenness metrics and qualitative ethical considerations, explores the persistent gap between conceptual understanding and systems-level education, and considers how cultural and epistemic pluralism reshapes chemical ethics. Ultimately, this synthesis aims to clarify the field's normative terrain and identify directions for future scholarship and practice.

Methods

Study Design

This study was conducted as a systematic review to synthesize and critically examine the philosophical, ethical, and justice-oriented dimensions of green chemistry as reported in the peer-reviewed literature published between 2016 and 2025. The review was designed and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, which provided a structured and transparent methodology for identifying, screening, and synthesizing relevant evidence. This approach was selected because it allows for a comprehensive and reproducible mapping of a conceptually diverse and rapidly evolving body of literature that spans philosophy, bioethics, environmental policy, and chemical education. Although PRISMA was originally developed for reviews of empirical and clinical studies, it was adopted here for its transparent, reproducible reporting structure. Reflexive frameworks designed specifically for qualitative and conceptual syntheses, such as ENTREQ or SANRA, were considered but not adopted, as PRISMA's staged reporting requirements offered clearer traceability for this conceptually heterogeneous literature.

Search Strategy and Information Sources

A comprehensive and systematic search was performed across multiple electronic databases, including Scopus, Web of Science, PubMed, and Google Scholar, to ensure broad disciplinary coverage spanning the natural sciences, humanities, and social sciences. The search strategy combined controlled vocabulary and free-text keywords such as "green chemistry," "sustainable chemistry," "philosophy," "ethics," "environmental justice," "sustainability education," and "systems thinking," which were combined using Boolean operators (AND/OR) to maximize sensitivity while maintaining topical relevance. The search was restricted to literature published between 2016 and 2025 in order to capture the most recent conceptual developments in the field. Reference lists of key articles were also manually screened to identify additional eligible studies that may not have been retrieved through the electronic search.

Eligibility Criteria

Studies were included if they were peer-reviewed journal articles, book chapters, or conference proceedings published in English between 2016 and 2025 that explicitly addressed the philosophical, ethical, educational, or justice-related dimensions of green chemistry. Eligible studies were required to engage substantively with conceptual, normative, or pedagogical aspects of sustainability in chemistry rather than reporting purely technical or laboratory-based findings. Studies were excluded if they focused exclusively on synthetic methodology, reaction optimization, or analytical technique development without meaningful engagement with the ethical, philosophical, or educational discourse surrounding green chemistry. Non-English publications, editorials, opinion pieces without theoretical grounding, and duplicate records were also excluded from the review.

Study Selection Process

The initial database search identified a total of 832 records. After the removal of duplicate entries, the titles and abstracts of the remaining records were independently screened against the eligibility criteria to exclude clearly irrelevant studies. The full texts of the remaining articles were then retrieved and assessed in detail to confirm their eligibility for inclusion. Disagreements regarding inclusion at any stage of the screening process were resolved through discussion and consensus. Following this multi-stage screening and eligibility assessment process, a final set of 38 studies met all inclusion criteria and were retained for qualitative synthesis. he complete study identification, screening, and inclusion process is illustrated in the PRISMA flow diagram below (Figure 1).

