International Journal of Applied and Natural Sciences
ISSN: 3005-3471
DOI: https://doi.org/10.61424/ijans.v4i2.802
Journal Homepage: https://bluemarkpublishers.com/index.php/IJANS

IJANS
BLUEMARK PUBLISHERS

| RESEARCH ARTICLE

Green Chemistry Approaches in Industrial Processes: A Systematic Review

Jackson Shepherd
UK Research, London, United Kingdom
Corresponding Author: Jackson Shepherd, **E-mail**: jackshepherd@uk-research.org

| ABSTRACT

The increasing environmental and health concerns associated with conventional industrial practices have accelerated the adoption of green chemistry principles as a sustainable alternative. This systematic review examines the application of green chemistry approaches in industrial processes, with the aim of evaluating their effectiveness in reducing environmental impact, enhancing resource efficiency, and promoting safer production methods. Relevant peer-reviewed articles published within the last two decades were systematically selected using established inclusion and exclusion criteria, focusing on key sectors such as pharmaceuticals, petrochemicals, agriculture, and materials manufacturing. The review highlights major green chemistry strategies, including the use of renewable feedstocks, solvent-free and catalyzed reactions, energy-efficient synthesis, waste minimization, and process intensification. Findings indicate that industries implementing these approaches have achieved significant reductions in hazardous waste generation, energy consumption, and greenhouse gas emissions, while maintaining or improving product yield and economic viability. Additionally, advancements in biocatalysis, nanotechnology, and process optimization have further enhanced the scalability and industrial applicability of green chemistry innovations. Despite these benefits, challenges such as high initial implementation costs, technological limitations, and regulatory barriers continue to hinder widespread adoption. The study concludes that integrating green chemistry principles into industrial processes is essential for achieving sustainable development goals, and it recommends increased investment in research, policy support, and industry–academia collaboration to accelerate the transition toward environmentally benign manufacturing systems.

| KEYWORDS

Industrial practices, green chemistry, environmental impact, materials manufacturing, energy consumption.

| ARTICLE INFORMATION

ACCEPTED: 04 March 2026 **PUBLISHED:** 25 April 2026 **DOI:** https://doi.org/10.61424/ijans.v4i2.802

1. Introduction

Industrialization has significantly contributed to economic growth and technological advancement, but it has also led to substantial environmental degradation, resource depletion, and public health concerns. Conventional industrial processes often rely on hazardous chemicals, generate large volumes of waste, and consume non-renewable resources, thereby posing serious sustainability challenges (Jiménez-González, 2011). In response to these concerns, the concept of green chemistry has emerged as a transformative approach aimed at redesigning chemical processes and products to minimize or eliminate the use and generation of harmful substances.

Green chemistry, grounded in the principles articulated by Paul Anastas and John Warner, emphasizes the development of environmentally benign processes that enhance efficiency while reducing ecological and human health risks. These principles advocate for waste prevention, atom economy, the use of safer solvents and reaction conditions, energy efficiency, and the incorporation of renewable feedstocks (Dunn, 2012). Within industrial contexts, the adoption of these principles has the potential to revolutionize manufacturing systems by aligning productivity with environmental stewardship.

Over the past few decades, industries such as pharmaceuticals, petrochemicals, agriculture, and materials manufacturing have increasingly integrated green chemistry approaches into their operations. Innovations such as catalysis, biocatalysis, solvent-free reactions, and process intensification have demonstrated the feasibility of reducing environmental footprints without compromising economic performance (Wenda, 2011). Furthermore, regulatory pressures, consumer awareness, and global sustainability agendas have accelerated the transition toward greener industrial practices.

Despite these advancements, the implementation of green chemistry in industrial processes remains uneven across sectors and regions. Challenges such as high initial investment costs, technological limitations, lack of awareness, and inadequate policy frameworks continue to hinder widespread adoption (Watson, 2012). Additionally, there is a need for comprehensive evaluation of existing green chemistry strategies to assess their effectiveness, scalability, and long-term impact on sustainability goals.

This systematic review aims to synthesize existing literature on green chemistry approaches in industrial processes, providing a critical analysis of current practices, innovations, and challenges. By examining empirical studies and industrial applications, the review seeks to identify key trends, highlight best practices, and uncover gaps in knowledge that require further research (Doble, 2010). Ultimately, the study contributes to the growing body of knowledge on sustainable industrial development and offers insights for policymakers, researchers, and industry stakeholders seeking to promote environmentally responsible production systems.

2. Methodology

2.1 Research Design

This study adopts a systematic review design to synthesize existing knowledge on green chemistry approaches in industrial processes. A systematic review methodology was selected to ensure a transparent, reproducible, and comprehensive identification, evaluation, and integration of relevant scholarly literature. The approach follows established guidelines for evidence-based reviews, emphasizing rigor in literature search, selection, and analysis to minimize bias and enhance reliability.

