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GREEN CHEMISTRY APPROACHES FOR MITIGATING WATER POLLUTION: INNOVATIONS AND CHALLENGES

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Abstract

Water pollution remains one of the greatest threats to environmental sustainability and human health in the 21st century. Conventional remediation strategies—such as chlorination, coagulation, and activated carbon adsorption—while effective, are resource-intensive, costly, and generate secondary pollutants. The principles of green chemistry, emphasizing sustainability, waste minimization, and the use of renewable feedstocks, offer promising alternatives for addressing water contamination. This review consolidates research on biodegradable adsorbents, plant-based coagulants, solar-driven photocatalysis, bio-inspired nanomaterials, and waste-to-resource innovations. It examines their effectiveness in removing heavy metals, pesticides, pharmaceuticals, dyes, and microplastics, while critically evaluating limitations such as scalability and by-product formation. The integration of green chemistry approaches into environmental management and policy frameworks is highlighted, alongside future directions for achieving clean and sustainable water resources.

Keywords: Green chemistry; Sustainable water treatment; Biodegradable adsorbents; Photocatalysis; Bio-inspired nanomaterials; Eco-remediation; Water sustainability

1. Introduction

Water pollution has emerged as one of the most pressing global environmental issues. The World Health Organization (WHO, 2020) estimates that nearly 2.2 billion people lack access to safe drinking water, with contaminated sources leading to widespread outbreaks of cholera, diarrhea, hepatitis, and cancer. Rapid industrialization, intensive agriculture, and urban growth have introduced an array of pollutants—ranging from heavy metals and pesticides to pharmaceuticals and microplastics—into aquatic ecosystems (Carpenter et al., 2016; Wang et al., 2016).

From a chemical standpoint, pollutants undergo diverse transformations such as hydrolysis, oxidation–reduction, photolysis, and complexation, which influence their persistence, toxicity, and transport (Petrović et al., 2019). While conventional remediation technologies such as coagulation, chlorination, and adsorption have been widely used, they often face challenges related to cost, energy consumption, incomplete removal, and the generation of secondary waste (Crini, 2015; Crini & Lichtfouse, 2019).

The principles of green chemistry, as articulated by Anastas and Warner (1998), emphasize reducing hazardous substances, minimizing waste, and using renewable resources. Applied to water pollution control, these principles have stimulated research into biodegradable adsorbents, plant-based coagulants, solar-driven photocatalysts, and biochar-supported nanomaterials (Bhatnagar & Sillanpää, 2010; Mohan et al., 2014).

This review examines the sources of water pollution, highlights green chemistry-inspired remediation methods, and evaluates their advantages, limitations, and future potential.

