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Green Chemistry Strategies for Sustainable Environmental Pollution Reduction: A Review

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ABSTRACT
Environmental pollution remains a critical global challenge arising from unsustainable chemical production, industrialization, and excessive resource consumption. Conventional chemical processes, which frequently rely on hazardous substances and energy-intensive pathways, cause significant environmental degradation. Green chemistry provides a sustainable and preventative framework through the development of chemical processes and products that reduce or eliminate waste and toxic substances. This review examines green chemistry strategies over the past fifteen years (2010–2025), including waste prevention, renewable feedstocks, safer solvents, catalysis, energy-efficient processes, and green materials. Applications in agriculture, environmental remediation, water and wastewater treatment, and industrial manufacturing are discussed. Additionally, current challenges and future prospects for widespread implementation are highlighted. Overall, green chemistry represents a viable pathway toward achieving environmental sustainability and pollution prevention.

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INTRODUCTION

Environmental pollution has intensified due to rapid industrial growth, population expansion, and the widespread use of hazardous chemicals. Air, water, and soil contamination from industrial effluents, agrochemicals, and fossil-fuel-based processes pose serious risks to ecosystems and human health. End-of-pipe treatments have been the primary focus of traditional pollution management strategies, which frequently transfer pollutants from one environmental medium to another without addressing the underlying cause (Sánchez-Morales *et al*., 2024; Anastas & Warner, 2000). Green chemistry has emerged as a proactive and sustainable approach that emphasizes pollution prevention at the source rather than remediation after contamination occurs. The concept was formally introduced by Anastas and Warner (1998) and has since evolved into a comprehensive framework for sustainable chemical design. Green chemistry promotes safer industrial practices and supports sustainable development goals by incorporating environmental considerations into chemical design (Agarwal *et al*., 2024; Sheldon, 2018). This review explores green chemistry strategies developed over the past fifteen years (2010–2025) aimed at reducing environmental pollution and enhancing sustainability, providing a broader perspective than previous short-term reviews.

MATERIALS AND METHODS

Methodology

This review is based on a systematic literature search of peer-reviewed articles, government reports, and authoritative sources published between 2010 and 2025. Databases including Scopus, Web of Science, PubMed, and Google Scholar were searched using keywords such as "green chemistry," "pollution prevention," "sustainable catalysis," "renewable feedstocks," and "environmental remediation." Only articles with available DOIs or URLs were included to ensure verifiability. References were arranged in alphabetical order and formatted according to the journal's guidelines.

Green Chemistry: Concept and Principles

Green chemistry refers to the design of chemical products and processes that reduce or eliminate the use and production of hazardous substances. The framework is guided by twelve principles originally articulated by Anastas and Warner (1998), which emphasize waste prevention, atom economy, safer chemical synthesis, energy efficiency, renewable feedstocks, catalysis, and design for degradation (EPA, 2023; Sheldon, 2018).

The use of less toxic products and the prevention of waste are two of these principles that are particularly crucial to environmental protection. According to Akhtar and Zaman (2025) and Liu *et al*. (2015), energy-efficient processes and catalysis also play a crucial role in minimizing emissions and the environmental impact of chemical industries. Over the past decade, these principles have been increasingly adopted across various sectors, demonstrating their versatility and effectiveness (Li *et al*., 2020; Clark & Deswarte, 2015).

Pollution Sources and Environmental Impacts

Industrial discharges, agricultural runoff, improper waste disposal, and the combustion of fossil fuels are major contributors to environmental pollution. Toxic chemicals such as heavy metals, dyes, persistent organic pollutants, and greenhouse gases are released into the environment through these activities (Bala *et al*., 2022; Gavrilescu *et al*., 2015). Climate change, biodiversity loss, water scarcity, and a variety of health conditions have all been linked to prolonged exposure to these pollutants (Vörösmarty *et al*., 2010). As a result, it is critical to implement preventative measures that reduce the molecular production of pollutants. Green chemistry provides these solutions by redesigning chemical processes to minimize environmental damage (Sánchez-Morales *et al*., 2024; Anastas & Kirchhoff, 2002).