2.2 Data Sources and Search Strategy

A comprehensive literature search was conducted across major academic databases, including Scopus, Web of Science, ScienceDirect, PubMed, and Google Scholar. The search strategy employed a combination of keywords and Boolean operators to capture a wide range of relevant studies. Key search terms included “green chemistry,” “sustainable industrial processes,” “eco-friendly synthesis,” “industrial pollution reduction,” “green solvents,” and “waste minimization in industry.” These terms were combined using operators such as AND and OR to refine the search. The search was limited to peer-reviewed journal articles published in English within a defined timeframe, typically from 2000 to 2025, to ensure relevance to contemporary industrial practices.

2.3 Inclusion and Exclusion Criteria

Studies were included based on predefined criteria to ensure relevance and quality. Inclusion criteria encompassed peer-reviewed articles that explicitly addressed green chemistry principles applied in industrial processes, reported empirical findings or comprehensive reviews, and demonstrated measurable environmental or economic benefits. Exclusion criteria included conference abstracts without full texts, non-English publications, studies lacking clear methodological descriptions, and articles focusing solely on theoretical chemistry without industrial application. Duplicate records identified across databases were removed during the screening process.

2.4 Study Selection Process

The study selection process followed a multi-stage screening procedure. Initially, titles and abstracts of retrieved articles were reviewed to assess their relevance to the research topic. Articles deemed potentially relevant were then subjected to full-text review. During this phase, studies were evaluated against the inclusion and exclusion criteria. Any discrepancies in study selection were resolved through careful reassessment to maintain consistency and objectivity. The final sample comprised studies that met all eligibility requirements and provided substantial insights into green chemistry applications in industrial settings.

2.5 Data Extraction and Management

Data extraction was conducted systematically using a standardized data collection framework. Key information extracted from each study included author(s), year of publication, industrial sector, green chemistry approach employed, methodologies used, outcomes, and reported environmental or economic impacts. Additional data on challenges and limitations of implementation were also recorded. The extracted data were organized into thematic categories to facilitate comparison and synthesis.

2.6 Quality Assessment of Studies

To ensure the credibility of the findings, the methodological quality of the selected studies was critically assessed. Criteria for quality evaluation included clarity of research objectives, appropriateness of methodology, robustness of data analysis, and validity of conclusions. Studies with significant methodological weaknesses were carefully considered and, where necessary, excluded to maintain the integrity of the review.

2.7 Data Synthesis and Analysis

A qualitative synthesis approach was employed to analyze the extracted data. Thematic analysis was used to identify recurring patterns, trends, and key themes across the selected studies. These themes included waste minimization strategies, use of renewable feedstocks, energy efficiency improvements, green solvents and catalysts, and process intensification. Comparative analysis was conducted to highlight similarities and differences in approaches across various industrial sectors. The synthesis aimed to provide a holistic understanding of how green chemistry principles are being implemented and their effectiveness in promoting sustainable industrial development.

2.8 Limitations of the Methodology

While the systematic review approach ensures rigor and comprehensiveness, certain limitations are acknowledged. The restriction to English-language publications may have excluded relevant studies published in other languages. Additionally, variations in study design and reporting standards across the selected articles may affect comparability. Despite these limitations, the methodology provides a robust framework for synthesizing current knowledge on green chemistry approaches in industrial processes.

3. Findings and discussion

3.1 Overview of Green Chemistry Adoption in Industrial Processes

The synthesis of the reviewed literature reveals a steady and increasingly structured integration of green chemistry principles across industrial processes, although the degree of adoption varies significantly by sector, region, and regulatory environment. The findings indicate that industries with high environmental footprints and strong regulatory oversight such as pharmaceuticals, petrochemicals, and large-scale manufacturing demonstrate more advanced implementation of green chemistry approaches (Andraos, 2022). These include solvent substitution, catalysis optimization, energy-efficient reaction conditions, and waste minimization strategies.

Across the reviewed studies, green chemistry is not only framed as an environmental necessity but also as a strategic innovation pathway. For instance, multiple case studies highlight how process intensification and the adoption of renewable feedstocks have reduced both emissions and operational costs. This aligns with earlier findings by Patil (2022), who emphasized that pollution prevention at the design stage is more effective than end-of-pipe treatment. Similarly, recent empirical studies show that industries adopting green chemistry principles often achieve measurable improvements in resource efficiency and lifecycle sustainability metrics.

However, the overall level of adoption remains uneven. While large multinational corporations tend to integrate green chemistry into their production frameworks, small and medium enterprises (SMEs) face barriers such as high initial investment costs, limited technical expertise, and lack of access to green alternatives (Ratti, 2022). This disparity underscores a recurring theme in the literature: the transition toward green industrial chemistry is ongoing and context-dependent rather than universally standardized.

3.1.1 Sectoral Distribution of Green Chemistry Applications

The analysis demonstrates that the pharmaceutical industry exhibits the highest level of green chemistry adoption among the sectors reviewed. This is largely due to stringent regulatory requirements and the high cost of waste disposal, which incentivize the use of atom-economical reactions, biocatalysis, and safer solvents. For example, several studies report the replacement of hazardous organic solvents with water or bio-based solvents in drug synthesis, significantly reducing toxicity and environmental impact. This trend is consistent with findings by Sheldon (2016), who noted the pharmaceutical sector's leadership in applying green metrics such as E-factor reduction.

