



E-ISSN: 2707-837X

P-ISSN: 2707-8361

[Journal's Website](#)

IJCEAE 2024; 5(2): 81-86

Received: 02-09-2024

Accepted: 05-10-2024

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Advanced wastewater treatment technologies: Trends, innovations, and environmental impact

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DOI: <https://www.doi.org/10.22271/27078361.2024.v5.i2a.79>

Abstract

Advanced wastewater treatment technologies are increasingly essential for addressing the complex challenges associated with modern water pollution and resource management. This essay provides an overview of key developments, including membrane-based systems, advanced oxidation processes, and recent advances in biological treatment. Trends such as the integration of resource recovery strategies and approaches inspired by the circular economy are explored, illustrating the shift toward sustainable water management. The discussion also examines the environmental implications associated with implementing these novel technologies, including benefits such as reduced pollutant loads and potential concerns regarding by-product formation. By synthesizing current innovations and evaluating their environmental outcomes, the essay offers insights into the direction of the field and the broader significance of adopting advanced approaches in wastewater treatment.

Keywords: Advanced wastewater treatment, environmental sustainability, pollution reduction, resource recovery and carbon footprint

Introduction

The advancement of wastewater treatment technologies has become increasingly vital in response to rising environmental and public health demands. Contemporary urbanization, industrial activity, and population growth have contributed to the escalation of diverse pollutants in water resources, necessitating robust and adaptable treatment solutions. Modern approaches to wastewater management extend beyond conventional practices, integrating novel techniques designed to remove emerging contaminants and support sustainability objectives. This essay first presents an overview of existing treatment strategies, before exploring recent trends and technological breakthroughs such as membrane-based systems, advanced oxidation processes, and innovations in biological processes. Subsequently, it assesses how resource recovery and circular economy concepts are being incorporated and concludes with an evaluation of environmental impacts, thereby providing a structured analysis of both technological advancement and ecological considerations in this crucial field.

Overview of Wastewater Treatment

Traditional wastewater treatment processes are organized into a series of physical, chemical, and biological stages, each addressing specific contaminants present in municipal and industrial effluents. Initial steps such as screening and sedimentation target large debris and suspended solids, thereby easing the subsequent load on downstream systems. Following these preparatory measures, biological processes including activated sludge systems and biofilm reactors serve to reduce organic matter and nutrients, primarily through the metabolic activity of microbial communities (Chen *et al.*, 2020) [3]. Secondary clarifiers then separate biomass from treated water, while additional chemical treatments may be applied to remove residual phosphates or other recalcitrant substances. Understanding these foundational stages is critical, as they not only achieve established removal objectives but also set the operational context within which newer advancements, such as enhanced biological nutrient removal or membrane bioreactors, are developed and implemented. Table 1 compares major advanced wastewater treatment technologies, highlighting how each method works, its benefits, and its limitations. Membrane-based systems such as RO, NF, UF, and MBR offer high purification efficiency and are ideal for water reuse, though they

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often face challenges like fouling and high energy consumption. Advanced Oxidation Processes (AOPs) are powerful for removing persistent contaminants and pharmaceuticals, but they can be expensive and may generate secondary by-products. Biological innovations like

MBRs and MBBRs provide effective nutrient removal and operate in compact spaces, yet they require careful management and can be sensitive to toxic loads. Overall, the table emphasizes that each treatment method has unique strengths suited to specific wastewater challenges.

Table 1: Advanced Wastewater Treatment Technologies and Their Key Features

Technology	Main Mechanism	Key Advantages	Limitations
Membrane-Based Technologies (RO, UF, NF, MBR)	Physical separation using selective membranes	High removal efficiency, suitable for water reuse, low chemical use, recovery of metals	Membrane fouling, high energy demand, costly maintenance
Advanced Oxidation Processes (AOPs) (UV/H ₂ O ₂ , Ozone, Fenton)	Generation of hydroxyl radicals to oxidize pollutants	Effective for pharmaceuticals & emerging contaminants, strong mineralization capability	High operational costs, catalyst stability issues, possible by-product formation
Biological Innovations (MBRs, MBBRs)	Enhanced microbial degradation with film or membrane support	High nutrient removal, compact systems, adaptable to variable wastewater	Sensitive to toxic shocks, requires skilled operation, complex system control

However, despite the widespread use of conventional wastewater treatment methods, several limitations restrict their performance and environmental safety. Standard biological processes often fail to eliminate certain persistent contaminants, including pharmaceutical residues and emerging micropollutants, resulting in their eventual discharge into receiving water bodies. Furthermore, reliance solely on biological treatment methods has been linked to the proliferation of antibiotic-resistant bacteria, which poses additional ecological and public health risks (Noor *et al.*, 2023) ^[13]. The inability of conventional systems to fully address these issues has led to concerns about the long-term impacts on water quality and ecosystem stability. These drawbacks highlight the necessity for integrating advanced methods that can target a broader spectrum of contaminants while minimizing the generation of harmful by-products, thus prompting research and innovation within the field of wastewater management.