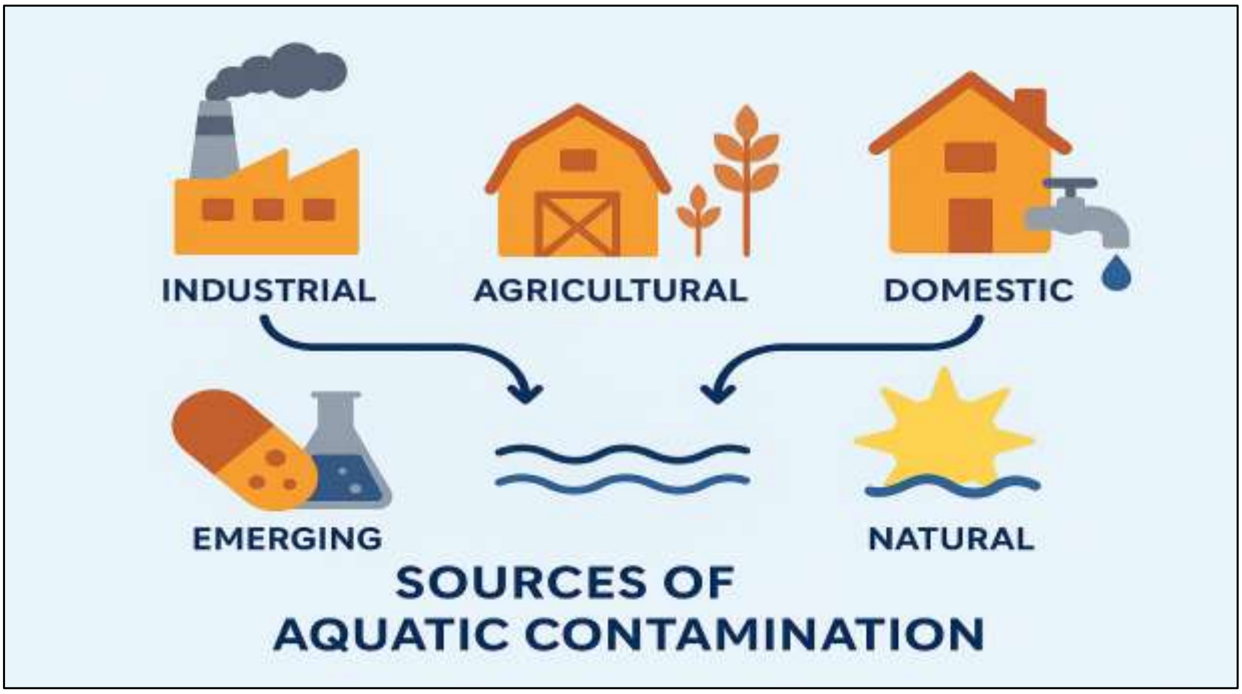
2. Sources of Water Pollution

Table 1. Major pollutant groups and their chemical characteristics

Source	Example Pollutants	Chemistry/Toxicity	Persistence
Industrial	Pb, Cd, Hg, Cr, phenols, dyes	Non-biodegradable, bioaccumulative, carcinogenic	High
Agricultural	Nitrates, phosphates, pesticides	Eutrophication, endocrine disruption	Moderate–high
Domestic	Detergents, pharmaceuticals	Surfactants, hormones, antibiotic resistance	Moderate
Emerging	PPCPs, microplastics, e-waste	Bioactive, endocrine-active, plastic additives	Very high
Natural	Arsenic, fluoride, acid rain	Geogenic contamination, pH shifts	Variable

Figure 1. Sources of water pollution

(Schematic showing industrial, agricultural, domestic, emerging, and natural sources contributing to aquatic contamination).



3. Green Chemistry Approaches

3.1 Biodegradable and Renewable Adsorbents

One of the most promising green chemistry-based solutions for water purification is the utilization of biodegradable and renewable adsorbents. Agricultural residues such as rice husk, coconut shell, banana peel, sugarcane bagasse, and sawdust have been widely studied because of their abundance, low cost, and carbon-rich composition. These materials can be chemically modified into biochar or activated carbon with enhanced porosity and surface area, improving their adsorption capacity for heavy metals, dyes, and pharmaceutical residues (Gupta & Suhas, 2009; Bhatnagar & Sillanpää, 2010).

Chitosan, a biopolymer derived from chitin (commonly obtained from shrimp and crab shells), has gained significant attention due to its amine functional groups, which facilitate chelation of metal ions such as Pb^{2+}, Cd^{2+}, Cr(VI), and Cu^{2+}. Its natural biodegradability, non-toxicity, and ease of chemical modification (e.g., grafting with functional groups or crosslinking with glutaraldehyde) further enhance its adsorption potential for both inorganic and organic pollutants (Crini, 2015).

Recent advances include nanostructured bioadsorbents, such as chitosan-coated nanoparticles and biochar composites, which combine the eco-friendly nature of biopolymers with the high reactivity of nanomaterials (Zhang, 2003). Moreover, enzymatic pretreatments of plant residues have been shown to increase porosity and adsorption sites, further improving pollutant uptake (Ali et al., 2013).

The advantages of biodegradable adsorbents lie in their renewability, local availability, and minimal secondary pollution. However, challenges include relatively lower adsorption capacities compared to synthetic adsorbents, potential leaching of organic matter, and difficulties in regeneration and reuse (Vilardi et al., 2018). Thus, future research is focusing on composite bioadsorbents that integrate natural polymers with nanostructures or photocatalysts for multifunctional pollutant removal.

3.2 Plant-Based Coagulants

Coagulation and flocculation are critical steps in water treatment for removing suspended solids, turbidity, and colloidal particles. Traditionally, inorganic coagulants such as aluminum sulfate (alum) and ferric chloride have been employed; however, they produce large volumes of non-biodegradable sludge, alter pH, and may pose long-term health risks (Sillanpää et al., 2018). To overcome these drawbacks, plant-based coagulants have gained increasing attention as eco-friendly alternatives.