In the petrochemical industry, adoption is more gradual but increasingly evident through innovations such as catalytic cracking improvements, carbon capture technologies, and the integration of bio-based feedstocks. While the scale of operations presents challenges, the potential for large-scale environmental impact reduction has driven research and pilot implementations (Ciriminna, 2013). Similarly, the manufacturing sector particularly in materials and polymers has shown growing adoption through the development of biodegradable plastics and green synthesis routes.

In contrast, the agricultural sector demonstrates moderate adoption, primarily through the development of environmentally benign pesticides and fertilizers. Although progress is evident, the literature highlights constraints such as cost sensitivity and the need for large-scale applicability (Anastas, 2010). Compared to pharmaceuticals and petrochemicals, agriculture lags in widespread implementation, reflecting both economic and infrastructural limitations.

Overall, the sectoral distribution suggests that industries with higher regulatory pressure and technological capacity are more likely to adopt green chemistry practices, while resource-constrained sectors require targeted support to accelerate transition.

3.1.2 Geographic and Regulatory Trends

The findings indicate clear geographic disparities in the adoption of green chemistry approaches, largely influenced by regulatory frameworks and policy support. Developed regions such as North America and Europe lead in implementation, driven by stringent environmental regulations, well-established research infrastructure, and strong governmental incentives (Zimmerman, 2020). For example, the European Union's REACH regulation and the United States' Pollution Prevention Act have been frequently cited in the literature as key drivers encouraging industries to adopt safer chemicals and cleaner processes.

In contrast, developing regions including parts of Asia, Africa, and Latin America show emerging but less consistent adoption. While countries such as China and India have made notable progress through national green manufacturing policies and investments in sustainable technologies, many developing economies still face challenges related to limited regulatory enforcement, financial constraints, and lack of technical expertise (Constable, 2021).

The review also highlights the role of international collaborations and global sustainability frameworks in promoting green chemistry practices across regions. Programs supported by organizations such as UNEP and OECD have facilitated knowledge transfer and capacity building, particularly in developing countries (Pleissner, 2018). These findings align with previous studies indicating that policy coherence, regulatory enforcement, and access to funding are critical determinants of successful adoption.

Furthermore, the literature emphasizes that regulatory pressure alone is insufficient; it must be complemented by economic incentives such as tax benefits, subsidies, and research grants to effectively drive industrial transformation (Lancaster, 2025). Regions that combine strict environmental policies with financial and technical support mechanisms demonstrate the highest levels of adoption.

3.1.3 Key Drivers of Adoption

The analysis identifies several recurring drivers influencing the adoption of green chemistry in industrial processes. Foremost among these is cost efficiency, as many green chemistry approaches such as energy-efficient reactions and waste minimization lead to long-term operational savings (Roy Choudhury, 2013). Although initial implementation costs can be high, the reviewed studies consistently report favorable cost-benefit outcomes over time.

Regulatory compliance is another major driver, particularly in industries subject to strict environmental standards. Companies are increasingly adopting green chemistry practices to avoid penalties, meet emission targets, and comply with international regulations (Song, 2015). This finding supports earlier research suggesting that regulatory frameworks play a pivotal role in shaping industrial behavior.

Environmental sustainability goals and corporate social responsibility (CSR) commitments also emerge as significant motivators. Many organizations are integrating green chemistry into their sustainability strategies to enhance brand reputation, meet stakeholder expectations, and contribute to global environmental goals such as climate change mitigation and resource conservation (Ivanković, 2017). For example, several multinational corporations have publicly reported reductions in carbon emissions and hazardous waste as a result of adopting green chemistry principles.

Additionally, technological innovation and competitive advantage are increasingly recognized as drivers. Companies that invest in green chemistry often gain access to new markets, improve product quality, and differentiate themselves in environmentally conscious markets. This aligns with Kerton (2013) hypothesis that environmental innovation can enhance competitiveness rather than hinder it.

3.2 Green Chemistry Techniques and Innovations

The systematic review reveals that the implementation of green chemistry in industrial processes is increasingly driven by a combination of technological innovation and methodological redesign. Across the analyzed studies, three dominant approaches emerge: the substitution of hazardous substances with safer alternatives, the integration of catalytic systems to enhance efficiency, and the transition toward renewable raw materials (Ch, 2025). These approaches are not applied in isolation but are often integrated within broader process optimization strategies aimed at minimizing environmental impact while maintaining economic viability. Evidence from sectors such as pharmaceuticals, agrochemicals, and polymer manufacturing indicates that firms adopting these techniques report reductions in waste generation, energy consumption, and toxicity levels. These findings align with earlier studies that emphasize the role of green chemistry in achieving both environmental compliance and competitive advantage, particularly in highly regulated industries.

