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Green Chemistry Approaches for Wastewater Treatment: A Sustainable Framework for Environmental Remediation

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Abstract

The continuous discharge of untreated and partially treated wastewater has emerged as a serious environmental concern due to rapid industrial expansion, urban growth, and intensified agricultural activities. Conventional wastewater treatment methods, although widely applied, often depend on chemical-intensive processes and high energy consumption, which can generate secondary pollution and operational inefficiencies. In response to these challenges, green chemistry has emerged as a promising alternative approach that emphasizes the design of environmentally benign, energy-efficient, and cost-effective treatment systems. This study critically reviews major green chemistry-based wastewater treatment strategies, including adsorption using natural materials, biochar applications, biosorption techniques, phytoremediation systems, photocatalytic degradation, membrane-based filtration, and constructed wetlands. The analysis highlights that these approaches significantly reduce pollutant loads such as heavy metals, dyes, nutrients, and organic contaminants while minimizing environmental footprint. However, limitations related to scalability, treatment duration, and environmental dependency still restrict widespread industrial application. The study concludes that integrated hybrid systems supported by green chemistry principles represent the most promising direction for future wastewater management.

Keywords: Green Chemistry, Wastewater Treatment, Biochar, Adsorption, Biosorption, Phytoremediation, Sustainable Remediation

1. Introduction

Water is a vital natural resource that supports life on Earth by maintaining ecological balance, enabling biological processes, and sustaining human, agricultural, and industrial activities. However, in recent decades, the quality and availability of freshwater resources have been continuously declining due to increasing anthropogenic pressures, especially the uncontrolled discharge of wastewater from domestic households, agricultural fields, and industrial sectors. This wastewater often carries a wide range of contaminants, including toxic heavy metals, persistent organic compounds, synthetic dyes, detergents, nutrients, pharmaceutical residues, and disease-causing microorganisms, which collectively contribute to serious environmental

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degradation and health risks (UNEP, 2021; WHO, 2022).

Conventional wastewater treatment methods such as sedimentation, coagulation-flocculation, chlorination, and activated sludge processes have been widely implemented for pollution control. Although these techniques are effective to a certain extent, they are often associated with several limitations, including high energy demand, chemical dependency, incomplete removal of emerging contaminants, and the generation of large volumes of sludge that require further treatment and safe disposal. In addition, some disinfection processes may produce secondary toxic compounds, which can further affect aquatic ecosystems and human health if not properly managed (Khan et al., 2021; Sharma & Bhattacharya, 2022).

To overcome these challenges, green chemistry has emerged as a sustainable and innovative approach in the field of environmental remediation and wastewater management. This approach emphasizes the prevention of pollution at its source rather than treating it after generation, while also encouraging the use of environmentally friendly, renewable, and non-toxic materials. In the context of wastewater treatment, green chemistry promotes the development of cleaner, energy-efficient, and cost-effective technologies that reduce environmental impact and improve treatment efficiency (Anastas & Eghbali, 2020).

Recent studies conducted after 2020 have shown increasing interest in natural and bio-based treatment methods such as biosorption, phytoremediation, biochar application, microbial degradation, and green-synthesized nanomaterials. These methods have demonstrated strong potential for removing a variety of pollutants including heavy metals, dyes, and pharmaceutical compounds while minimizing secondary pollution and reducing reliance on synthetic chemicals (Zhang et al., 2022; MDPI Water, 2023). Such advancements reflect a clear shift toward integrated and sustainable wastewater treatment systems that align with global environmental goals, particularly the United Nations Sustainable Development Goal 6, which focuses on ensuring availability and sustainable management of clean water and sanitation for all.

2. Aim and Objectives

Aim

To evaluate and analyze environmentally sustainable green chemistry approaches for wastewater treatment and their effectiveness in pollutant removal.

Objectives

- To examine various eco-friendly wastewater treatment technologies
- To assess the role of natural and biological materials in pollutant removal
- To compare the efficiency of different green treatment methods
- To identify challenges affecting their large-scale application
- To suggest future improvements in sustainable water treatment systems

3. Methodology

The present study is designed as a qualitative, literature-based analytical review that systematically synthesizes existing scientific knowledge related to green chemistry approaches in wastewater treatment. Rather than relying on primary experimental or field-based data collection, this research compiles and critically examines information obtained from credible secondary sources, including peer-reviewed journal articles, scientific research papers, academic books, and recognized institutional and governmental reports published in the field of environmental science and engineering.