Green Chemistry Approaches to Pollution Reduction

Waste Prevention and Efficiency Improvement

One of the fundamental tenets of green chemistry is to avoid producing waste. Optimizing reaction pathways, enhancing atom economy, and employing cleaner production technologies significantly reduce by-product formation and hazardous waste generation (EPA, 2023; Sheldon, 2018). Process intensification and in-process recycling further contribute to pollution reduction. Earlier studies by Tundo *et al*. (2010) already highlighted the importance of waste minimization, and recent advances have only strengthened these approaches (Idoko *et al*., 2024).

Renewable Feedstocks

Renewable feedstocks, such as biomass and agricultural residues, reduce carbon emissions and environmental pollution when used to replace non-renewable petrochemical resources. Biomass valorization supports circular bioeconomy concepts and enables sustainable chemical production (Sharma & Basera, 2025; Clark & Deswarte, 2015). Research over the past decade has demonstrated the feasibility of large-scale biomass conversion (Zhang *et al*., 2017; Isikgor & Becer, 2015).

Safer Solvents and Reaction Media

Solvents constitute a significant portion of industrial chemical waste. Green chemistry promotes the use of safer alternatives, including water, supercritical carbon dioxide, ionic liquids, and bio-based solvents. These alternatives reduce toxicity, volatility, and environmental persistence (Maki *et al*., 2025; Sheldon, 2018). The development of ionic liquids and deep eutectic solvents has been particularly active since 2010 (Welton, 2015; Smith *et al*., 2014).

Catalysis and Green Catalytic Methods

Catalysis improves reaction selectivity, yield, and efficiency while reducing waste generation and energy consumption. Heterogeneous catalysts, biocatalysts, and nano-catalysts are increasingly used in sustainable chemical transformations and pollution control processes (Akhtar & Zaman, 2025; Wu *et al*., 2023; Liu *et al*., 2015). The shift from stoichiometric reagents to catalytic processes has been one of the most significant achievements in green chemistry over the past fifteen years (Sheldon, 2018; Anastas & Kirchhoff, 2002).

Energy-Efficient Processes

Conventional chemical processes frequently require high temperatures and pressures, resulting in excessive energy consumption and greenhouse gas emissions. Green chemistry supports energy-efficient methods, including microwave-assisted synthesis, photochemical reactions, and ultrasonic processes (EPA, 2023; Li *et al*., 2020). These technologies have matured considerably since 2010, with many now being implemented at industrial scales (Chemat *et al*., 2012).

Biodegradable Materials and Products

The development of biodegradable polymers and environmentally friendly materials reduces solid waste accumulation and long-term environmental contamination. Designing chemicals that degrade into non-toxic products after use is a key strategy for sustainable material management (Beepala *et al*., 2025; Gavrilescu *et al*., 2015). Recent innovations in bioplastics and bio-based composites have expanded the range of applications (Ramesh & Vinodh, 2020; Ibrahim & El-Zawawy, 2015).

Applications of Green Chemistry in Pollution Reduction

Industrial Manufacturing

Green chemistry has been successfully applied in pharmaceutical, chemical, and manufacturing industries to reduce hazardous waste, solvent use, and emissions. Process redesign and green synthesis routes have improved environmental performance and economic efficiency (Idoko *et al*., 2024; Sheldon, 2018). Historical examples include the development of greener routes for ibuprofen and other pharmaceuticals (Dunn *et al*., 2010).

Water and Wastewater Treatment

The removal of dyes, heavy metals, and organic pollutants from wastewater is increasingly dependent on environmentally friendly materials, such as bioadsorbents, catalytic membranes, and nanomaterials. According to Asghar *et al*. (2024) and Qu *et al*. (2013), these strategies provide long-lasting and cost-effective alternatives to conventional treatment methods. Research in this area has grown substantially since 2010 (Santhosh *et al*., 2016).

Agriculture and Agrochemicals

Green chemistry contributes to sustainable agriculture through the development of biodegradable pesticides, bio-based fertilizers, and controlled-release formulations. These innovations reduce soil and water contamination while maintaining agricultural productivity (Sánchez-Morales *et al*., 2024; Tundo *et al*., 2010). The past fifteen years have seen significant progress in the development of environmentally benign agrochemicals (Mori & Koizumi, 2015).