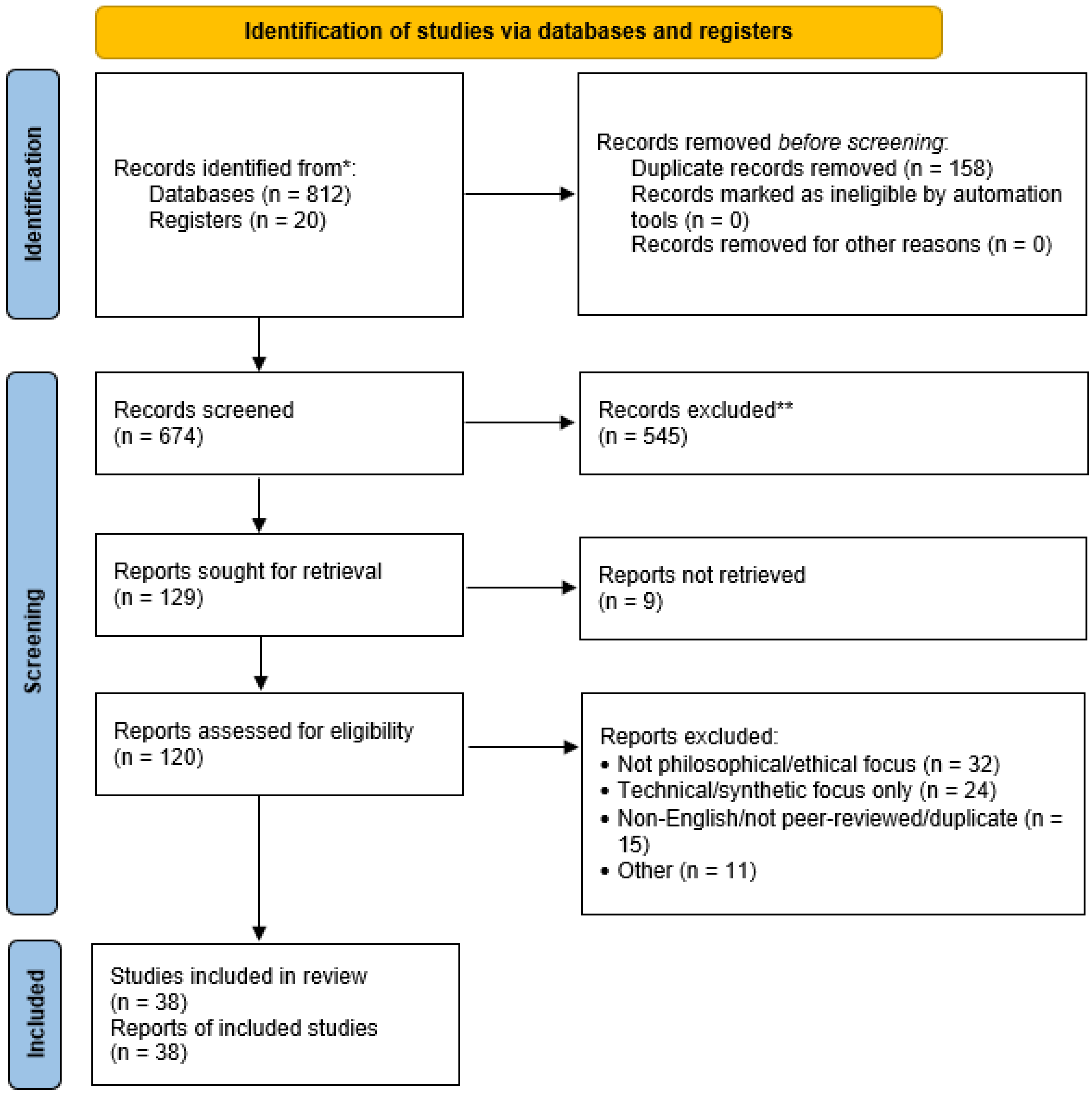

Figure 1. PRISMA flow diagram of the study identification, screening, and inclusion process

The initial database search identified a total of 832 records (812 from databases and 20 from registers). After removing 158 duplicate records, 674 unique records remained for screening. The titles and abstracts of the remaining records were independently screened against the eligibility criteria, excluding 545 records as clearly irrelevant, leaving 129 reports sought for retrieval, of which 9 could not be retrieved. The full texts of the remaining 120 articles were then retrieved and assessed in detail, of which 81 were excluded (32 not philosophical/ethical in focus, 24 technical/synthetic focus only, 15 non-English, not peer-reviewed, or duplicate, and 11 for other reasons). Disagreements regarding inclusion at any stage were resolved through discussion and consensus. Following this multi-stage process, a final set of 38 studies met all inclusion criteria and were retained for qualitative synthesis.

Data Extraction

A standardized data extraction form was developed to systematically capture key information from each of the 38 included studies, including the author(s), year of publication, geographic and disciplinary context, theoretical or philosophical framework employed, key ethical or educational themes addressed, and principal findings or arguments. Data extraction was performed by carefully reading the full text of each article and organizing the extracted information into a structured matrix to facilitate cross-study comparison. This process enabled the identification of recurring conceptual patterns, thematic clusters, and areas of scholarly consensus or divergence across the included literature.