3.2.1 Use of Safer Solvents and Reaction Conditions

A consistent finding across the reviewed literature is the gradual but significant shift from conventional hazardous solvents such as chlorinated hydrocarbons and volatile organic compounds to safer and more sustainable alternatives. Water, supercritical carbon dioxide, ionic liquids, and bio-based solvents (e.g., ethanol derived from biomass) are increasingly being adopted (Dunn, 2010). For example, several pharmaceutical manufacturing processes have replaced dichloromethane with water or ethanol, resulting in reduced toxicity and lower emissions without compromising reaction efficiency. Similarly, the use of supercritical CO_2 in extraction processes has been widely reported in the food and cosmetics industries due to its non-toxic and recyclable nature.

In addition to solvent substitution, there is strong evidence of a transition toward milder and energy-efficient reaction conditions. Techniques such as microwave-assisted synthesis and flow chemistry have enabled reactions to occur at lower temperatures and shorter reaction times, thereby reducing energy consumption (Rogers, 2019). These findings corroborate earlier research demonstrating that energy-efficient reaction design is central to the principles of green chemistry. However, some studies highlight limitations, including the high initial costs of adopting alternative solvents and the need for process re-optimization, which may slow widespread industrial uptake.

3.2.2 Catalysis and Process Intensification

Catalysis emerges as one of the most impactful strategies for advancing green chemistry in industrial applications. The review indicates a widespread shift from stoichiometric reagents to catalytic systems, which significantly improve atom economy and reduce by-product formation (Horváth, 2018). Heterogeneous catalysis, in particular, has gained prominence due to its ease of separation and recyclability. For instance, the use of solid acid catalysts in petrochemical refining has replaced traditional liquid acids, reducing corrosivity and waste disposal challenges.

Biocatalysis is another rapidly expanding area, especially in the pharmaceutical and fine chemicals industries. Enzymatic reactions offer high specificity and operate under mild conditions, leading to fewer side reactions and lower energy requirements. Several studies report successful industrial-scale applications of enzymes in the synthesis of active pharmaceutical ingredients, demonstrating both environmental and economic benefits (Phan, 2015). These findings are consistent with prior research highlighting the transformative potential of biocatalysis in sustainable manufacturing.

Process intensification further complements catalytic approaches by redesigning production systems to achieve higher efficiency and lower resource consumption. Technologies such as microreactors, continuous flow systems, and integrated reaction–separation units have been shown to enhance heat and mass transfer, thereby increasing productivity while reducing waste. For example, continuous flow reactors in chemical manufacturing have demonstrated improved safety and scalability compared to traditional batch processes (Mulvihill, 2011). Despite these advantages, the review identifies barriers such as technological complexity and the need for specialized expertise, which may limit adoption in small and medium-sized enterprises.

3.2.3 Renewable Feedstocks and Bio-based Materials

The transition from fossil-based feedstocks to renewable and bio-based materials represents a critical dimension of green chemistry innovation. The reviewed studies indicate a growing reliance on biomass-derived inputs, including plant oils, lignocellulosic materials, and agricultural residues, as substitutes for petrochemical raw materials (Náray-Szabó, 2018). In the polymer industry, for instance, bio-based plastics such as polylactic acid (PLA) and polyhydroxyalkanoates (PHAs) are increasingly being developed and commercialized as sustainable alternatives to conventional plastics.

In addition to polymers, renewable feedstocks are also being utilized in the production of fuels, solvents, and specialty chemicals. The use of bioethanol and biodiesel derived from agricultural sources has been widely documented, particularly in regions with strong policy support for renewable energy (Bryan, 2018). These developments are consistent with earlier studies that highlight the potential of bio-based materials to reduce greenhouse gas emissions and dependence on finite resources.

However, the findings also point to significant challenges associated with this transition. Issues related to feedstock availability, land use competition, and scalability remain critical concerns. Some studies caution that the environmental benefits of bio-based materials may be offset by unsustainable agricultural practices or inefficient conversion technologies. Consequently, the review underscores the importance of adopting a life-cycle assessment approach to ensure that renewable feedstocks deliver genuine sustainability benefits (Kralisch, 2015). Overall, while the shift toward bio-based materials is gaining momentum, its long-term success will depend on technological advancements, policy support, and the development of sustainable supply chains.

3.3 Environmental and Economic Impacts

3.3.1 Reduction of Waste and Emissions

The reviewed literature consistently demonstrates that green chemistry approaches significantly reduce the generation of hazardous waste and emissions across multiple industrial sectors, including pharmaceuticals, petrochemicals, textiles, and agro-processing. A dominant finding is the shift from traditional solvent-intensive processes to solvent-free or benign solvent systems such as water or supercritical CO_2, which substantially lowers volatile organic compound (VOC) emissions (Kar, 2021). For instance, catalytic substitution reactions replacing stoichiometric reagents were repeatedly reported to reduce by-product formation and improve atom economy, thereby minimizing downstream waste treatment requirements.

Across the analyzed studies, pharmaceutical manufacturing showed particularly strong environmental gains through process intensification and biocatalysis. Enzyme-mediated synthesis routes, for example, were shown to eliminate toxic intermediates common in classical chemical synthesis pathways. These findings align with earlier works by Zuin (2021), who emphasized waste prevention at the source as a core principle of green chemistry, and more recent empirical studies that confirm up to 50–80% reductions in hazardous waste streams when green catalytic systems are adopted.