The collected literature was carefully screened, categorized, and analyzed in order to ensure relevance, reliability, and scientific validity. A structured approach was adopted to extract meaningful insights from diverse studies, enabling a comprehensive understanding of the current advancements and limitations in green wastewater treatment technologies. Particular emphasis was placed on recent publications to ensure that the analysis reflects contemporary developments in sustainable environmental remediation practices.

The synthesized information was evaluated to understand several key aspects of wastewater treatment systems, including the underlying mechanisms involved in pollutant removal, the operational principles of green chemistry-based treatment methods, and the comparative efficiency of different eco-friendly technologies. In addition, attention was given to assessing the environmental benefits associated with these approaches, such as reduced chemical usage, lower sludge generation, energy efficiency, and minimized secondary pollution.

Furthermore, the study critically examines the limitations and challenges associated with the practical implementation of green treatment techniques, particularly in real-world conditions where factors such as cost, scalability, operational stability, and environmental variability play a significant role. The applicability of these methods at industrial, municipal, and rural levels has also been considered to provide a realistic perspective on their effectiveness beyond laboratory-scale studies.

Overall, the research adopts a comparative analytical framework rather than an experimental design, allowing for an in-depth evaluation of multiple treatment strategies. This approach helps in identifying gaps in existing knowledge, highlighting promising sustainable technologies, and providing a holistic understanding of green chemistry applications in wastewater treatment systems.

4. Green Chemistry-Based Wastewater Treatment Approaches

4.1 Natural Adsorption Processes

In recent years, natural adsorbents have emerged as a highly promising and sustainable alternative for wastewater treatment due to their low environmental impact, economic feasibility, and wide availability. A growing body of research highlights the effectiveness of various agricultural waste materials, clay-based minerals, and plant-derived carbonaceous substances in the removal of a broad spectrum of water pollutants. Materials such as coconut shell, rice husk, sawdust, banana peels, sugarcane bagasse, and other lignocellulosic wastes have demonstrated significant potential in treating contaminated water due to their porous structure, high surface area, and presence of functional groups capable of binding pollutants.

The mechanism of action in these natural adsorbents primarily involves surface adsorption processes, where contaminants present in wastewater adhere to the active sites available on the adsorbent surface. These interactions may include physical adsorption, ion exchange, electrostatic attraction, and complexation reactions depending on the nature of both the pollutant and the adsorbent material. The porous architecture of these biomaterials enhances their ability to trap suspended particles, heavy metal ions, and organic dye molecules, thereby improving overall water quality in an efficient and eco-friendly manner.

One of the major advantages of using natural adsorbents is their low production cost, as they are often derived from agricultural or plant-based waste materials that are abundantly available and otherwise considered disposal problems. Their utilization not only reduces environmental pollution but also contributes to waste valorization and circular economy practices. Additionally, these materials have shown strong efficiency in the removal of toxic heavy metals such as lead, cadmium, and chromium, as well as synthetic dyes commonly released from textile and industrial effluents.

Another important benefit is their environmentally safe disposal, as spent adsorbents are generally biodegradable or can be safely incinerated without producing highly toxic residues. This makes them a more sustainable option compared to conventional synthetic adsorbents or chemical treatment agents. However, despite these advantages, certain limitations still exist. The adsorption capacity of these materials is often restricted by the saturation of active binding sites over time, which reduces their long-term effectiveness. In addition, many natural adsorbents exhibit limited regeneration and reuse potential, which can affect their practical applicability in large-scale or continuous treatment systems.

Therefore, while natural adsorbents represent an efficient and eco-friendly approach to wastewater treatment, further research is required to enhance their adsorption capacity, improve regeneration techniques, and optimize their performance for long-term and large-scale environmental applications.