Data Synthesis and Analysis

Given the conceptual and interdisciplinary nature of the included literature, a narrative and thematic synthesis approach was adopted rather than a quantitative meta-analysis. Extracted data were iteratively coded and grouped into overarching thematic categories, including philosophical and ethical foundations, methodological and technical assessment frameworks, and educational and sociopolitical dimensions of green chemistry. These themes were then critically analyzed to trace the evolution of the discourse between 2016 and 2025, identify gaps in the existing literature, and highlight emerging directions for future research and practice in the philosophy and ethics of green chemistry.

Quality Assessment

The methodological and conceptual rigor of the included studies was appraised qualitatively, taking into account the clarity of the theoretical framework, the coherence of argumentation, and the relevance of each study's contribution to the philosophical and ethical discourse on green chemistry. Given the predominantly conceptual and theoretical nature of the included literature, formal quantitative risk-of-bias tools designed for empirical or clinical studies were not applied; instead, emphasis was placed on the credibility of the source, the rigor of the argumentation, and the extent of peer engagement with the work, consistent with established practices for qualitative and conceptual systematic reviews. This appraisal informed the depth of critical engagement with each study during synthesis rather than producing a formal strength-based classification; the Results and Discussion therefore do not present a separate quality-stratified breakdown of included studies.

Results

A total of 38 studies met the eligibility criteria and were included in this systematic review. The included literature spans the period from 2016 to 2025 and reflects a diverse range of disciplinary perspectives, including philosophy, bioethics, environmental policy, chemical education, and sustainability science. Collectively, these studies illustrate the conceptual evolution of green chemistry from a primarily technical and pollution-prevention paradigm toward a broader, interdisciplinary framework grounded in ethical responsibility, systems thinking, and social and environmental justice. The findings are organized thematically below, beginning with the philosophical and ethical foundations of the field, followed by methodological and technical developments, and concluding with its educational and sociopolitical dimensions.

The conceptual landscape of green chemistry has transitioned significantly between 2016 and 2025, evolving from narrow pollution prevention to a holistic integration within sustainability science (Constable, 2021; Psillakis, 2025). This period emphasizes a move beyond the twelve fundamental principles to encompass circular analytical chemistry and systems thinking (Nowak et al., 2021; Psillakis, 2025). Industrial and academic discourse now highlights the limitations of incremental technical improvements, advocating instead for systemic transformations that respect absolute environmental boundaries (Constable, 2021; Winterton, 2016). By acknowledging the complex nature-society interactions defining sustainable development, researchers argue for an integrated approach that balances molecular functionality with planetary safety (Serra et al., 2025; Zimmerman et al., 2020). Consequently, contemporary frameworks prioritize long-term resilience over immediate efficiency gains, positioning chemistry as a central actor in achieving global sustainability goals (Caillol, 2025; Mehlich, 2024).

Table 1. Philosophical, Ethical, and Justice Frameworks in Green Chemistry

Author(s) and Year	Principal Theoretical Framework	Justice/Ethical Focus	Key Philosophical Argument	Contribution to Green Chemistry
Winterton (2016)	Scientific Realism	Validity and Scrutiny	Limits of principles vs. laws	Critique of green claims
Jordan & Kristjánsson (2017)	Aristotelian Virtue Ethics	Harmony with Nature	Character traits for sustainability	Sustainability virtue education
Sovacool et al. (2017)	Multi-perspective Ethics	Energy Justice	Fairness in resource distribution	Justice in energy transitions
Pellow (2018)	Critical Environmental Justice	Power and Exclusion	Socio-environmental divide roots	Critical justice theory update
Vermeylen (2019)	Epistemic Justice	Epistemic Violence	Knowledge distribution rights	Environmental knowledge ethics
Muradian & Gómez-Baggethun (2021)	Ecological Economics	Care-based Morality	Shared fate over exploitation	Care-centered environmentalism
Droz (2022)	Environmental Philosophy	Anthropocentrism Review	Ethics of human-nature gap	Review of anthropocentric roots
Richie (2022)	Green Bioethics	Distributive Justice	Resource conservation in tech	Sustainable healthcare AI ethics
Popa et al. (2023)	Philosophical Pluralism	Complex Equality	Balancing moral gains and residue	Profile for artificial synthesis
Mammino (2024)	Precautionary Principle	Harm Prevention	"Doing good" moral imperative	Ethics in chemistry education
Paleri (2025)	Indian Hindu Philosophy	Dharma and Karma	Universal consciousness in SynBio	Alternative non-dualist ethics
Psillakis (2025)	Systems Theory	Circularity Goals	Systems thinking for sustainability	Theoretical circularity framework