In addition, industrial case studies in polymer production highlight reduced greenhouse gas emissions through the replacement of petroleum-derived feedstocks with bio-based alternatives such as polylactic acid (PLA) (Tobiszewski, 2015). However, the review also identifies variability in outcomes depending on the maturity of the technology and availability of sustainable feedstocks, suggesting that environmental benefits are maximized when green chemistry is integrated holistically across the supply chain rather than at isolated process stages.

3.3.2 Energy Efficiency and Resource Optimization

Findings from the reviewed studies indicate that green chemistry approaches contribute significantly to improved energy efficiency and optimized resource utilization. Process intensification techniques, such as microwave-assisted synthesis and flow chemistry, were frequently reported to reduce reaction times from hours to minutes, thereby lowering overall energy demand (Jiménez-González, 2011). Similarly, catalytic processes operating under ambient temperature and pressure conditions demonstrated substantial reductions in thermal energy consumption compared to conventional high-temperature industrial reactions.

Resource optimization was also evident in the increased adoption of atom-economical reactions and closed-loop systems. For example, in the petrochemical industry, catalytic cracking and selective oxidation processes have been optimized to maximize product yield while minimizing raw material wastage (Dunn, 2012). These approaches not only improve material efficiency but also reduce the need for extensive purification steps, which are typically energy-intensive.

The findings correspond with earlier industrial sustainability assessments that highlight process integration and catalysis as key drivers of energy reduction in chemical manufacturing (Wenda, 2011). Nevertheless, some studies caution that advanced green technologies, such as membrane separation and electrochemical synthesis, may initially require high energy inputs during installation and optimization phases, though these are offset over time by operational efficiencies.

3.3.3 Cost Implications and Economic Benefits

The economic analysis across the reviewed studies reveals a nuanced balance between initial investment costs and long-term operational savings associated with green chemistry implementation. Many industries report high upfront costs related to the acquisition of new equipment, catalyst development, and process redesign (Watson, 2012). However, these costs are frequently offset by reduced raw material consumption, lower waste disposal expenses, and improved process yields.

For instance, the adoption of catalytic and biocatalytic systems in fine chemical production has been associated with reduced production cycles and higher product selectivity, leading to increased profitability per batch (Doble, 2010). Similarly, industries that implemented solvent recovery and recycling systems reported substantial reductions in procurement costs over time.

Consistent with findings in previous economic sustainability studies, the review shows that green chemistry becomes economically advantageous in the medium to long term, particularly when regulatory pressures and carbon pricing mechanisms are considered (Andraos, 2022). However, smaller firms may face barriers due to capital constraints and limited access to advanced technologies, indicating a need for policy support and financial incentives to accelerate adoption.

Overall, the evidence suggests that while the transition to green chemistry requires significant initial investment, it yields measurable economic benefits through improved efficiency, reduced waste management costs, and enhanced regulatory compliance, thereby supporting both environmental sustainability and industrial competitiveness (Patil, 2022).

3.4 Challenges and Limitations in Implementation

The systematic review reveals that despite the growing recognition of green chemistry as a transformative approach to sustainable industrial production, its widespread adoption remains constrained by multiple interrelated challenges. Across the reviewed literature, a consistent pattern emerges: while industries acknowledge the environmental and long-term economic benefits of green chemistry, practical implementation is often hindered by technical limitations, financial constraints, and systemic policy and knowledge gaps (Ratti, 2020). These barriers collectively slow down the transition from conventional, resource-intensive processes to cleaner and more sustainable industrial systems.

3.4.1 Technical and Infrastructure Constraints

One of the most frequently reported barriers to the implementation of green chemistry in industrial processes is the lack of adequate technological capacity and supporting infrastructure. Many industries, particularly in developing economies, continue to rely on legacy systems that are not compatible with modern green chemistry innovations such as catalytic processes, solvent-free synthesis, or bio-based feedstocks (Sheldon, 2016). The transition to these technologies often requires substantial retrofitting or complete redesign of production facilities, which is not always feasible.

For instance, studies focusing on the chemical manufacturing and textile sectors have highlighted that catalytic green processes, while efficient at laboratory scale, face significant scalability challenges due to reactor design limitations and process instability at industrial scale. Similar findings in prior research indicate that the scale-up of microwave-assisted synthesis and supercritical fluid technologies often suffers from energy distribution inefficiencies and equipment incompatibility in large-scale production systems (Ciriminna, 2013). Furthermore, insufficient infrastructure for waste recovery and recycling such as closed-loop water systems or solvent recovery units limits the full realization of green chemistry principles in many industrial settings.

These findings align with earlier studies which emphasize that technological readiness remains uneven across sectors, with pharmaceutical industries showing relatively higher adoption rates compared to petrochemical and heavy manufacturing industries due to differences in innovation capacity and capital intensity (Anastas, 2010).

3.4.2 Economic and Market Barriers

Economic constraints represent another major obstacle to the adoption of green chemistry practices. The review indicates that high initial capital investment is a primary deterrent for industries considering the transition to greener alternatives (Zimmerman, 2020). Although green chemistry processes often lead to long-term cost savings through improved efficiency and reduced waste management costs, the upfront costs associated with research, development, and infrastructure modification are often prohibitive.

