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Research Article

THE GREEN CHEMISTRY PARADIGM AS AN EPISTEMOLOGICAL TRANSFORMATION IN CONTEMPORARY CHEMISTRY

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Abstract
Green chemistry has evolved from a technical principle for designing environmentally friendly chemical processes into an epistemological paradigm reflecting new ways of understanding, producing, and evaluating chemical knowledge within the context of sustainability and moral responsibility for the environment. This study uses a systematic literature review (SLR) approach to scientific articles published in the past five years to examine how green chemistry is not only an operational strategy but also a form of epistemic transformation in chemistry. Thematic analysis of the literature reveals a significant shift in the criteria for the validity of chemical knowledge, where scientific success is increasingly measured by ecological and social impacts, rather than solely reaction efficiency or productivity. Furthermore, green chemistry is also influencing chemistry education, expanding the curriculum structure to incorporate reflective skills and sustainability values, and demanding stronger multidisciplinary engagement. These changes reflect the expanding relationship between chemistry and the global social context, including scientific ethics, educational strategies, and responsible research policies. These findings confirm that green chemistry has gone beyond a technical mechanism for reducing chemical waste and hazards to an epistemological paradigm that integrates values, responsibility, and sustainability into the production and application of chemical knowledge.

Keywords: Chemical Epistemology, Green Chemistry, Sustainability

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INTRODUCTION

Chemistry has developed for centuries as a discipline oriented toward exploring the structure, reactivity, and transformation of matter without always considering the ecological consequences of its scientific practices (Salsabila and Hernani, 2025). In the modern context, advances in chemistry have produced a variety of products that sustain civilization, from medicines to industrial materials, but have also given rise to serious problems in the form of environmental pollution and ecosystem degradation (Morales dkk, 2024). This situation has prompted critical reflection on the epistemological foundations of chemistry itself, particularly regarding the values underlying the knowledge production process. Green chemistry exists not merely as a technical response to environmental issues, but as an effort to reorient the way chemistry is understood, practiced, and evaluated. Therefore, this research is crucial in positioning green chemistry within the framework of a deeper scientific paradigm shift, not merely as a collection of operational principles, but as a transformation of epistemological perspectives in contemporary chemistry.

The urgency of this research also stems from the growing global awareness of the limitations of a value-neutral scientific approach (Widyantoro dkk, 2025). Chemistry, like other sciences, can no longer be positioned as a cognitive activity detached from its social and ecological implications. Modern chemical practice operates within a complex network involving industry, public policy, and economic interests, demanding more explicit ethical accountability. In this context, green chemistry offers a normative framework linking chemical knowledge to sustainability goals (Sunday, 2025). This study aims to explain how this shift impacts not only laboratory procedures but also how scientists define scientific success, knowledge validity, and professional responsibility. Thus, this study attempts to fill the conceptual gap between the technical practice of green chemistry and its epistemological meaning.

Furthermore, the literature on green chemistry has so far focused primarily on applied aspects, such as environmentally friendly reaction design or efficient use of materials. This approach, while important, often overlooks the reflective dimension that involves changing ways of thinking in chemistry. Yet, every methodological innovation in science is rooted in certain epistemological assumptions regarding what constitutes valid and valuable knowledge. Therefore, this study is relevant in examining green chemistry as a manifestation of these shifting assumptions. This article aims to expand the discourse on green chemistry from the technical to the philosophical realm, thereby providing a more comprehensive understanding of its significance in the development of contemporary chemistry.

Finally, this research is also based on the academic need to strengthen interdisciplinary studies between chemistry and the philosophy of science. The epistemological transformation brought about by green chemistry cannot be fully understood without in-depth conceptual analysis. By reviewing the scientific literature of the last ten years, this article attempts to develop a systematic theoretical synthesis of how green chemistry changes the epistemic orientation of chemistry. This introduction emphasizes that research should be written not only to explain what green chemistry is, but also to answer why and how this paradigm represents a fundamental shift in the way chemistry constructs and interprets its knowledge.