Central to the ethical discourse is the fundamental obligation of moral agents to maximize societal benefits while simultaneously minimizing potential harms (Mammino, 2024). The precautionary principle serves as a critical guideline during this decade, prioritizing health and environmental protection when outcomes remain uncertain or potentially devastating (Mammino, 2024; Richie, 2022). Literature from 2016 to 2025 underscores that "doing good" requires a deep integration of ethical expertise into chemical research, where practitioners are responsible for the entire life cycle of their innovations (Mehlich, 2024; Richie, 2022). Furthermore, emerging frameworks such as green bioethics emphasize distributive justice and resource conservation (Richie, 2022). These ethical considerations are increasingly viewed as essential professional competencies rather than optional supplements to technical training, reflecting a broader commitment to global justice (Mehlich et al., 2017).

Table 2. Greenness Metrics and Assessment Tools in Green Chemistry

Author(s) and Year	Methodological Metric/Tool	Evaluation Parameters	Scope of Application	Research/Technical Impact
Guidotti (2018)	Occupational Health Agenda	Risk/Quality Assurance	Post-industrial health	Regenerative chemistry focus
Zimmerman et al. (2020)	Systems Thinking Framework	Synergistic Thinking Lines	Molecular sustainability basis	Sustainable future design
Constable (2021)	Life Cycle Thinking	Systems-level impacts	Batch to continuous flow	Interdisciplinary flow practice
Nowak et al. (2021)	RGB Additive Color Model	Whiteness/Functionality	Analytical method evaluation	Reconciling GAC and utility
Patiño-Ruiz et al. (2021)	Cradle-to-Gate LCA	Ecosystem quality/depletion	Iron oxide nanoparticle synthesis	Coprecipitation method comparison
Brambila et al. (2022)	DOZN 2.0 Evaluator	12 Principles of GC	Silica production greenness	Nanomaterial greenness scoring
Martinengo et al. (2024)	One Health Integration	Antiparasitic pipeline	Drug design for neglected disease	Sustainable medicinal chemistry
Mansour et al. (2024)	Modified Green Star (MoGSA)	Toxicity and hazard potential	Laboratory chemical reactions	Flexible assessment software
Caillol (2025)	Market/Innovation Review	Carbon capture integration	Global material production	Bio-based polymer advancements
Cao et al. (2025)	Multi-modal Integration	Property prediction	LLM-based drug discovery	Autonomous chemical research
Elagamy et al. (2025)	Integrated Metric Review	Performance/Practicality	Analytical method comparison	Comprehensive evaluation software
Serra et al. (2025)	Safe and Sustainable by Design	Holistic decision-making	Unified safety metrics	Framework for integrated assessment
Xin et al. (2025)	GEMAM Pictogram	Reagents/Waste/Energy	Analytical method greenness	Comprehensive software metric

The development of robust metrics between 2016 and 2025 has been essential for quantifying the "greenness" of chemical processes and fostering accountability (Elagamy et al., 2025; Xin et al., 2025). Traditional tools have been supplemented by comprehensive software like AGREE, DOZN 2.0, and the GEMAM pictogram (Brambila et al., 2022; Xin et al., 2025). These metrics evaluate diverse factors, including energy consumption, reagent toxicity, and waste generation, providing visual scores to facilitate comparative analysis (Elagamy et al., 2025; Mansour et al., 2024). However, researchers warn that a focus on isolated subsystems may obscure broader environmental costs, necessitating a transition toward life cycle assessments (LCA) (Patiño-Ruiz et al., 2021; Psillakis, 2025). By capturing the total environmental footprint from cradle to gate, LCAs ensure that sustainability claims remain grounded in empirical evidence and do not merely represent greenwashing efforts (Patiño-Ruiz et al., 2021; Winterton, 2016).