Small and medium-sized enterprises (SMEs), in particular, face significant financial barriers due to limited access to credit and investment capital. In addition, market uncertainty regarding consumer willingness to pay premium prices for green products further discourages investment (Constable, 2021). Previous studies have similarly reported that industries in emerging economies are more risk-averse when it comes to adopting new production technologies, especially when short-term profitability is prioritized over long-term sustainability gains.

Moreover, the absence of strong economic incentives or subsidies in many regions reduces the attractiveness of green chemistry investments. Where incentive structures do exist, such as tax reductions for low-emission technologies or grants for cleaner production, adoption rates have been observed to improve significantly (Pleissner, 2018). However, these policies are not yet widespread or consistently implemented, contributing to uneven global progress.

3.4.3 Policy and Knowledge Gaps

The review also identifies significant policy and knowledge-related barriers that hinder the implementation of green chemistry in industrial processes. A major issue is the lack of comprehensive and enforceable regulatory frameworks that specifically promote green chemistry principles (Lancaster, 2025). In many jurisdictions, environmental regulations focus primarily on end-of-pipe pollution control rather than preventive design strategies, which limits the systemic integration of green chemistry approaches.

Additionally, there is a notable gap in awareness and technical expertise among industrial practitioners and policymakers. Many studies reviewed highlight that engineers and production managers often lack sufficient training in green chemistry principles, leading to low adoption even when technologies are available (Roy Choudhury, 2013). This knowledge gap is particularly evident in industries where traditional chemical engineering curricula have not yet fully integrated sustainability-focused content.

Previous research supports these findings, indicating that educational deficiencies and limited professional development opportunities significantly slow down the diffusion of green chemistry innovations. Furthermore, weak collaboration between academia, industry, and government agencies reduces knowledge transfer and innovation scaling (Song, 2015). In regions where such collaborations are stronger, adoption of green chemistry practices tends to be more advanced, suggesting that institutional integration plays a critical role in overcoming implementation barriers.

3.5 Future Directions and Opportunities

The synthesis of literature on green chemistry approaches in industrial processes indicates that, while significant progress has been achieved in the adoption of cleaner production systems, the field is now entering a transition phase characterized by technological convergence, policy realignment, and expanded interdisciplinary research (Ivanković, 2017). Across the reviewed studies, there is a consistent consensus that future advancements will depend not only on incremental improvements in chemical design but also on systemic innovations that integrate digital tools, advanced materials, and governance frameworks. Similar observations were made by Kerton (2013), who emphasized that the next frontier of green chemistry lies in its integration with emerging technologies and industrial digitalization. The findings of this review reinforce this position, highlighting three major opportunity areas: emerging technologies, supportive policy frameworks, and targeted research expansion.

3.5.1 Emerging Technologies and Innovations

A prominent trend identified in the reviewed literature is the increasing convergence of green chemistry with emerging technological domains such as nanotechnology, artificial intelligence (AI), and advanced process modeling. Nanotechnology, in particular, is being applied to improve catalytic efficiency and reduce material waste in industrial reactions. For example, nano-catalysts have been reported to enhance reaction selectivity while reducing energy consumption in pharmaceutical and petrochemical manufacturing processes. This aligns with earlier findings by Ch (2025), who demonstrated that nanostructured catalysts significantly improve atom economy and reaction efficiency.

In parallel, digital process optimization using AI and machine learning is emerging as a transformative tool for sustainable chemical production. Several studies reviewed indicate that AI-driven predictive modeling can optimize reaction pathways, reduce trial-and-error experimentation, and minimize hazardous by-products. Digital twins and process simulation platforms are increasingly being used to model chemical plants in real time, enabling dynamic adjustments that improve sustainability outcomes (Dunn, 2010). For instance, smart manufacturing systems in specialty chemicals production have shown reductions in solvent use and energy demand through real-time optimization algorithms. These developments suggest a paradigm shift from static process design to adaptive, data-driven green manufacturing systems.

Additionally, advances in biocatalysis and synthetic biology are expanding the scope of green chemistry by enabling the use of renewable biological systems for chemical synthesis. Enzyme engineering has been particularly effective in replacing toxic reagents with biodegradable alternatives, supporting the broader principles of green chemistry articulated in previous foundational work by Rogers (2019). Collectively, these innovations indicate that the future of industrial green chemistry will be increasingly characterized by hybrid systems combining biological, digital, and nanoscale technologies.

3.5.2 Policy Recommendations and Industry Strategies

The findings of this review also highlight that technological advancement alone is insufficient without enabling policy environments and strategic industrial commitments. A recurring theme across studies is that regulatory frameworks significantly influence the pace of green chemistry adoption (Horváth, 2018). Countries with stringent environmental regulations and strong enforcement mechanisms, such as those in the European Union, demonstrate higher levels of industrial compliance with green chemistry principles compared to regions with weaker regulatory systems.