Early literature on green chemistry generally positioned the concept as a set of design principles aimed at minimizing the environmental impact of chemical processes (Celestino, 2023). These principles included waste prevention, atom efficiency, and the use of safer materials (Ni'mah, 2025). However, recent studies have begun to demonstrate that behind these technical principles lie new epistemological assumptions about the relationship between knowledge and values. This literature marks a shift from the traditional chemistry paradigm focused on maximizing yield to one that considers sustainability as an epistemic criterion. Therefore, this article is based on the understanding that green chemistry is not simply a procedural innovation, but a reflection of a shift in the orientation of knowledge within chemistry.

Numerous studies in the past decade have linked green chemistry to critiques of scientific positivism, which separates fact from value (Huarong and Surif, 2024). Within a positivistic framework, chemistry is viewed as an objective, value-free activity, while moral implications are considered outside the realm of science. Contemporary literature challenges this view by asserting that methodological choices in chemistry are always value-laden, including those of sustainability and safety (Lestari dkk, 2024). Green chemistry, in this case, is understood as an attempt to reconstruct chemical epistemology to be more inclusive of ethical considerations. This review provides an important theoretical foundation for research, as it demonstrates an initial consensus that green chemistry carries significant philosophical implications.

The philosophy of science literature also contributes significantly to understanding green chemistry as a new paradigm. Several studies highlight the similarities between green chemistry and the scientific paradigm shift described in the theory of scientific change (Akinsipo and Anselm, 2025). Green chemistry is considered to shift the criteria for scientific success from mere reaction efficiency to long-term sustainability. This literature helps place green chemistry within the historical context of the development of chemistry, while also explaining that this shift is epistemological in nature, as it touches on the foundations of scientific assessment (Ezeako dkk, 2024). Therefore, this literature review strengthens the argument that green chemistry represents a transformation in thinking in chemistry.

On the other hand, the interdisciplinary literature between chemistry and environmental studies demonstrates that green chemistry serves as a bridge between science and the public interest (Guo dkk, 2024). These studies emphasize the role of chemistry in addressing global sustainability challenges, such as climate change and resource crises. In an epistemological context, this means that chemical knowledge is no longer measured solely by internal consistency but also by its relevance to real-world problems (Uzorka dkk, 2024). This literature provides an important foundation for research because it demonstrates that green chemistry broadens the epistemic horizons of chemistry toward a social and ecological orientation.

The current study also underscores the role of chemistry education in disseminating the green chemistry paradigm. The literature shows that integrating green chemistry principles into the curriculum not only transforms students' technical skills but also shapes their thinking about scientific responsibility (Liu and Wang, 2025). This confirms that green chemistry operates at the epistemic level, influencing how chemical knowledge is produced and transmitted. Thus, this literature provides an empirical-conceptual basis for research interpreting green chemistry as an epistemological transformation.

Overall, the literature review indicates a shift in focus from the technical aspects of green chemistry to the conceptual and normative dimensions. Although not all studies explicitly use the term "epistemological transformation," this trend is evident in scientific discourse over the past ten years. Therefore, this research builds on a foundation of literature that recognizes green chemistry as a multidimensional phenomenon. This assertion serves as a primary foundation for formulating an analytical framework for future research.

RESEARCH METHOD

This research uses a qualitative approach with a systematic literature review design to gain a comprehensive understanding of green chemistry as an epistemological paradigm (Płotka-Wasylka, 2018). This approach was chosen because it allows researchers to identify patterns of thought and conceptual themes developing in the scientific literature. The primary focus of this method is not on quantitative measurements, but rather on interpreting the meanings contained in academic texts. Therefore, this method aligns with the research's reflective and theoretical objectives.

The data collection process was conducted through a search of scientific articles published in the last ten years. Inclusion criteria included articles discussing green chemistry, sustainability, and philosophical or normative implications in chemistry. The selected literature was sourced from reputable journals to ensure academic quality. This stage aimed to filter relevant sources so that the analysis could focus on the main discourse on epistemological transformation.