4.2 Biochar-Based Wastewater Treatment

Biochar is a carbon-rich, porous material produced through the thermal decomposition of biomass under controlled conditions with limited oxygen supply, a process commonly referred to as pyrolysis. In recent years, it has gained significant attention in environmental remediation due to its high surface area, stable carbon structure, and strong adsorption potential. The physicochemical properties of biochar, including pore size distribution, surface functional groups, and aromatic carbon content, make it highly suitable for capturing a wide range of contaminants from aqueous environments.

Biochar has been widely applied for the removal of heavy metals such as lead, cadmium, arsenic, and chromium, as well as organic pollutants including dyes, pesticides, and pharmaceutical residues. Its effectiveness is largely attributed to mechanisms such as surface adsorption, ion exchange, and complexation reactions, which allow contaminants to bind strongly to its surface.

One of the major advantages of biochar is its ability to utilize agricultural and organic waste materials such as crop residues, wood chips, and forestry waste, thereby contributing to waste valorization and sustainable resource management. Additionally, biochar exhibits long-term carbon stability, which not only enhances its durability in environmental applications but also contributes to carbon sequestration, making it a climate-friendly material. Its relatively high adsorption capacity further strengthens its applicability in large-scale wastewater treatment systems.

However, despite these advantages, the performance of biochar is not uniform and may vary significantly depending on the type of feedstock used, pyrolysis temperature, heating rate, and production conditions. These variations can influence its surface chemistry and adsorption efficiency, thereby posing challenges for standardization and large-scale implementation.

4.3 Biosorption Techniques

Biosorption is an eco-friendly wastewater treatment process that utilizes biological materials, including both living and non-living biomass such as bacteria, fungi, algae, and yeast, for the removal of pollutants from contaminated water. This method primarily relies on passive binding mechanisms, where metal ions and other contaminants adhere to functional groups present on the surface of microbial cell walls, including carboxyl, hydroxyl, phosphate, and amino groups.

This technique has demonstrated high efficiency in removing toxic heavy metals such as lead, cadmium, mercury, and chromium from industrial effluents. The process is particularly attractive because it does not require the metabolic activity of living organisms, making it applicable even under non-growth conditions.

Biosorption is considered cost-effective and environmentally sustainable due to the use of naturally available biological materials and minimal chemical input. However, its performance can be influenced by several environmental factors, including pH, temperature, presence of competing ions, and ionic strength of the solution. These factors may reduce adsorption efficiency and operational stability under varying real-world conditions.

4.4 Phytoremediation Systems

Phytoremediation is a green and sustainable wastewater treatment approach that employs aquatic and terrestrial plants to absorb, accumulate, transform, or stabilize pollutants present in contaminated water bodies. Commonly used plant species include water hyacinth (*Eichhornia crassipes*), duckweed (*Lemna minor*), and cattail (*Typha latifolia*), all of which are known for their high tolerance to polluted environments and rapid growth rates.

This method operates through natural biological processes such as phytoextraction, phytodegradation, rhizofiltration, and phytostabilization, making it an environmentally friendly and low-energy treatment option. In addition to pollutant removal, phytoremediation systems also contribute to habitat creation and ecological restoration.

Despite its sustainability, phytoremediation has certain limitations. The overall treatment process is relatively slow compared to conventional technologies, and its efficiency is highly dependent on climatic and seasonal conditions that affect plant growth. Furthermore, extreme pollutant concentrations may inhibit plant survival and reduce system effectiveness.

4.5 Photocatalytic Treatment

Photocatalytic wastewater treatment is an advanced oxidation process that utilizes semiconductor materials such as titanium dioxide (TiO_2), zinc oxide (ZnO), and other modified photocatalysts to degrade organic pollutants under ultraviolet or solar radiation. When exposed to light energy, these materials generate reactive oxygen species, including hydroxyl radicals and superoxide ions, which are highly effective in breaking down complex organic compounds.

This process is particularly efficient in the degradation of persistent pollutants such as synthetic dyes, pharmaceutical residues, and industrial organic waste, converting them into harmless end products such as carbon dioxide, water, and mineralized ions.

Photocatalysis is considered an environmentally safe technology because it does not require additional chemical reagents and can utilize solar energy as a renewable resource. However, its effectiveness is often limited by dependence on light intensity, wavelength sensitivity of catalysts, and difficulties associated with catalyst recovery and reuse after treatment.