Table 3. Educational and Policy Applications of Green Chemistry

Author(s) and Year	Educational/Social Context	Evaluated Population	Implementation Strategy	Outcomes for Sustainability
Maxim (2017)	Scientific Movement Study	Academia (USA/France)	Socio-political interviews	Strategic GC role identification
Mehlich et al. (2017)	European Chemical Sciences	Academic stakeholders	Ethical domain identification	Identification of professional ethics

Author(s) and Year	Educational/Social Context	Evaluated Population	Implementation Strategy	Outcomes for Sustainability
Mahaffy et al. (2019)	Molecular Sustainability	Undergraduate students	Learning outcome development	Paradigm for sustainability science
Zidny & Eilks (2020)	Indigenous Knowledge Systems	Secondary/Tertiary students	Perspective integration	Sustainable science education
Fawehinmi et al. (2020)	Green Human Resources	Organizational employees	Personal norms interplay	Enhanced pro-environmental behavior
Herranen et al. (2021)	Eco-reflexive Bildung	Chemistry teacher education	Didaktik modeling framework	Holistic sustainability education
Linkwitz & Eilks (2022)	High School Curriculum	Secondary chemistry students	Action research teacher journey	Long-term GC principle retention
Rahmawati et al. (2022)	STEAM Education	Secondary school students	Ethical dilemma stories	Empowerment as change agents
Mitarlis et al. (2023)	Undergraduate Program	Chemistry education students	Project Based Learning (PBL)	Conservational learning methods
Rahmawati et al. (2023)	Cultural Sustainability	Chemistry learners	CRTT learning model	Engagement through ethnochemistry
Mehlich (2024)	European Green Deal	Professional chemists	Responsible chemistry training	Transition competencies for R&I
Stouthart et al. (2025)	Science Teachers' Views	Science teachers	Q methodology factor analysis	Consensus on student competencies
Teplá et al. (2025)	Wood Biorefinery Units	Secondary education students	Mixed-methods understanding	Evolved conceptual GC associations

Integrating systems thinking into chemistry is identified as a vital strategy for addressing the "wicked problems" of sustainability (Constable, 2021; Mahaffy et al., 2019). This approach encourages practitioners to look beyond immediate molecular results and examine how chemical choices intersect with ecological and economic systems (Constable, 2021; Zimmerman et al., 2020). By recognizing causal loops and inter-system interactions, chemists can avoid shifting environmental risks to different parts of the global value chain (Constable, 2021; Psillakis, 2025). Systems thinking also facilitates the application of artificial intelligence and flow chemistry, which enhance process efficiency and accelerate sustainable material discovery (Caillol, 2025; Cao et al., 2025). Ultimately, this paradigm shift fosters a resilient scientific culture capable of adapting to global resource challenges and evolving regulatory demands (Mehlich, 2024; Serra et al., 2025). This holistic perspective ensures that innovation remains aligned with planetary safety.

Science education plays a pivotal role in disseminating green chemistry principles and fostering competencies for a sustainable future (Mitarlis et al., 2023; Teplá et al., 2025). Studies indicate that while students hold positive views, their conceptual understanding is often limited to vague environmental friendliness without grasping the twelve principles (Teplá et al., 2025; Linkwitz & Eilks, 2022). Innovative teaching models, such as using wood biorefineries or ethical dilemma stories, enhance students' ability to engage in scientific argumentation and value reflection (Rahmawati et al., 2022; Teplá et al., 2025). Professional development for teachers is crucial to ensure sustainability is not treated as an isolated topic but as a foundational element of chemistry curricula (Linkwitz & Eilks, 2022; Stouthart et al., 2025). Furthermore, higher education institutions are increasingly adopting "eco-reflexive Bildung" to prepare future chemists for their roles as responsible societal innovators (Herranen et al., 2021; Mehlich, 2024).

The inclusion of diverse cultural and philosophical perspectives, such as Confucian ecological ethics or Hindu metaphysics, enriches the global understanding of chemical ethics (Paleri, 2025). These pluralistic narratives challenge the anthropocentric worldviews prevalent in Western science, advocating for a relationship with nature based on care rather than exploitation (Droz, 2022; Muradian & Gómez-Baggethun, 2021). For instance, the concept of "agentised chemistry" views matter as an active participant in shaping the world, promoting a symbiotic relationship between humans and the environment (Armstrong, 2024). By integrating indigenous knowledge and non-Western viewpoints, chemistry education empowers students to act as moral agents within specific cultural contexts (Rahmawati et al., 2023). This epistemic justice ensures that sustainability solutions are culturally relevant and socially acceptable across different global communities (Sovacool et al., 2017; Vermeylen, 2019).

