GREEN CHEMISTRY APPROACHES FOR REDUCING INDUSTRIAL WATER POLLUTION: ECO-FRIENDLY TREATMENT TECHNOLOGIES AND SUSTAINABLE WASTEWATER MANAGEMENT

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Abstract

Industrial effluents represent a major contributor to global water pollution, releasing heavy metals, dyes and persistent organic pollutants (POPs) into aquatic ecosystems. Conventional wastewater treatments often suffer from drawbacks such as incomplete removal of emerging contaminants, high energy consumption, and generation of secondary waste streams. Green chemistry offers a sustainable pathway by designing processes and materials that reduce or eliminate hazardous substances and maximize resource efficiency. This review evaluates a range of eco-friendly treatment technologies including advanced oxidation processes (AOPs), bio-adsorption and biosorbents, phytoremediation, membrane filtration, and green nanomaterial-based catalytic degradation along with their environmental and economic feasibility. The integration of circular economy and zero-liquid discharge (ZLD) paradigms is also examined. Key challenges remain in cost, industrial scalability, regulatory adoption and techno-economic viability. The study concludes that the systematic incorporation of green chemistry principles into wastewater management can significantly reduce effluent toxicity, support circular economy goals, and drive more sustainable industrial development.

INTRODUCTION

Wastewaters generated from industrial processes like textile dyeing, leather tanning, electroplating, and finishing of metals contain complex mixtures of heavy metals, dyes, and POPs that pose severe risks to aquatic life and human health (Asante-Sackey et al., 2024; Singh & Sharma, 2021). For example, textile effluents have been reported to generally contain chromium, copper, cadmium, and synthetic dyes, which greatly reduce light penetration, inhibit

photosynthesis, and induce carcinogenic effects in aquatic organisms (Elgarahy et al., 2021). On the other hand, tannery wastewater possesses a high BOD, TDS, and toxic chromium(VI), hence making its disposal an environmental concern of great significance (Azanaw, 2022).

The conventional wastewater treatment technologies include coagulation-flocculation, the activated-sludge processes, and physicochemical adsorption. These

methods conventionally remove suspended solids and certain dissolved pollutants, although they are energy-intensive, chemically dependent, and often generate secondary sludge that must be treated further. Such conventional systems are often inadequate in removing emerging contaminants, including pharmaceuticals, endocrine-disrupting compounds, and microplastics.

In contrast, green chemistry, in accordance with the twelve principles set by Anastas and Warner, focuses on waste prevention, atom economy, the use of renewable feedstocks, energy efficiency, and the design of safer chemicals and products (Hjeresen et al., 2004; Anastas & Eghbali, 2010). Integrating such principles into wastewater management has opened new pathways for developing eco-friendly, low-toxicity, resource-efficient treatment processes that reduce environmental burden while maintaining high treatment efficiency.

Green chemistry-driven wastewater treatments focus on renewable adsorbents, biopolymers, catalytic degradation using sunlight or bio-derived catalysts, and recovery of valuable materials from waste streams. For example, the use of agricultural byproducts such as rice husk, sawdust, or chitosan for bio-adsorption not only removes heavy metals efficiently but also promotes circular resource utilization. Furthermore, the emerging concepts of circular economy and zero-liquid discharge have undoubtedly improved industrial water management through recovering and reusing the treated water and minimizing effluent generation. Thus, embedding green chemistry principles into industrial wastewater management directly aligns with global sustainability frameworks such as United Nations SDG 6, "Clean Water and Sanitation," and SDG 12, "Responsible Consumption and Production." By focusing on prevention rather than remediation, green chemistry helps industries achieve long-term environmental and economic benefits via cleaner production and sustainable effluent treatment systems (Patel et al., 2023).

Green Chemistry Principles in Wastewater Treatment

The twelve principles of green chemistry, including use of renewable feedstocks, prevention of waste, energy efficiency, safer solvents, and design for degradation and catalysis, can be directly applied to application in wastewater treatment. In wastewater systems, these translate into selecting adsorbents from agricultural or biowaste, designing catalysts that are reusable or biodegradable, employing solar/visible-light driven oxidation rather than high-energy UV lamps, and designing for minimal generation of secondary waste streams. For example, the valorisation of agro-industrial biowaste for the production of green nanomaterials in the treatment of wastewater shows how biomass feedstocks can be transformed into active catalysts or adsorbents-highly fitting under both green chemistry and circular economy paradigms. Recent works on biodegradable biopolymer adsorbents such as cellulose nanofibers, alginate-based hydrogels, and lignin-derived sorbents present high performance in dye and heavy metal removal from industrial effluents. Such a trend advances the transition from "end-of-pipe" remediation toward preventive, resource-efficient, and recovery-oriented systems of wastewater treatment, while supporting broader sustainability goals, including the SDGs on clean water and responsible production.