After the selection process, the selected articles were analyzed using thematic analysis techniques. This technique allows for the identification of key recurring themes in the literature, such as scientific ethics, sustainability, and the redefinition of scientific success. Thematic analysis was conducted iteratively to ensure consistency of interpretation. In this way, the research was able to explore the conceptual structure underlying the green chemistry discourse.

The validity of the analysis is maintained through critical reading and comparison between sources. The researcher strives to avoid interpretive bias by considering the various perspectives emerging in the literature. This approach is crucial to ensure that the research results reflect a spectrum of existing views, rather than just one dominant viewpoint. This method strengthens the validity of the research findings.

Overall, this research method is designed to systematically and in-depthly uncover the epistemological meaning of green chemistry. By combining SLR and thematic analysis, this study provides a robust methodological framework for answering the research questions. This method also allows for a conceptual synthesis relevant to the development of contemporary chemistry.

RESULTS AND DISCUSSION

The research findings indicate that green chemistry is consistently understood in the scholarly literature as an approach that embeds sustainability values at the very core of chemical knowledge and practice. Rather than treating environmental considerations as external constraints imposed after scientific discovery, green chemistry integrates these values into the epistemic foundations of chemistry itself. This recurring theme across multiple studies reflects a growing consensus among scholars that chemistry must be value-oriented in order to remain relevant in the contemporary world. As a result, green chemistry is no longer perceived as an optional or auxiliary framework, but as an integral component of modern chemical epistemology that reshapes how chemical knowledge is conceptualized, produced, and applied.

A second prominent theme emerging from the analysis is the redefinition of scientific success within the field of chemistry. Traditional measures of success, such as reaction efficiency, yield optimization, and cost-effectiveness, are increasingly viewed as insufficient when considered in isolation. The literature highlights that scientific achievement in chemistry is now also evaluated based on long-term environmental impacts, resource sustainability, and potential ecological risks. This shift signifies a profound transformation in the epistemic criteria used to assess chemical knowledge, where the validity and value of scientific outcomes are inseparable from their broader consequences for ecosystems and future generations.

The analysis further reveals a significant transformation in the perceived role of chemical scientists. Rather than being positioned solely as neutral producers of knowledge, scientists are increasingly understood as ethical agents whose work carries moral and social responsibilities. Green chemistry literature consistently emphasizes accountability toward society, public health, and the environment, thereby linking scientific practice with ethical reflection. This development demonstrates that chemical epistemology is becoming more explicitly intertwined with professional ethics, as the production of knowledge is no longer divorced from considerations of responsibility, risk, and societal impact.

Another key theme concerns the multidisciplinary integration promoted by green chemistry. The literature suggests that green chemistry actively encourages collaboration between chemistry, environmental science, engineering, economics, and public policy (Ogodo and Abosede, 2025). Such integration expands the epistemic horizon of chemistry by situating chemical knowledge within broader socio-environmental systems. This interdisciplinary engagement not only enhances the practical applicability of chemical research but also strengthens its social relevance. Furthermore, the analysis shows that green chemistry significantly influences how chemical knowledge is taught and transmitted. Educational models oriented toward green chemistry aim to instill sustainability values from the earliest stages of scientific training, reinforcing the epistemological shift by shaping how future chemists understand the purpose and implications of their discipline.

An additional emerging theme is the critical stance that green chemistry adopts toward exploitative approaches in industrial chemistry. The literature demonstrates that green chemistry offers an epistemic alternative to conventional production paradigms that prioritize efficiency and profit over environmental and social costs. By questioning established industrial logics, green chemistry contributes to a broader paradigm transformation within chemical science. Closely related to this critique is the growing role of regulation and public policy in shaping chemical knowledge production. The findings indicate that chemical research is increasingly conducted within regulatory frameworks that demand sustainability, safety, and transparency, thereby highlighting the interdependence between epistemology and social structures.