Green chemistry functions as both a scientific movement and a socio-political strategy adapted to external regulatory conditions (Maxim, 2017; Mehlich, 2024). Its development is heavily influenced by policies like the European Green Deal and funding programs prioritizing industrial competitiveness alongside environmental protection (Maxim, 2017; Mehlich, 2024). While this adaptability has fostered institutionalization, it presents risks of the terminology losing its original environmental relevance to corporate interests (Maxim, 2017; Psillakis, 2025). Genuine sustainability requires shifting economic models to prioritize regeneration and respecting absolute planetary boundaries (Winterton, 2016; Psillakis, 2025). Therefore, chemists must participate actively in policy discourses to ensure progress remains aligned with global justice and ecological integrity (Mehlich et al., 2017; Mehlich, 2024). Integrating green human resource management further enhances pro-environmental behavior within organizations, reinforcing the ethical culture necessary for a green transition (Fawehinmi et al., 2020; Richie, 2022).

Discussion

This systematic review synthesized 38 studies published between 2016 and 2025 to map the evolving philosophical and ethical landscape of green chemistry. The purpose was to evaluate how the discipline has transitioned from a technical pollution-prevention movement to an interdisciplinary sustainability science. The findings illustrate a robust pattern of development: the proliferation of quantitative "greenness" metrics is increasingly contrasted with qualitative ethical frameworks that emphasize moral agency and global justice (Mammino, 2024; Mehlich et al., 2017). Furthermore, a significant shift toward systems thinking and life cycle assessment reflects a growing recognition that incremental molecular improvements are insufficient without addressing systemic ecological boundaries (Constable, 2021; Psillakis, 2025). Collectively, these findings suggest that the field is maturing into a more reflexive and pluralistic discipline.

A critical tension exists between the proliferation of quantitative greenness metrics and the fundamental "doing good" moral imperative. While tools like DOZN 2.0 and the GEMAM pictogram provide essential accountability (Brambila et al., 2022; Xin et al., 2025), they risk reducing complex environmental ethics to a series of mathematical scores. This methodological reductionism may obscure broader ethical obligations, such as distributive justice or the precautionary principle (Mammino, 2024; Richie, 2022). Comparing these technical assessments with frameworks like "White Analytical Chemistry" suggests a need to balance environmental "greenness" with functional "whiteness" (Nowak et al., 2021). Ultimately, metrics must serve as aids to, rather than replacements for, the moral reasoning required of chemists acting as societal moral agents (Mehlich, 2024; Mehlich et al., 2017).

The adoption of systems thinking marks a paradigm shift away from "weak sustainability," which relies on simple chemical substitutions. Literature between 2016 and 2025 emphasizes that true sustainability requires understanding the molecular basis of planetary health within complex Nature-Society interactions (Psillakis, 2025; Zimmerman et al., 2020). This systems-level approach, supported by interdisciplinary flow chemistry and artificial intelligence, aims to prevent the shifting of environmental risks across global value chains (Caillol, 2025; Constable, 2021). However, the implementation of life cycle assessments from "cradle to gate" remains methodologically challenging, as shown in comparative nanoparticle studies (Patiño-Ruiz et al., 2021). This transition necessitates that chemists look beyond immediate laboratory results to consider the long-term resilience of the ecological systems they inhabit (Constable, 2021; Serra et al., 2025).

A persistent gap remains between students' positive attitudes toward green chemistry and their shallow conceptual understanding of its principles. While learners generally support environmental protection, they often lack a rigorous grasp of the twelve principles, viewing "green" as a vague marketing term (Linkwitz & Eilks, 2022; Teplá et al., 2025). To address this, contemporary pedagogical research advocates for "eco-reflexive Bildung" and the use of ethical dilemma stories to foster scientific argumentation (Herranen et al., 2021; Rahmawati et al., 2022). These models successfully transition students from passive knowledge reception to active roles as change agents (Rahmawati et al., 2022). Nevertheless, without better professional development for teachers, sustainability may remain an isolated, marginalized topic in chemistry curricula rather than a foundational competency (Stouthart et al., 2025).