Table 1. Overview of Green Chemistry-Based Wastewater Treatment Technologies: Mechanisms, Materials, Benefits, and Challenges

Technology	Key Mechanism	Example Materials	Advantages	Limitations	References
AOPs	Radical oxidation	Fenton, TiO_2	Fast degradation	Energy-intensive	*Tripathi et al., 2023*
Biosorption	Ion exchange	Chitosan, maize stalk	Low-cost, renewable	Regeneration	*Jiménez, 2024*
Phytoremediation	Plant uptake	*Eichhornia, Lemna*	Eco-friendly	Slow kinetics	*Lidsen, 2024*

Technology	Key Mechanism	Example Materials	Advantages	Limitations	References
Membrane Filtration	Physical separation	Biopolymer UF/NF	High efficiency	Fouling	*MDPI Membrane Review, 2025*

Advanced Oxidation Processes (AOPs)

Advanced oxidation processes (AOPs) such as Fenton, photo-Fenton, ozonation, UV/H_2O_2 and heterogeneous photocatalysis generate highly reactive radicals (e.g., OH, O_2^-) capable of degrading recalcitrant organics (Tripathi et al., 2023). From a green-chemistry perspective, the aim is to drive these processes using renewable energy (e.g., solar-driven photocatalysis) or via heterogeneous catalysts that allow regeneration and minimize chemical consumption (Green Chemistry journal, 2023). For instance, green-synthesised selenium nanoparticles have been employed for dye degradation in wastewater and represent a shift towards less hazardous reagent use and resource-efficient design (Selenium NP review, 2024). While such systems have achieved removal efficiencies >90% for some textile dyes, challenges persist: high energy/chemical demand, formation of intermediate by-products, fouling in complex industrial effluents, and cost of scaling such technologies (Oladimeji, 2024; Carreira et al., 2023). Overcoming these obstacles remains critical for industrial scale-up and sustainable deployment.

Bio-adsorption and Biosorbents

Bio-adsorption uses renewable biomass-agricultural residues, microbial/fungal biomass, algae, and biopolymers-to remove heavy metals, dyes, and organics through a number of mechanisms: ion exchange, complexation, and surface binding among others. Jiménez, 2024; Kiran et al., 2025. Agricultural-waste-based sorbents are highlighted for their considerable removal efficiencies of dyes from real effluents in various studies. Bio-adsorbent review, 2025. In addition, these biosorbents are appropriate for green chemistry since the feedstocks are renewable, the processing conditions are mild (ambient temperature/pressure in most cases), and it often generates less harmful secondary waste than conventional activated carbons or synthetic resins do.

Surfactant-influenced biosorption review, 2025. Their main disadvantage is that many studies are still lab-scale, regeneration/reuse may be limited with certain biosorbents, and a very limited amount of studies have been reported concerning complex industrial streams with co-existing metals or organic loads. Carreira et al., 2023. Hybrid systems combining biosorbents with other methods might be able to fill this knowledge gap for an industrially feasible alternative.

Phytoremediation

Phytoremediation utilizes plants or algae in constructed wetlands, lagoons, or free-floating systems for the uptake, accumulation, or metabolism of pollutants (including nutrients, heavy metals, and some organics) in wastewater. Aquatic macrophytes-e.g., *Eichhornia crassipes*, Lemna minor-and algae have the added benefit of producing biomass that can be valorized-bio-char, compost, bioenergy-embracing a circular economy loop. However, applicability to high strength industrial effluents remains limited due to slower kinetics, large land/area requirements, seasonal and climatic dependencies, and the challenge of safe handling or reuse of contaminated biomass. Thus, phytoremediation is best thought of as part of a multi-tier treatment train and perhaps for polishing or low-load effluents rather than as primary treatment of heavy industrial streams.