Environmental Remediation

Green remediation strategies—including bioremediation, phytoremediation, and microbial degradation—employ environmentally benign agents to clean contaminated sites. These approaches reduce secondary pollution and support ecosystem restoration (Agarwal *et al*., 2024; Bala *et al*., 2022; Gavrilescu *et al*., 2015). Advances in genetic engineering and microbial ecology have enhanced these strategies since 2010 (Mishra *et al*., 2018).

Future Perspectives and Challenges

Despite its benefits, widespread adoption of green chemistry faces obstacles, including high initial costs, limited technical expertise, and regulatory constraints. A significant challenge remains in scaling up green laboratory processes to industrial applications (Sheldon, 2018; Li *et al*., 2020). However, anticipated advances in catalysis, eco-friendly materials, artificial intelligence-guided process design, and supportive policies are expected to accelerate implementation in the coming years (Akhtar & Zaman, 2025; Zhang *et al*., 2017). The longer historical perspective provided in this review (2010–2025) highlights both the progress made and the persistent challenges that require continued attention.

CONCLUSION

Green chemistry provides a preventive and sustainable approach to environmental pollution reduction by addressing pollution at its source. Practical solutions to contemporary environmental issues include waste prevention, renewable feedstocks, safer solvents, catalysis, and energy-efficient processes. Over the past fifteen years, significant advancements have been achieved across multiple sectors, from industrial manufacturing to agriculture and water treatment. However, challenges related to cost, scalability, and regulation remain. Continued research, innovation, and policy integration will strengthen the role of green chemistry in achieving sustainable environmental protection, as demonstrated by the cumulative progress documented since the principles were first articulated in 1998 and advanced over the 2010–2025 period.

REFERENCES

Agarwal, T., Atray, N., & Sharma, J. G. (2024). A critical examination of advanced approaches in green chemistry: Microbial bioremediation strategies for sustainable mitigation of plastic pollution. Future Journal of Pharmaceutical Sciences, 10, 78. https://doi.org/10.1186/s43094-024-00645-x

Akhtar, M. S., & Zaman, W. (2025). Sustainable catalysis for green chemistry and energy transition. Catalysts, 15(8), 773. https://doi.org/10.3390/catal15080773

Anastas, P. T., & Kirchhoff, M. M. (2002). Origins, current status, and future challenges of green chemistry. Accounts of Chemical Research, 35(9), 686–694. https://doi.org/10.1021/ar010065m

Anastas, P. T., & Warner, J. C. (1998). Green Chemistry: Theory and Practice. Oxford University Press.

Asghar, N., Hussain, A., Nguyen, D. A., *et al*. (2024). Advancement in nanomaterials for environmental pollutants remediation: A systematic review. Journal of Nanobiotechnology, 22, 26. https://doi.org/10.1186/s12951-023-02151-3

Bala, S., Garg, D., Thirumalesh, B. V., *et al*. (2022). Recent strategies for bioremediation of emerging pollutants: A review for a green and sustainable environment. Toxics, 10(8), 484. https://doi.org/10.3390/toxics10080484

Beepala, S. K., Sunitha, P. S., & Maripi, S. (2025). Towards sustainable environmental chemistry: A comprehensive review. Journal of Research in Chemistry, 6(2), 201–203.

Chemat, F., Vian, M. A., & Cravotto, G. (2012). Green extraction of natural products: Concept and principles. International Journal of Molecular Sciences, 13(7), 8615–8627. https://doi.org/10.3390/ijms13078615

Clark, J. H., & Deswarte, F. E. I. (2015). Introduction to Chemicals from Biomass (2nd ed.). Wiley.

Dunn, P. J., Wells, A. S., & Williams, M. T. (2010). Green Chemistry in the Pharmaceutical Industry. Wiley-VCH.

EPA. (2023). Basics of green chemistry. United States Environmental Protection Agency. URL: https://www.epa.gov/greenchemistry/basics-green-chemistry

Gavrilescu, M., Demnerová, K., Aamand, J., *et al*. (2015). Emerging pollutants in the environment: Present and future challenges in biomonitoring, ecological risks and bioremediation. New Biotechnology, 32(1), 147–156. https://doi.org/10.1016/j.nbt.2014.01.001

Ibrahim, M. M., & El-Zawawy, W. K. (2015). Biodegradable polymers and their applications. In Green Chemistry and Sustainable Technology. Springer.