Moringa oleifera seeds contain cationic proteins (polyelectrolytes) that neutralize negatively charged particles, enabling aggregation and sedimentation (Ndabigengesere & Narasiah, 1998). They are particularly effective in removing turbidity, bacteria, and even pesticide residues from surface waters, while generating fully biodegradable sludge. Similarly, cactus (Opuntia ficus-indica) extracts, rich in mucilage polysaccharides, act as natural flocculants by bridging suspended particles (Bhuptawat et al., 2007). Tannin-based coagulants, derived from tree bark or nuts, have also demonstrated strong binding affinity for heavy metals and organic pollutants, offering an additional pathway for natural coagulation (Santos et al., 2011).

A major advantage of natural coagulants lies in their low cost, local availability, and safety for human and environmental health. In rural and low-income communities, plant-based coagulants can be used directly without sophisticated processing, making them a sustainable choice (Sharma & Malaviya, 2021). Moreover, their application reduces dependency on imported chemicals, thereby enhancing water security.

However, limitations exist: seasonal availability of raw materials, variability in coagulant protein content, and lower efficiency compared to conventional alum at very high turbidity levels (Sillanpää et al., 2018). Current research aims to overcome these challenges by developing blended formulations (plant extracts + low-dose inorganic salts), optimizing extraction techniques, and using nanostructured carriers to enhance stability and performance (Crini & Lichtfouse, 2019).

Table 2. Comparison between conventional and green coagulants

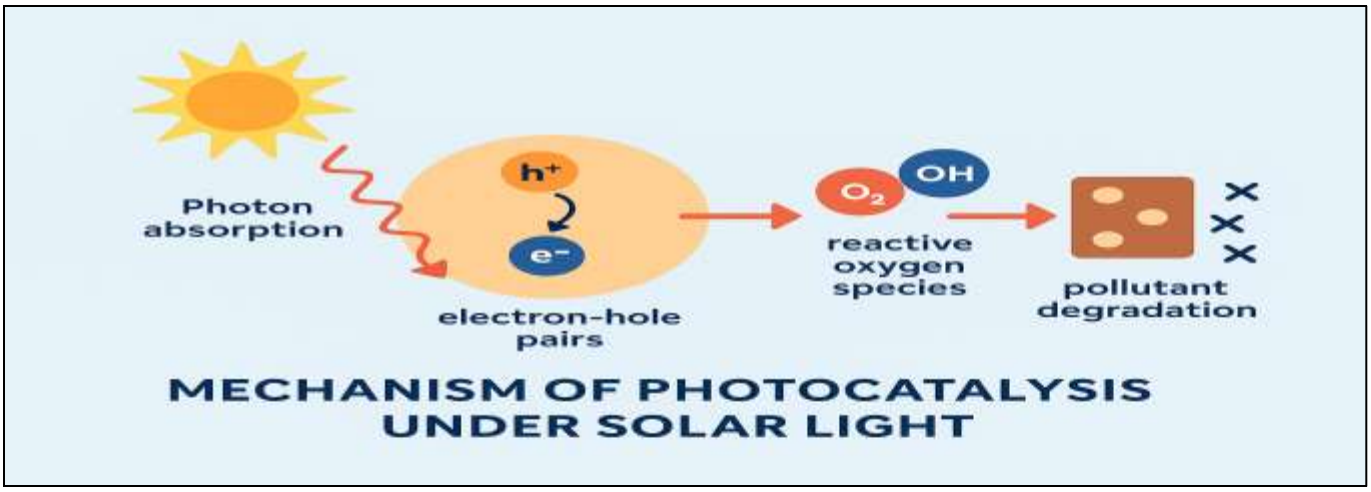
Coagulant Type	Example	Advantages	Limitations
Conventional	Alum, ferric salts	Effective, inexpensive	Toxic sludge, alters pH
Green Coagulants	Moringa, cactus	Biodegradable, non-toxic	Seasonal supply

3.3 Solar-Driven Photocatalysis

Semiconductors such as TiO_2, ZnO, and Fe_2O_3 degrade organic pollutants through photocatalytic reactions under solar or UV light (Hoffmann et al., 1995). Doping with metals or carbon enhances visible-light absorption and efficiency (Zhang, 2003).