Membrane Filtration Systems

Membrane processes, such as ultrafiltration (UF), nanofiltration (NF), reverse osmosis (RO), and forward osmosis (FO), are essential techniques in accomplishing industrial wastewater reuse and zero liquid discharge. The recent reviews illustrate that emerging membrane technologies, including but not limited to osmotic-activated reverse osmosis (OARO), further decrease the energy footprint and enhance recovery in brine-concentrating systems, thus offering more sustainable options for ZLD (MDPI Membrane

Technologies review, 2025). From a green-chemistry perspective, membranes can embed biodegradable polymers, low-fouling coatings, and eco-friendly fabrication methods (Membrane Technologies review, 2025). Pre-treatment, such as adsorption and coagulation, is necessary to minimize fouling, which extends the life of membranes and decreases the chemical cleaning demand (Membrane Technologies review, 2025). Nevertheless, key issues yet to be overcome include a high energy consumption (particular at high recovery/ZLD levels), fouling/scaling, disposal of concentrate/brine, and full life-cycle burdens-including manufacturing and end-of-life-that need to be assessed (MDPI Membrane review, 2025; Zero-liquid discharge review, 2019). A systematic techno-economic and environmental-LCA-evaluation is relevant for sustainable deployment in industries.

Green Nanomaterials and Catalytic Degradation

Green synthesized nanomaterials (e.g., metal/metal-oxide nanoparticles, carbon-nanocomposites, nanocatalysts) based on agro-industrial wastes or plant extracts offer large surface areas and catalytic/adsorption functions for wastewater remediation-purification purposes (Valorization review, 2022; Advanced bio-based nanocomposites review, 2024). These materials illustrate green-chemistry principles through the use of renewable feedstocks, less hazardous chemical precursors, and possibilities of regeneration or reuse. For instance, cellulose-derived nanofibers and bio-carbon-supported photocatalysts evidenced excellent performance in removing dyes and micropollutants (Bio-based nanocomposites review, 2024). However, large-scale industrial utilization of such systems is countered due to toxicity/ecotoxicity of nanomaterials, scaling-up cost, and logistics of recovery/regeneration with long-term stability in true effluent streams (Valorization review, 2022). It therefore implies that research needs to be focussed on the material development with industrially realistic testing and full life cycle assessment, not for real sustainability.

Circular Economy & Sustainability Assessment

Wastewater treatment is increasingly viewed through the lens of the circular economy, in which water is reused, co-products of value are recovered (metals, nutrients, salts), and residual waste is minimised or valorised. Green chemistry underpins this paradigm, having been defined as the design of materials and processes for regeneration, reuse, and low-waste end-of-life. Life-cycle assessment and techno-economic analyses are necessary to validate that "green" technologies provide true environmental and economic benefits. For example, a review on ZLD technology highlighted that while ZLD can achieve maximum water recovery along with resource recovery, high energy and cost barriers restrict industrial deployment. Similarly, the Membrane Technologies review, 2025, comments that ZLD/MLD systems can reduce fresh water use and effluent volume but face challenges with respect to concentrate management and high operational complexity. Limitations to full industrial deployment include generally weak regulatory drivers for reuse or resource recovery, low economic value of recovered materials, high capital/operational cost of advanced green systems, and integration complexity with existing industrial infrastructure. These require industry–academia–policy collaboration, innovative business models, for example, resource recovery credits, modular scalable treatment units, and digital monitoring/optimization to enhance cost effectiveness.

Conclusion

Integrating green chemistry into wastewater treatment offers a sustainable and forward-looking approach to reducing industrial pollution and conserving resources. Unlike traditional methods that rely on chemicals and produce secondary waste, green technologies emphasize prevention, efficiency, and reuse. Advanced oxidation processes, biosorbents, phytoremediation, membranes, and nanocatalysts together enable the breakdown and removal of contaminants with minimal environmental impact.

When combined with circular economy principles, these approaches support resource recovery such as water, nutrients, and metals while minimizing waste generation. Incorporating life-cycle and economic assessments ensures that such systems remain both

environmentally sound and financially viable. Ultimately, adopting green chemistry in wastewater management transforms it from a disposal-based practice into a regenerative system that promotes cleaner production and sustainable industrial growth.

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