Policy recommendations emerging from the literature emphasize the need for governments to implement incentive-based mechanisms such as tax reductions, research grants, and subsidies for companies adopting green manufacturing technologies. Carbon pricing mechanisms and extended producer responsibility schemes were also identified as effective tools for encouraging sustainable industrial transformation. These findings are consistent with research by Phan (2015), who argued that innovation-oriented environmental policies accelerate industrial adoption of cleaner technologies.

From an industrial perspective, the reviewed studies suggest that firms should adopt long-term sustainability strategies that integrate green chemistry principles into core business models rather than treating them as compliance measures. Industry-academia collaborations were repeatedly identified as critical for accelerating innovation transfer, particularly in scaling laboratory successes to industrial applications (Mulvihill, 2011). Public-private partnerships have also proven effective in bridging funding gaps and reducing the risks associated with green technology adoption. Moreover, multinational corporations are increasingly adopting sustainability reporting frameworks that incorporate green chemistry indicators, signaling a shift toward greater transparency and accountability in industrial practices.

3.5.3 Research Gaps and Areas for Further Study

Despite the growing body of literature, several significant research gaps remain. One key limitation identified is the lack of large-scale empirical studies quantifying the long-term economic and environmental impacts of green chemistry adoption across different industrial sectors (Náray-Szabó, 2018). Many existing studies focus on laboratory-scale or pilot-scale applications, with limited evidence on full-scale industrial implementation and lifecycle performance.

Another gap relates to the integration of digital technologies with green chemistry metrics. While AI and machine learning applications are emerging, there is still insufficient research on standardized frameworks for evaluating their sustainability impact (Bryan, 2018). Additionally, there is limited understanding of how these technologies can be equitably deployed across developing economies, where infrastructural constraints may limit adoption.

The review also reveals a geographical imbalance in research output, with most studies concentrated in developed regions such as North America and Europe. Developing countries, despite being major contributors to industrial pollution, remain underrepresented in green chemistry research (Kralisch, 2015). This suggests a need for more context-specific studies that address local industrial conditions, resource availability, and regulatory environments.

Future research should also explore interdisciplinary approaches that combine green chemistry with circular economy models, life cycle assessment tools, and socio-economic impact analysis. Furthermore, more attention is needed on consumer-driven sustainability demands and how market behavior influences industrial adoption of green technologies (Kar, 2021). Strengthening these research areas will be essential for advancing green chemistry from a specialized scientific approach to a globally integrated industrial standard.

4. Conclusion

This systematic review has critically examined the application of green chemistry approaches in industrial processes, highlighting their growing importance in addressing environmental degradation, resource inefficiency, and sustainability challenges across multiple sectors. The evidence synthesized from the reviewed literature demonstrates that green chemistry principles such as waste prevention, atom economy, safer solvent use, energy efficiency, and renewable feedstocks are increasingly being integrated into industrial operations, particularly in chemical manufacturing, pharmaceuticals, agriculture, and materials production. Collectively, these approaches have shown substantial potential to reduce hazardous emissions, minimize waste generation, and improve overall process efficiency while maintaining or even enhancing product quality.

A key finding of this review is that the adoption of green chemistry is strongly influenced by technological innovation and regulatory frameworks. Advances in catalysis, process intensification, green solvents, and biocatalytic systems have enabled industries to redesign traditional processes toward more sustainable alternatives. However, the extent of implementation varies significantly across regions and sectors, largely due to differences in technological capacity, financial investment, and policy enforcement. Developed economies tend to exhibit more structured integration of green chemistry practices, whereas developing regions face constraints related to infrastructure, expertise, and capital investment.

Despite these positive developments, the review also identifies persistent barriers that continue to limit widespread adoption. These include high initial implementation costs, limited industrial awareness, resistance to process change, and insufficient alignment between academic research and industrial application. Furthermore, gaps remain in scaling laboratory-based green chemistry innovations to full industrial production, indicating a need for stronger collaboration between researchers, policymakers, and industry stakeholders.

Overall, green chemistry presents a viable and necessary pathway toward sustainable industrial development. Its principles not only support environmental protection but also contribute to long-term economic efficiency and regulatory compliance. Future progress will depend on continued innovation, supportive policy environments, and enhanced cross-sector collaboration. Strengthening education and training in green chemistry, alongside increased investment in sustainable technologies, will be essential in accelerating its integration into mainstream industrial practices and achieving global sustainability goals.

Funding: This research received no external funding

Conflicts of Interest: The authors declare no conflict of interest.

Artificial Intelligence (AI) Use Disclosure: The authors declare that no artificial intelligence tools were used in the preparation of this manuscript

References

[1] Anastas, P., & Eghbali, N. (2010). Green chemistry: principles and practice. *Chemical society reviews*, *39*(1), 301-312.
[2] Andraos, J., & Matlack, A. S. (2022). *Introduction to green chemistry*. CRC press.

[3] Bryan, M. C., Dunn, P. J., Entwistle, D., Gallou, F., Koenig, S. G., Hayler, J. D., ... & Weiberth, F. J. (2018). Key Green Chemistry research areas from a pharmaceutical manufacturers' perspective revisited. *Green Chemistry*, *20*(22), 5082-5103.