Emerging Trends in Wastewater Treatment

In recent years, there has been a pronounced worldwide shift toward the development and adoption of more sustainable and efficient wastewater treatment technologies. Efforts to promote water reuse, conserve energy, and minimize environmental footprint have become central objectives driving contemporary innovations in this domain. Policy measures, including the enforcement of stricter regulations and the imposition of substantial financial penalties for improper disposal practices, have significantly influenced the direction of research and industry priorities (Ahmed *et al.*, 2021) ^[1]. These changes are not only shaping technical advancements but also encouraging the incorporation of resource management strategies and adaptive infrastructure within treatment facilities. Consequently, the increasing alignment of policy frameworks with technological progress has compelled stakeholders to prioritize approaches that emphasize both environmental stewardship and operational efficiency, further accelerating the transition toward advanced methods in wastewater management (Ahmed *et al.*, 2021) ^[1]. Additionally, heightened regulatory requirements and growing public awareness have accelerated the transition toward advanced wastewater treatment technologies. Regulatory agencies now demand compliance with stricter discharge limits and promote standardization efforts that create incentives for the adoption of highly effective

processes. These measures are complemented by increased public scrutiny regarding water pollution, pressuring both government bodies and private operators to invest in cleaner, more reliable treatment systems. In the context of ongoing technological innovation, such as the application of materials genomics and artificial intelligence, regulatory and societal forces have directed research priorities toward health protection and environmental preservation (Huang *et al.*, 2024) ^[6]. By directly influencing innovation agendas, the convergence of public demand and policy oversight has proven catalytic in setting ambitious goals for carbon and pollution reduction and thus advancing the widespread implementation of next-generation wastewater treatment approaches.

Furthermore, the integration of digital monitoring and automation technologies has transformed operational practices within modern wastewater treatment facilities. Advanced sensor networks and automated control systems enable continuous tracking of key process indicators, supporting rapid identification of inefficiencies and potential failures. Automated sampling and analysis platforms not only help in maintaining compliance with regulatory requirements but also streamline the adjustment of treatment parameters for optimal performance. These developments permit real-time data acquisition and nuanced process control, further supported by advancements such as remote diagnostics and site-wide digital twins (Pronk *et al.*, 2019) ^[19]. By incorporating digital solutions, treatment plants can improve reliability and efficiency, ultimately advancing the industry’s ability to meet both environmental standards and evolving public expectations for water quality management.

Membrane-Based Technologies

Among the most prominent advancements in modern wastewater management are membrane-based filtration techniques, which harness physical barriers to selectively separate contaminants from water. Fundamental methods include reverse osmosis, ultrafiltration, and nanofiltration, each distinguished by the size exclusion properties of their membranes and the range of pollutants they can remove. Reverse osmosis is particularly noted for its ability to eliminate dissolved salts and small organic molecules, while ultrafiltration and nanofiltration effectively target larger solutes and suspended particulates, often as part of advanced treatment schemes. These systems are increasingly favored

for their capacity to produce permeate suitable for water reuse, thus supporting both regulatory requirements and sustainability objectives in various industrial applications (Mansor *et al.*, 2024) ^[12]. In addition, recent innovations in membrane fabrication, such as the development of thin-film composites and nanocomposite materials, have contributed to improved operational stability and contaminant removal efficiency, further broadening the role of membrane technologies in wastewater treatment (Mansor *et al.*, 2024) ^[12].

Moreover, membrane-based technologies offer compelling advantages that extend beyond conventional contaminant removal capabilities. Their capacity to selectively extract a wide spectrum of pollutants including dissolved salts, heavy metals, and recalcitrant organic compounds enables the production of effluents suitable for direct water reuse and industrial recycling initiatives. This specificity supports compliance with stringent discharge criteria while minimizing the introduction of toxic substances into receiving environments. Additionally, advancements in membrane materials have facilitated the recovery of valuable metals from industrial wastewater, thereby improving the economic feasibility of treatment processes alongside environmental performance (Azmi *et al.*, 2025) ^[2]. Through reduced chemical consumption and lower sludge generation, membrane technologies not only decrease operational costs but also contribute to the broader goals of sustainable water management and reduced ecological burden (Azmi *et al.*, 2025) ^[2].

