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Review Article

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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 an excessive use of resources all contribute to environmental pollution, which remains a major global problem. Significant environmental degradation is caused by conventional chemical processes, which frequently rely on hazardous substances and energy-intensive pathways. By developing chemical processes and products that reduce or eliminate the production of waste and toxic substances, green chemistry provides a framework that is both sustainable and preventative. Waste prevention, renewable feedstocks, safer solvents, catalysis, energy-efficient processes, and green materials are just a few of the recent green chemistry strategies examined in this review. Green chemistry's applications in agriculture, environmental remediation, water and wastewater treatment, and industrial manufacturing are also discussed. In addition, the present difficulties and potential outcomes of widespread implementation are highlighted. Overall, green chemistry represents a viable pathway toward achieving environmental sustainability and pollution prevention.

Keywords: Green Chemistry, Environmental Pollution, Sustainability, Catalysis, Renewable Resources, Pollution Prevention

Introduction

Environmental pollution has intensified due to rapid industrial growth, population expansion, and the widespread use of hazardous chemicals. Air, water, and soil contamination caused by 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 [1]. Green chemistry has emerged as a proactive and sustainable approach that emphasizes pollution prevention at the source rather than remediation after contamination occurs. Green chemistry promotes safer industrial practices and supports sustainable development goals by incorporating environmental considerations into chemical design [2]. This review explores recent green chemistry strategies (2022–2025) aimed at reducing environmental pollution and enhancing sustainability.

Green Chemistry

Its Concept and Principles The design of chemical products and processes that reduce or eliminate the use and production of hazardous substances is referred to as "green chemistry." The framework is guided by twelve principles that emphasize waste prevention, atom economy, safer chemical synthesis, energy efficiency, renewable feedstocks, catalysis, and design for degradation [3].

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 & Zaman, energy-efficient processes and catalysis also play a crucial role in minimizing emissions and the environmental impact of chemical industries [4].

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Pollution's Origins and Effects on the Environment Industrial discharges, agricultural runoff, improper waste disposal, and the combustion of fossil fuels are major contributors to environmental pollution. Toxic chemicals like heavy metals, dyes, persistent organic pollutants, and greenhouse gases are released into the environment by these activities [5]. Climate change, biodiversity loss, water scarcity, and a variety of health conditions have all been linked to prolonged exposure to these pollutants. As a result, it's critical to implement preventative measures that cut down on the molecular production of pollutants. According to Sanchez-Morales, green chemistry provides these solutions by redesigning chemical processes to minimize environmental damage [1].

Green Chemistry Approaches to Reducing Pollution

Reducing Wastage and Improving Efficiency One of the fundamental tenets of green chemistry is to avoid producing waste. By-product formation and the generation of hazardous waste are significantly reduced by optimizing reaction pathways, enhancing the atom economy, and employing cleaner production technologies [3]. Process intensification and in-process recycling further contribute to pollution reduction.

Using Feedstocks That Are Renewable Carbon emissions and environmental pollution are reduced when renewable feedstocks like biomass and agricultural residues replace non-renewable petrochemical resources. Biomass valorization supports circular bioeconomy concepts and enables sustainable chemical production [6].

Safer Reaction Media and Solvents A significant amount of industrial chemical waste is made up of solvents. Green chemistry promotes the use of safer alternatives such as water, supercritical carbon dioxide, ionic liquids, and bio-based solvents. These alternatives reduce toxicity, volatility, and environmental persistence [7].

Green Catalytic Methods and Catalysis Reaction selectivity, yield, and efficiency are all improved through catalysis, which also reduces waste generation and energy consumption. Heterogeneous catalysts, biocatalysts, and nano-catalysts are increasingly used in sustainable chemical transformations and pollution control processes [4,8].

Low-temperature, energy-efficient processes High temperatures and pressures are frequently required in conventional chemical processes, which results in excessive energy consumption and emissions of greenhouse gases. Microwave-assisted synthesis, photochemical reactions, and ultrasonic processes are examples of energy-efficient methods that are supported by green chemistry [3].

Eco-friendly Products and Materials Solid waste accumulation and long-term environmental contamination are reduced by the development of biodegradable polymers and environmentally friendly materials. Designing chemicals that degrade into non-toxic products after use is a key strategy for sustainable material management [9].

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 [10].

Water and Wastewater Treatment

The removal of dyes, heavy metals, and organic pollutants from wastewater is becoming increasingly dependent on environmentally friendly materials like bioadsorbents, catalytic membranes, and nanomaterials. According to Asghar these strategies provide alternatives to conventional treatment strategies that are long-lasting and cost-effective [11].

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 [1].

Environmental Remediation

Green remediation strategies such as bioremediation, phytoremediation, and microbial degradation use environmentally benign agents to clean contaminated sites. These approaches reduce secondary pollution and support ecosystem restoration [2,5].

Perspectives for the Future and Challenges Green chemistry's widespread adoption faces obstacles such as high initial costs, limited technical expertise, and regulatory constraints despite its benefits. A significant obstacle remains in the way of industrializing green laboratory processes. It is anticipated that advances in catalysis, eco-friendly materials, process design guided by artificial intelligence, and supportive policies will accelerate implementation in the future [4].

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. Continued research, innovation, and policy integration will strengthen the role of green chemistry in achieving sustainable environmental protection.

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