4.6 Membrane-Based Green Filtration Systems

Membrane filtration technologies, including ultrafiltration, nanofiltration, and reverse osmosis, have become increasingly important in modern wastewater treatment due to their ability to produce high-quality effluent with effective removal of suspended solids, dissolved salts, and organic contaminants. Recent advancements in green chemistry have led to the development of bio-based and energy-efficient membrane materials designed to reduce chemical usage and operational costs.

These membrane systems operate by selectively allowing water molecules to pass through while retaining contaminants based on size exclusion, charge repulsion, and diffusion mechanisms. As a result, they provide a highly efficient barrier against a wide range of pollutants.

However, membrane technologies are often affected by fouling, which refers to the accumulation of organic matter, microorganisms, and inorganic particles on the membrane surface. This issue reduces permeability, increases maintenance requirements, and may lead to higher operational costs if not properly managed.

4.7 Constructed Wetlands

Constructed wetlands are engineered ecological systems designed to replicate the natural processes occurring in wetlands for the treatment of wastewater. These systems integrate vegetation, soil or substrate media, and microbial communities to facilitate the removal of pollutants through physical, chemical, and biological processes.

The treatment mechanisms include sedimentation, filtration, microbial degradation, plant uptake, and nutrient transformation, making constructed wetlands a highly sustainable and nature-based solution for wastewater management. They are particularly effective in treating domestic sewage, agricultural runoff, and low-strength industrial effluents.

One of the major advantages of constructed wetlands is their low energy requirement and minimal operational cost, as they rely primarily on natural processes rather than mechanical or chemical inputs. However, their application is limited by the requirement of large land areas and their sensitivity to seasonal variations, which can influence plant growth and microbial activity, thereby affecting overall treatment efficiency.

5. Comparative Evaluation of Methods

Treatment Method	Efficiency	Cost	Environmental Impact	Scalability
Natural Adsorption	High	Low	Very Low	Medium
Biochar	High	Low–Medium	Very Low	Medium
Biosorption	High (metals)	Low	Very Low	Low–Medium
Phytoremediation	Moderate	Very Low	Very Low	Low
Photocatalysis	Very High	Medium	Very Low	Medium
Wetlands	High	Low	Very Low	Medium

6. Discussion

The reviewed literature collectively demonstrates that green chemistry-based approaches offer highly effective, sustainable, and environmentally responsible solutions for modern wastewater treatment challenges. A consistent finding across recent studies is that conventional treatment systems alone are often insufficient for managing emerging pollutants; therefore, eco-friendly and hybridized treatment strategies are increasingly being adopted to enhance removal efficiency and reduce environmental burden (Sharma & Bhattacharya, 2022; Zhang et al., 2022).

Among the various green treatment techniques examined, adsorption-based methods and biochar-derived systems have shown particularly strong performance in the removal of heavy metals, dyes, and persistent organic contaminants. The high surface area, tunable surface chemistry, and porous structure of biochar significantly improve its adsorption capacity, making it one of the most promising low-cost materials for large-scale wastewater remediation. Recent studies further confirm that modified biochar and composite adsorbents can achieve enhanced removal efficiency due to improved functional group availability and increased surface reactivity (Verma & Singh, 2023; Gupta & Nayak, 2024). These findings highlight adsorption as one of the most reliable and scalable green chemistry tools for water purification.

Biological treatment approaches such as biosorption and phytoremediation also present sustainable and energy-efficient alternatives by utilizing natural biological systems for pollutant removal. Biosorption, in particular, has demonstrated strong affinity for toxic metal ions through interactions with microbial cell wall functional groups, while phytoremediation systems utilize plant uptake and transformation mechanisms to reduce pollutant loads in contaminated water bodies. However, despite their environmental advantages, these biological methods are often constrained by relatively slow processing rates, seasonal variability, and sensitivity to environmental conditions such as pH, temperature, and pollutant concentration (Khan et al., 2021; Frontiers in Environmental Science, 2021). These limitations reduce their applicability in high-load industrial wastewater treatment scenarios.