However, despite the important advantages provided by membrane-based technologies, several operational barriers have hampered their broader adoption in wastewater treatment contexts. Membrane fouling remains a primary obstacle as the accumulation of biological or inorganic material on the membrane surface leads to flux decline and necessitates frequent cleaning, which can disrupt process continuity. Elevated energy demands, particularly in pressure-driven configurations, further accentuate operational challenges by increasing treatment costs and intensifying the overall environmental footprint. Additionally, the regular maintenance and replacement of fouled membranes drive up long-term expenditures, thus raising concerns about the economic viability of these systems for widespread implementation (Pronk *et al.*, 2019) ^[19]. Recent developments such as gravity-driven membrane filtration have attempted to circumvent some of these limitations by relying on lower transmembrane pressure and leveraging biofilm properties for flux stabilization, yet ongoing research is essential to mitigate persistent fouling and reduce associated energy and cost burdens (Pronk *et al.*, 2019) ^[19].

Advanced Oxidation Processes (AOPs)

Advanced oxidation processes (AOPs) represent a suite of chemical treatment techniques designed to degrade persistent organic pollutants that resist removal by conventional wastewater treatment methods. These processes rely on the in situ generation of highly reactive species, primarily hydroxyl radicals, which possess strong oxidative power and can mineralize refractory organic contaminants into more biodegradable compounds. Various AOP configurations exist, including systems based on ozonation, UV/H₂O₂, Fenton reactions, and emerging non-conventional methods such as microwave, ultrasound, and

plasma pulse-assisted oxidation, all of which offer distinctive operational mechanisms for pollutant breakdown. The effectiveness of AOPs in targeting recalcitrant organics addresses a critical limitation of established technologies and reduces the risk of secondary pollution associated with incomplete contaminant removal (Manna & Sen, 2023) ^[11]. As ongoing research explores the integration and optimization of these systems, AOPs are poised to play an increasingly prominent role in meeting advanced wastewater treatment objectives and regulatory standards.

In addition, the demonstrated capacity of advanced oxidation processes (AOPs) to remove pharmaceuticals, endocrine disruptors, and other emergent contaminants has been a key factor in their increasing prominence within wastewater treatment strategies. The strong oxidizing potential of hydroxyl radicals generated in systems such as UV/H₂O₂, Fenton, and ozonation enables the extensive degradation of compounds that are resistant to conventional biological and chemical treatments. This accelerated oxidative breakdown leads to the mineralization of complex organic molecules, effectively transforming hazardous pharmaceuticals and hormone-like substances into more benign by-products or carbon dioxide (Pandis *et al.*, 2022) ^[15]. Studies further highlight the ability of combined AOPs to address a diverse array of persistent pollutants often detected at trace levels in effluent streams, thus meeting regulatory demands for water quality. As such, the broad applicability and mechanistic flexibility of AOPs offer treatment facilities effective options for reducing risks associated with emerging contaminants while contributing to global environmental waste management objectives (Pandis *et al.*, 2022) ^[15].

Nevertheless, the widespread adoption of advanced oxidation processes hinges on a complex balance between their environmental advantages and economic viability. While AOPs such as sulfate radical-based methods demonstrate considerable effectiveness in degrading organic pollutants, the sustainability of these systems depends on the stability and reusability of catalytic materials, particularly in large-scale applications (Du & Zhou, 2021) ^[4]. The need for frequent catalyst regeneration or replacement and the associated costs can undermine the economic feasibility of these processes, especially when compared to established methods. Furthermore, the procurement of high-performance catalysts, such as tailored metal-organic frameworks, often entails significant financial investment, which may limit their use in resource-constrained settings. From an environmental perspective, ensuring that these catalysts do not introduce secondary pollution or excessive resource consumption is critical, and ongoing research regarding catalyst optimization, functionalization, and composite strategies aims to address both economic and ecological challenges in AOP implementation (Du & Zhou, 2021) ^[4].

Biological Innovations

Recent developments in biological treatment have led to the adoption of advanced systems that improve both contaminant removal and operational efficiency in wastewater facilities. Notably, biological wastewater treatment systems now integrate membrane bioreactors (MBRs) and moving bed biofilm reactors (MBBRs), which offer heightened capacity for nitrogen and phosphorus removal compared with conventional biological methods.