Figure2. Mechanism of photocatalysis under solar light

(Photon absorption → electron–hole pairs → reactive oxygen species → pollutant degradation).



3.4 Waste-to-Resource Nano materials

In recent years, the transformation of agricultural and industrial residues into waste-derived nanomaterials has emerged as a cutting-edge approach within green chemistry for sustainable water remediation. Agricultural by-products such as fly ash, sugarcane bagasse, rice husk, coconut shells, and sawdust are abundant, carbon-rich, and inexpensive. Through pyrolysis, hydrothermal carbonization, or chemical activation, these residues can be converted into biochar, which is then functionalized or combined with nanoparticles to enhance adsorption and catalytic properties (Mohan et al., 2014; Bhatnagar & Sillanpää, 2010).

Magnetic biochar composites are particularly significant because they combine high adsorption capacity with the advantage of easy recovery using external magnetic fields. For instance, biochar impregnated with iron oxide (Fe_3O_4) nanoparticles shows remarkable efficiency in removing arsenic, cadmium, lead, and pharmaceuticals from aqueous systems (Mohan et al., 2014). Similarly, nanoscale zero-valent iron (nZVI) embedded in biochar matrices has been employed to reduce toxic Cr(VI) to the less harmful Cr(III), while simultaneously immobilizing heavy metals on biochar surfaces (Zhang, 2003).

Another promising direction is the development of biochar-supported photocatalysts, such as TiO_2 or ZnO deposited on carbon substrates, which improve charge separation during photocatalytic reactions and extend activity into the visible-light region (Hoffmann et al., 1995). In addition, carbon nanotube–biochar hybrids derived from waste sources have shown strong adsorption for organic dyes and hydrophobic pollutants, further broadening their scope.

The advantages of waste-to-resource nanomaterials lie in their dual benefits: reducing waste disposal issues while simultaneously creating cost-effective adsorbents and catalysts. However, potential limitations include the risk of nanoparticle leaching, high production costs at large scale, and variability in raw material properties (Vilardi et al., 2018). Thus, future research must focus on standardizing production protocols, enhancing material stability, and evaluating long-term environmental safety before large-scale adoption.

3.5 Enzyme- and Microbe-Assisted Green Processes

Biological processes play a critical role in green chemistry-inspired water treatment by harnessing the catalytic efficiency of enzymes and microorganisms to degrade toxic compounds. Unlike conventional chemical oxidation, enzyme- and microbe-assisted remediation is highly specific, eco-friendly, and operates under mild conditions.

Enzymes such as laccase, peroxidase, and tyrosinase have been extensively studied for the degradation of phenols, aromatic dyes, and pharmaceuticals (Robinson et al., 2001). Laccase, a copper-containing oxidase, catalyzes the oxidation of phenolic and non-phenolic compounds by reducing molecular oxygen to water, thereby breaking down complex pollutants into less harmful intermediates. Similarly, horseradish peroxidase and manganese peroxidase use hydrogen peroxide to oxidize a wide range of organic contaminants, including endocrine-disrupting chemicals and textile dyes (Fenner et al., 2013).

Microbial approaches involve the use of single strains or consortia of bacteria, fungi, or algae capable of metabolizing pesticides, pharmaceuticals, and heavy metals. For instance, Pseudomonas and Bacillus species degrade chlorinated pesticides, while fungi such as Trametes versicolor are highly effective in degrading synthetic dyes through ligninolytic enzymes (Ali et al., 2013). Algal-bacterial consortia also play a role in nutrient removal, reducing nitrogen and phosphorus loads that cause eutrophication.

The integration of biological systems with nanomaterials has created hybrid remediation platforms. For example, immobilizing laccase on magnetic nanoparticles or biochar enhances enzyme stability, reusability, and pollutant degradation efficiency. Similarly, microbial biofilms supported on nanostructured carriers have been shown to accelerate pesticide and pharmaceutical breakdown (Patel et al., 2020).

Enzyme- and microbe-assisted processes offer the advantages of biodegradability, low energy input, and minimal secondary pollution, making them highly attractive for green chemistry-based water treatment. However, limitations such as enzyme instability, slow degradation rates, and sensitivity to pH and temperature remain significant challenges. Current research is focusing on genetically engineered enzymes, immobilization techniques, and microbial consortia optimization to overcome these barriers and scale up applications for real-world wastewater treatment.