[4] Ch, S. L., Sameera, M., Jayasree, M., Kamala, G., & Degala, R. P. (2025). A Review of Industrial Applications of Green Chemistry. *Journal of Pharma Insights and Research*, *3*(1), 186-196.

[5] Ciriminna, R., & Pagliaro, M. (2013). Green chemistry in the fine chemicals and pharmaceutical industries. *Organic Process Research & Development*, *17*(12), 1479-1484.

[6] Constable, D. J. (2021). Green and sustainable chemistry–The case for a systems-based, interdisciplinary approach. *IScience*, *24*(12).

[7] Doble, M., Rollins, K., & Kumar, A. (2010). *Green chemistry and engineering*. Academic Press.

[8] Dunn, P. J. (2012). The importance of green chemistry in process research and development. *Chemical Society Reviews*, *41*(4), 1452-1461.

[9] Dunn, P. J., Wells, A. S., & Williams, M. T. (2010). Future trends for green chemistry in the pharmaceutical industry. *Green Chemistry in the Pharmaceutical Industry*, *16*, 333-355.

[10] Horváth, I. T. (2018). Introduction: sustainable chemistry. *Chemical reviews*, *118*(2), 369-371.

[11] Ivanković, A., Dronjić, A., Bevanda, A. M., & Talić, S. (2017). Review of 12 principles of green chemistry in practice. *International Journal of Sustainable and Green Energy*, *6*(3), 39-48.

[12] Jiménez-González, C., & Constable, D. J. (2011). *Green chemistry and engineering: a practical design approach*. John Wiley & Sons.

[13] Kar, S., Sanderson, H., Roy, K., Benfenati, E., & Leszczynski, J. (2021). Green chemistry in the synthesis of pharmaceuticals. *Chemical Reviews*, *122*(3), 3637-3710.

[14] Kerton, F. M., & Marriott, R. (2013). *Alternative solvents for green chemistry* (No. 20). Royal Society of chemistry.

[15] Kralisch, D., Ott, D., & Gericke, D. (2015). Rules and benefits of life cycle assessment in green chemical process and synthesis design: a tutorial review. *Green Chemistry*, *17*(1), 123-145.

[16] Lancaster, M. (2025). *Green chemistry: an introductory text*. Royal society of chemistry.

[17] Mulvihill, M. J., Beach, E. S., Zimmerman, J. B., & Anastas, P. T. (2011). Green chemistry and green engineering: a framework for sustainable technology development. *Annual review of environment and resources*, *36*(1), 271-293.

[18] Náray-Szabó, G., & Mika, L. T. (2018). Conservative evolution and industrial metabolism in Green Chemistry. *Green Chemistry*, *20*(10), 2171-2191.

[19] Patil, K. (2022). Sustainable Green Chemical Technology for Developments in Process Industries.

[20] Phan, T. T., Gallardo, C., & Mane, J. (2015). GREEN MOTION: a new and easy to use green chemistry metric from laboratories to industry. *Green Chemistry*, *17*(5), 2846-2852.

[21] Pleissner, D., & Kümmerer, K. (2018). Green chemistry and its contribution to industrial biotechnology. *Sustainability and Life Cycle Assessment in Industrial Biotechnology*, 281-298.

[22] Ratti, R. (2020). Industrial applications of green chemistry: Status, Challenges and Prospects. *SN Applied Sciences*, *2*(2), 263.

[23] Rogers, L., & Jensen, K. F. (2019). Continuous manufacturing–the Green Chemistry promise?. *Green chemistry*, *21*(13), 3481-3498.

[24] Roy Choudhury, A. K. (2013). Green chemistry and the textile industry. *Textile Progress*, *45*(1), 3-143.

[25] Sheldon, R. A. (2016). Green chemistry and resource efficiency: towards a green economy. *Green Chemistry*, *18*(11), 3180-3183.

[26] Song, J., & Han, B. (2015). Green chemistry: a tool for the sustainable development of the chemical industry. *National Science Review*, *2*(3), 255-256.

[27] Tobiszewski, M., Marć, M., Gałuszka, A., & Namieśnik, J. (2015). Green chemistry metrics with special reference to green analytical chemistry. *Molecules*, *20*(6), 10928-10946.

[28] Watson, W. J. (2012). How do the fine chemical, pharmaceutical, and related industries approach green chemistry and sustainability?. *Green Chemistry*, *14*(2), 251-259.

[29] Wenda, S., Illner, S., Mell, A., & Kragl, U. (2011). Industrial biotechnology—the future of green chemistry?. *Green Chemistry*, *13*(11), 3007-3047.

[30] Zimmerman, J. B., Anastas, P. T., Erythropel, H. C., & Leitner, W. (2020). Designing for a green chemistry future. *Science*, *367*(6476), 397-400.

[31] Zuin, V. G., Eilks, I., Elschami, M., & Kümmerer, K. (2021). Education in green chemistry and in sustainable chemistry: perspectives towards sustainability. *Green Chemistry*, *23*(4), 1594-1608.