The inclusion of cultural and epistemic pluralism provides a vital challenge to the Western-centric, anthropocentric worldviews that have dominated chemical discourse. Frameworks drawing on Indian Hindu philosophy or Confucian ecological ethics offer alternative narratives of interconnectedness and "care-based" morality (Paleri, 2025; Zidny & Eilks, 2020). These non-Western perspectives explicitly address the "epistemic violence" inherent in ignoring indigenous knowledge systems (Vermeylen, 2019). By integrating ethnochemistry and culturally responsive teaching, educators can empower students to act as moral agents within their specific cultural contexts (Rahmawati et al., 2023). This shift toward "agentised chemistry" views matter as an active participant in shaping the world, promoting a more symbiotic relationship between human innovation and the environment (Armstrong, 2024; Sovacool et al., 2017).

Green chemistry's institutionalization through policies like the European Green Deal reveals its dual nature as both a scientific movement and a socio-political strategy. While alignment with external regulatory and economic drivers has secured essential research funding, it presents a risk of terminology co-optation (Maxim, 2017; Mehlich, 2024). Maxim (2017) notes that "green" boundaries shift according to audience and funding availability, potentially diluting the original environmental intent. Genuine sustainability requires that chemists participate actively in policy discourses to ensure that progress is not sacrificed for corporate competitiveness (Maxim, 2017; Mehlich, 2024). Protecting the term "sustainable" from greenwashing necessitates a commitment to strong sustainability, where environmental limits are respected as absolute boundaries for all chemical and economic activity (Psillakis, 2025; Winterton, 2016).

The findings of this review suggest several practical and strategic directions. For professional chemists, it is imperative to integrate systems thinking and ethical expertise into daily laboratory practices to move beyond mere compliance with technical metrics. Educators should prioritize eco-reflexive didaktik models that encourage students to engage in scientific argumentation and value reflection, rather than rote memorization of principles. Industry leaders and human resource managers must foster organizational cultures that reward pro-environmental behavior and ethical transparency throughout the supply chain. Finally, policymakers should ensure that research funding is directed toward holistic "Safe and Sustainable by Design" frameworks that account for socio-economic externalities and respect the absolute ecological boundaries of the planet.

Several limitations must be acknowledged regarding this systematic review. First, the search was restricted to peer-reviewed journal articles, book chapters, and conference proceedings published in English, which may have excluded significant local studies on indigenous knowledge or non-Western chemical ethics published in other languages or formats. Second, the reliance on a narrative synthesis approach, while appropriate for the conceptual and interdisciplinary nature of the studies, introduces a degree of subjectivity in the coding of philosophical themes. Third, the date restriction to 2016–2025, while intended to capture recent developments, may overlook the foundational context of earlier philosophical debates. Fourth, although methodological and conceptual rigor was qualitatively appraised during data extraction, this appraisal was not reported as a distinct quality-stratified analysis in the Results or Discussion, limiting transparency regarding how individual study quality shaped the synthesis. Finally, the diverse disciplinary backgrounds of the included studies—ranging from bioethics to analytical chemistry—made comparisons across technical and theoretical methodologies difficult to standardize.

Future research should focus on developing actionable ethical frameworks that can be directly integrated into automated and AI-driven chemical research. There is also a significant need for longitudinal studies that evaluate whether "eco-reflexive" education actually translates into pro-environmental behavior among chemistry professionals. Scholars should further explore the intersection of green chemistry with energy justice and global health disparities, particularly in the Global South. Additionally, more research is needed to refine "strong sustainability" metrics that can quantify the impact of chemical processes on absolute planetary boundaries. Finally, expanding interdisciplinary collaborations between chemists and philosophers of science is essential to resolve unsettled ethical dilemmas in synthetic biology.

Conclusion

This systematic review demonstrates that the philosophy and ethics of green chemistry have evolved from a narrow focus on waste reduction toward a comprehensive, systems-based framework grounded in moral responsibility and global justice. The central contribution of this work is the identification of a disciplinary shift where technical metrics are no longer sufficient without the integration of eco-reflexive reasoning and epistemic pluralism. The take-home message for the scientific community is clear: genuine sustainability in chemistry requires more than incremental efficiency; it demands a fundamental rethinking of the chemist's role as a moral agent responsible for the entire life cycle of their innovations and their impact on the planet's absolute ecological boundaries.

Funding
The authors extend their appreciation to Prince Sattam bin Abdulaziz University for funding this research work through the project number (PSAU/2025/01/34544).

Acknowledgments
The authors extend their appreciation to Prince Sattam bin Abdulaziz University for funding this research work through the project number (PSAU/2025/01/34544).

Conflicts of Interest
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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