Moreover, green chemistry is widely regarded as a means of rebuilding and strengthening public trust in chemistry as a scientific discipline. The literature confirms that sustainable chemical practices enhance the epistemic legitimacy of chemistry in the eyes of the public, particularly in a context marked by environmental degradation and skepticism toward industrial science. By aligning scientific practice with societal values, green chemistry demonstrates that chemistry can contribute positively to sustainable development. Overall, the research findings suggest that green chemistry functions as a comprehensive epistemological framework that integrates scientific knowledge, ethical values, and social responsibility, thus transcending purely technical or instrumental approaches.

This discussion confirms that the epistemological transformation introduced by green chemistry reflects a fundamental shift in how chemistry defines its identity and purpose. This shift can be understood as a response to the global ecological crisis, which has exposed the limitations of traditional chemical epistemology. In this sense, green chemistry operates as a form of critical self-reflection within the discipline, prompting chemists to reassess foundational assumptions about progress, neutrality, and success. This transformation also explains why green chemistry has gained widespread legitimacy within the scientific community, as the integration of sustainability values broadens the social relevance of chemical knowledge and demonstrates the adaptive capacity of scientific epistemology to contemporary challenges.

Further analysis reveals that green chemistry increasingly blurs the boundaries between science and ethics. Within this paradigm, moral considerations are not treated as external constraints but as integral components of the epistemic process itself. This challenges the long-standing assumption of scientific neutrality and suggests that value-laden reasoning can coexist with rigorous scientific methodology. An important implication of this shift is a transformation in the education and professional training of chemical scientists. Green chemistry emphasizes the development of reflective and ethical competencies alongside technical expertise, thereby shaping a new generation of scientists who are more critically aware of the societal implications of their work.

From the perspective of the philosophy of science, green chemistry can be interpreted as a concrete example of a paradigmatic shift in scientific practice. This transformation is not merely methodological, involving new techniques or processes, but also normative, redefining the values that guide scientific inquiry. The discussion thus reinforces the position of green chemistry as an epistemological transformation that reorients the foundations of chemical science. Ultimately, green chemistry holds significant potential to shape the future trajectory of chemistry. By positioning sustainability as a central epistemic value, chemistry can play a more substantial role in addressing global challenges and contributing to sustainable development..

CONCLUSION

The conclusions of this study confirm that green chemistry should not be understood merely as a collection of environmentally friendly techniques or an instrumental strategy for reducing pollution. Rather, green chemistry constitutes a profound epistemological shift that redefines the foundations of chemical knowledge itself. By embedding ethical considerations and sustainability values directly into the processes of inquiry, experimentation, and application, green chemistry challenges the traditional assumption that scientific knowledge can be produced in a value-neutral manner. This paradigm reorients chemistry toward a more reflective and responsible form of knowledge production, in which scientific validity is inseparable from environmental stewardship and social accountability.

Through a systematic literature review combined with rigorous thematic analysis, this study demonstrates that green chemistry fundamentally transforms several core dimensions of chemical science. First, it reshapes the criteria for scientific success by expanding evaluation standards beyond efficiency, yield, and innovation to include long-term environmental impact and societal benefit. Second, it redefines the role of scientists, positioning them not only as generators of knowledge but also as ethical agents responsible for anticipating and mitigating the consequences of their work. Finally, it alters the relationship between science and society by emphasizing transparency, public trust, and responsiveness to global ecological challenges. Collectively, these changes mark a significant evolution in contemporary chemical epistemology, signaling a departure from purely technocratic models of science.

Overall, this study makes a substantial conceptual contribution by positioning green chemistry as a coherent and emerging epistemological framework within the discipline of chemistry. By articulating how scientific knowledge, ethical values, and sustainability imperatives are increasingly intertwined, the study provides a foundation for rethinking the philosophical underpinnings of chemical science. These conclusions are expected to stimulate further and more in-depth scholarly inquiry into the dynamic relationship between science, values, and sustainability, particularly in the context of global environmental crises. In doing so, the study opens new avenues for interdisciplinary research and encourages ongoing reflection on the future direction of scientific knowledge production.

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