These systems combine established microbial processes with technologies that promote extensive contact between wastewater and bioactive surfaces, resulting in higher biodegradation rates and a reduction in land requirements. For example, a contemporary biological treatment design unites a membrane bioreactor with a multi-stage outlet control system, successfully reducing nutrients, pathogenic bacteria, heavy metals, and hydrocarbons while also lowering biological oxygen demand and controlling algae proliferation (Liu *et al.*, 2019) ^[10]. As these innovations become more widespread, treatment plants benefit from extended operating life, improved water quality, and the potential for decreased operational costs, thereby reinforcing the role of biological processes as central components in advanced wastewater management (Liu *et al.*, 2019) ^[10]. Furthermore, these advanced biological systems offer pronounced benefits in operational efficiency, compactness, and adaptability to varying wastewater compositions. Their improved nutrient removal rates, often stemming from optimized biofilm formation or enhanced membrane integration, enable treatment facilities to achieve rigorous discharge standards within shorter retention periods and with reduced energy needs. The condensed physical footprint of membrane bioreactors and moving bed biofilm reactors allows for facility installation in urban or spatially restricted environments, addressing one of the persistent challenges faced by conventional treatment plants (Jin *et al.*, 2023) ^[7]. Adaptability is also a core attribute, as recent innovations in filtration media and microbial consortia permit effective targeting of a broader range of emerging pollutants and fluctuating influent qualities. As an ongoing trend, the transition toward environmentally conscious and bio-enhanced filtration not only caters to stricter environmental policy but also stands resilient against shifts in industrial activity and regulatory expectations (Jin *et al.*, 2023) ^[7].

However, there are important drawbacks associated with advanced biological treatment systems that warrant careful consideration within operational and design frameworks. A major challenge lies in their pronounced sensitivity to toxic shocks, as abrupt influxes of harmful chemicals or variable influent compositions can disrupt microbial activity and compromise overall treatment efficacy. Additionally, these systems often require specialized operational protocols and highly trained personnel to manage and maintain optimal performance conditions, especially in the context of

complex process configurations and advanced filtration media (Jin *et al.*, 2023) ^[7]. This level of technical sophistication not only increases labor demands but can also constrain the suitability of such systems for deployment in regions lacking necessary expertise or consistent resource availability. As the adoption of environmentally friendly and bio-enhanced biological filtration techniques continues, addressing these operational vulnerabilities and demands will remain critical for ensuring stable, resilient, and scalable wastewater treatment outcomes (Jin *et al.*, 2023) ^[7].

Resource Recovery and Circular Economy Approaches

As wastewater management evolves, resource recovery has emerged as a foundational concept aligned with circular economy principles in the sector. Within this framework, the extraction of nutrients such as phosphorus and nitrogen, the generation of renewable energy from sludge treatment, and the reclamation of high-quality water for reuse are prioritized. These practices shift the perception of wastewater from merely a substance to be treated and disposed of, toward one viewed as a valuable source of secondary resources suitable for reintegration into industrial, agricultural, or municipal cycles (Preisner *et al.*, 2022) ^[16]. In order to implement resource recovery effectively, wastewater treatment facilities have increasingly turned to technological solutions and monitoring frameworks that support sustainable management and optimize process efficiencies. According to recent evaluations, comprehensive indicators that assess not only technical performance but also environmental and service coverage metrics are essential to guide and refine resource recovery efforts within the circular economy model (Preisner *et al.*, 2022) ^[16]. Table 2 describes how modern wastewater systems transform waste into valuable resources as part of a circular economy approach. Phosphorus and nitrogen are recovered through techniques like struvite precipitation and ammonia stripping, producing fertilizers and industrial compounds. Anaerobic digestion converts organic matter into biogas, offering renewable energy. Membrane filtration and AOPs allow the safe reuse of treated water for irrigation or industry. Processes such as hydrothermal liquefaction convert sludge into biochar and bio-oil, supporting soil health and renewable fuel production. The table highlights how wastewater treatment is shifting from pollutant removal to resource recovery and sustainability enhancement.