4. Case Studies

Table 3. Case studies using green chemistry methods

Pollutant	Method	Removal Efficiency
Pb^{2+}, Cd^{2+}	Chitosan, biochar adsorbents	>95%
Azo dyes	Solar TiO_2 photocatalysis	~90%
Pesticides	*Moringa oleifera* coagulants	80–90%
Pharmaceuticals	Magnetic biochar composites	High adsorption
Microplastics	Modified bio-based adsorbents	Significant removal

5. Challenges

Despite promising results, green chemistry approaches face challenges:

1. Scalability: Many lab-scale successes are difficult to scale up (Vilardi et al., 2018).
2. Selectivity: Adsorbents often lack specificity for target pollutants (Bhatnagar & Sillanpää, 2010).
3. By-products: Photocatalysis may generate harmful intermediates (Fenner et al., 2013).
4. Standardization: Lack of harmonized testing protocols complicates comparisons (Petrie et al., 2015).

Figure 3. Challenges and opportunities of green chemistry approaches

6. Future Perspectives

Future directions include

- Development of multifunctional adsorbents integrating adsorption and catalysis (Gupta et al., 2020).
- Expansion of solar-driven photocatalysis in rural areas (Hoffmann et al., 1995; Zhang, 2003).
- Integration of waste-to-resource principles in water management (Mohan et al., 2014).
- Adoption of circular economy frameworks to reuse agricultural residues (United Nations, 2019).
- Enhanced research on enzyme-based remediation (Ali et al., 2013; Patel et al., 2020).

7. Conclusion

Green chemistry offers a sustainable and transformative framework for mitigating water pollution by prioritizing eco-friendly materials, renewable energy inputs, and waste minimization. By employing biodegradable adsorbents derived from agricultural residues, natural coagulants such as Moringa oleifera seeds and tannin-rich plants, solar-driven photocatalysis using visible-light-active catalysts, and bio-inspired nanomaterials, this approach significantly reduces environmental impacts while effectively addressing a wide range of pollutants including heavy metals, pesticides, dyes, pharmaceuticals, and microplastics. Unlike conventional treatment methods, green chemistry-inspired strategies are designed not only for efficiency but also for compatibility with natural systems, ensuring minimal secondary contamination and long-term ecological balance.

Although challenges remain in scalability, by-product management, and cost-effectiveness, ongoing advances in nanotechnology, enzyme-assisted degradation, and hybrid chemical–biological systems demonstrate that green chemistry can complement, and in some cases replace, conventional water treatment technologies (Crini & Lichtfouse, 2019; Mohan et al., 2014). One of the most promising trends is the valorization of waste streams, where agricultural residues, industrial by-products, and even municipal wastes are transformed into valuable adsorbents or catalysts, aligning water treatment directly with circular economy principles.Looking forward, further research must focus on the development of multifunctional materials capable of simultaneously adsorbing, degrading, and detoxifying multiple pollutants. Additionally, solar-driven and low-energy photocatalytic systems must be adapted for use in rural and resource-limited settings, particularly in developing countries where access to advanced treatment technologies is limited. Importantly, the environmental risks associated with nanoparticles and photocatalytic by-products must be carefully studied to ensure that remediation strategies do not inadvertently introduce new hazards (Koelmans et al., 2019; Zhang, 2003).Aligning these innovations with global sustainability policies and frameworks such as the United Nations Sustainable Development Goals (SDG 6: Clean Water and Sanitation) will be crucial in ensuring safe, accessible, and sustainable water resources for future generations (United Nations, 2019). Beyond technological advances, achieving this vision requires interdisciplinary collaboration between chemists, engineers, biologists, economists, and policymakers. Only through such integrated efforts can green chemistry truly evolve from a research focus into a globally implemented solution for clean water access.

In conclusion, green chemistry is not merely a set of techniques but a paradigm shift in environmental management, moving society toward a future where water purification is efficient, sustainable, and harmonized with natural systems. By embracing innovation while addressing current limitations, green chemistry can play a central role in tackling the global water crisis, ensuring environmental resilience and human well-being in the decades to come.

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