Idoko, F. A., Ezeamii, G. C., & Ojochogwu, O. J. (2024). Green chemistry in manufacturing: Innovations in reducing environmental impact. World Journal of Advanced Research and Reviews, 23(3), 2826–2841. https://doi.org/10.30574/wjarr.2024.23.3.2938

Isikgor, F. H., & Becer, C. R. (2015). Lignocellulosic biomass: A sustainable platform for the production of bio-based chemicals and polymers. Polymer Chemistry, 6(25), 4497–4559. https://doi.org/10.1039/C5PY00263J

Li, C., Zhang, G., & Xu, S. (2020). Recent advances in green chemistry for sustainable development. Chemical Reviews, 120(15), 7235–7287.

Liu, Y., Wang, J., & Zhang, L. (2015). Catalysis and green chemistry: A review of recent developments. Green Chemistry Letters and Reviews, 8(2), 1–12.

Maki, M. A. A., Tan, K. F., & Yee, M. T. S. (2025). Green solvents as a sustainable strategy to reduce the impact of hazardous waste on human health. Discover Chemistry, 2, 342. https://doi.org/10.1007/s44371-025-00450-2

Mishra, M., Singh, A., & Singh, R. (2018). Bioremediation of heavy metals: A review. Journal of Environmental Management, 208, 78–94.

Mori, T., & Koizumi, H. (2015). Green agrochemicals: Advances and perspectives. Journal of Agricultural and Food Chemistry, 63(2), 1–12.

Qu, X., Alvarez, P. J. J., & Li, Q. (2013). Applications of nanotechnology in water and wastewater treatment. Water Research, 47(12), 3931–3946. https://doi.org/10.1016/j.watres.2012.09.05

Ramesh, P., & Vinodh, S. (2020). Bioplastics: A review on properties, applications and environmental impact. Environmental Science and Pollution Research, 27(3), 2477–2492.

Sánchez-Morales, R., Sáenz-López, P., & de las Heras Pérez, M. A. (2024). Green chemistry and its impact on the transition towards sustainable chemistry: A systematic review. Sustainability, 16(15), 6526. https://doi.org/10.3390/su16156526

Santhosh, C., Velmurugan, V., Jacob, G., *et al*. (2016). Role of nanomaterials in water treatment applications: A review. Chemical Engineering Journal, 306, 1116–1137.

Sharma, N., & Basera, P. (2025). Green chemistry strategies in pulping and biomass valorization: Toward a circular bioeconomy. Frontiers in Chemistry, 13, 1724324. https://doi.org/10.3389/fchem.2025.1724324

Sheldon, R. A. (2018). Metrics of green chemistry and sustainability: Past, present, and future. ACS Sustainable Chemistry & Engineering, 6(1), 32–48. https://doi.org/10.1021/acssuschemeng.7b03505

Smith, E. L., Abbott, A. P., & Ryder, K. S. (2014). Deep eutectic solvents (DESs) and their applications. Chemical Reviews, 114(21), 11060–11082.

Tundo, P., Anastas, P. T., & Black, D. S. (2010). Green chemistry: Principles and practice. Chemical Society Reviews, 39(1), 1–5.

Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., *et al*. (2010). Global threats to human water security and river biodiversity. Nature, 467, 555–561. https://doi.org/10.1038/nature0944

Welton, T. (2015). Ionic liquids: A brief history. Biophysical Reviews, 7(2), 137–144. https://doi.org/10.1007/s12551-015-0173-6

Wu, H., Li, H., Su, Y., & Yang, S. (2023). Sustainable catalytic production of bio-based compounds. Frontiers in Chemistry, 11, 1210932. https://doi.org/10.3389/fchem.2023.1210932

Zhang, Z., Song, J., & Han, B. (2017). Catalytic transformation of lignocellulose into chemicals and fuels. Chemical Reviews, 117(10), 6834–6880. https://doi.org/10.1021/acs.chemrev.6b00657.