Photocatalytic treatment systems represent another highly efficient green technology capable of degrading complex organic pollutants through reactive oxygen species generated under UV or solar irradiation. Semiconductor materials such as TiO_2 and ZnO have been widely studied for their strong oxidative potential and ability to mineralize dyes, pharmaceuticals, and other persistent organic compounds into harmless end products. However, literature indicates that the practical application of photocatalysis is still limited by dependency on light availability, catalyst recovery challenges, and the need for improved visible-light-active materials for real-world environmental conditions (Zhang et al., 2022).

Overall, the comparative analysis of different green chemistry approaches suggests that no single method is sufficient to address the complexity of wastewater pollution. Instead, hybrid treatment systems that integrate multiple green technologies—such as adsorption combined with biological treatment, or photocatalysis coupled with membrane filtration—are emerging as the most promising and effective direction for future wastewater management strategies. These integrated systems offer synergistic benefits, including improved pollutant removal efficiency, reduced operational limitations, and enhanced adaptability to varying wastewater compositions, thereby aligning with global sustainability goals and circular economy principles (Anastas & Eghbali, 2020; Gupta & Nayak, 2024).

7. Challenges and Limitations

Despite significant progress, several issues still restrict widespread adoption:

- Lack of large-scale industrial implementation
- Variability in performance under changing environmental conditions
- Limited regeneration of natural materials
- Slow processing rates in biological systems
- Requirement for optimization in hybrid systems

8. Future Perspectives

Future research in this field is expected to focus on:

- Development of nanomaterial-enhanced green adsorbents
- Integration of artificial intelligence for treatment optimization
- Solar-driven photocatalytic systems

- Circular economy-based wastewater recovery models
- Large-scale sustainable treatment plants using hybrid systems

9. Conclusion

Green chemistry-based wastewater treatment strategies represent a significant shift from conventional pollution control approaches toward more sustainable, resource-efficient, and environmentally responsible solutions. These methods are designed not only to remove contaminants from water but also to minimize the generation of secondary pollution, reduce dependency on hazardous chemicals, and lower overall energy consumption during treatment processes. In comparison to traditional physicochemical and biological treatment systems, green chemistry approaches emphasize pollution prevention at the source and the use of renewable, non-toxic, and naturally derived materials, making them highly relevant in the context of increasing global water stress and environmental degradation.

Among the various techniques studied, adsorption-based processes, biochar applications, biosorption systems, phytoremediation, and photocatalytic degradation have demonstrated considerable effectiveness in addressing a wide range of water pollutants. Adsorption and biochar-based systems are particularly efficient in capturing heavy metals, dyes, and organic contaminants due to their high surface area, porous structure, and tunable surface chemistry. Similarly, biosorption and phytoremediation utilize biological organisms and plant systems to naturally uptake or immobilize pollutants, offering an eco-friendly and low-energy alternative for wastewater purification. Photocatalytic processes further enhance treatment efficiency by utilizing light-driven reactions to degrade complex organic compounds into less harmful or mineralized end products, thereby improving overall water quality without extensive chemical usage.

Despite these significant advantages, several limitations still restrict the large-scale and long-term application of these green treatment technologies. Issues such as variability in raw material properties, limited regeneration capacity of adsorbents, slower treatment rates in biological systems, and dependency on environmental conditions continue to pose challenges in practical implementation. In addition, scaling laboratory-optimized processes to industrial or municipal levels requires further optimization in terms of design, cost-effectiveness, and operational stability.

However, continuous progress in materials science, nanotechnology, biotechnology, and environmental engineering is steadily addressing many of these limitations. Recent research indicates that the development of modified biochar, engineered adsorbents, advanced microbial systems, and visible-light-responsive photocatalysts is significantly improving treatment efficiency and broadening the applicability of green technologies. These innovations are making it possible to design more robust, adaptive, and high-performance wastewater treatment systems that can operate effectively under diverse environmental conditions.

Overall, the future of sustainable wastewater management is likely to be driven by integrated or hybrid treatment systems that combine multiple green chemistry approaches within a single framework. Such combined systems can harness the strengths of different technologies while compensating for their individual limitations, thereby achieving higher pollutant removal efficiency and greater operational reliability. This integrated approach aligns closely with global environmental sustainability goals and represents a promising pathway toward the development of next-generation wastewater treatment strategies.

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