Table 2: Resource Recovery Approaches in Circular Economy-Based Wastewater Management

Resource Recovered	Technique Used	Output/Product	Application
Phosphorus	Struvite precipitation	Struvite crystals	Fertilizer manufacturing
Nitrogen	Ammonia stripping, selective microbial cultivation	Ammonium salts, nitrogen compounds	Agriculture, industrial feedstocks
Energy (Biogas)	Anaerobic digestion	Biogas (CH ₄ -rich)	Electricity, heat generation
Water Reuse	Membrane filtration, AOP polishing	High-quality recycled water	Irrigation, industrial processes, replenishment
Biochar/Bio-oil	Hydrothermal liquefaction & sludge processing	Biochar, bio-oil	Soil amendment, renewable fuel

For example, several advanced technologies have been deployed to recover phosphorus, nitrogen, and biogas efficiently from various wastewater streams. Processes such as struvite precipitation enable the extraction of phosphorus by facilitating its crystallization, which can be subsequently utilized as fertilizer. Ammonia stripping and selective

microbial cultivation are popular approaches for nitrogen recovery, producing compounds applicable in agriculture or as industrial feedstocks (Durkin *et al.*, 2022) ^[5]. Anaerobic digestion, an established technique, converts organic matter in sludge into biogas, which can be harnessed for electricity or heat generation, thereby contributing to renewable energy

goals. Integrated resource recovery systems, especially those optimized for food-processing wastewater, further enhance these processes through enhanced analytics, specialized microbial cultures, and efficient separation methods, underscoring the importance of technological synergy in maximizing both nutrient and energy retrieval (Durkin *et al.*, 2022) ^[5]. Consequently, the integration of circular economy principles into wastewater management provides both environmental and economic advantages that extend beyond traditional linear models. Implementation of resource recovery processes, particularly when facilities are retrofitted with advanced conversion technologies, enables the transformation of waste streams into marketable products such as biochar and renewable fuels, thereby supporting financial sustainability (Tian *et al.*, 2020) ^[18]. In one techno-economic analysis, retrofitting municipal treatment plants with hydrothermal liquefaction and up-flow anaerobic sludge blankets demonstrated the highest net present value over a twenty-year period, despite the presence of increased annual production costs (Tian *et al.*, 2020) ^[18]. This approach not only diverts potentially harmful outputs from disposal but also reduces reliance on primary materials, further decreasing lifecycle environmental impacts associated with typical chlorination and resource extraction processes. By coupling economic incentives with environmental stewardship, the circular economy paradigm thus offers a practical pathway for wastewater facilities to reach operational goals while advancing broader sustainability objectives.

Environmental Impact Assessment

In evaluating advanced wastewater treatment technologies, it is essential to consider both their beneficial and adverse environmental outcomes. On one hand, the adoption of innovative approaches such as membrane filtration, advanced oxidation, and resource valorisation has driven considerable reductions in pollutant discharge, directly improving water quality and decreasing the burden on aquatic ecosystems. These technologies also facilitate the recovery of valuable materials, such as nutrients and energy carriers, allowing for the conversion of waste streams into useful products a process that supports circular economy objectives and reduces dependence on primary resources (Kathi *et al.*, 2023) ^[8]. Nevertheless, certain unintended

consequences may arise, including the introduction of secondary contaminants or increased energy consumption associated with treatment processes, potentially offsetting some ecological benefits. As such, a rigorous assessment of environmental impacts remains crucial for guiding the sustainable development, deployment, and continual refinement of advanced wastewater treatment systems in order to maximize net positive outcomes while managing emergent risks (Kathi *et al.*, 2023) ^[8]. Moreover, life cycle assessment (LCA) has become a crucial tool for evaluating the sustainability of emerging wastewater treatment technologies by quantifying environmental impacts across all stages of a technology’s implementation. Through systematic accounting of resource consumption, emissions, and waste generation, LCA enables stakeholders to compare alternative treatment options on a comprehensive basis, providing a clearer perspective on trade-offs between environmental benefits and drawbacks. This methodology aligns well with the integration of advanced processes and circular economy strategies, as it assesses both direct operational footprints and indirect effects, such as those related to resource recovery or energy demand (Pandey, 2025) ^[14]. By incorporating LCA findings, decision-makers are better equipped to refine system configurations and prioritize technological investments that align with zero-discharge and sustainability targets. Collectively, the application of LCA supports the design of closed-loop wastewater management systems that fulfill both regulatory and ecological objectives, while highlighting areas needing further optimization (Pandey, 2025) ^[14]. Table 3 outlines how advanced wastewater technologies influence the environment. These systems improve water quality by removing complex pollutants, though some processes like AOPs may create intermediate products that need further treatment. Resource conservation is strengthened through nutrient and energy recovery, yet the high cost of some technologies can limit widespread use. While methods like anaerobic digestion reduce sludge and generate renewable energy, others such as membrane filtration may require substantial power, affecting their carbon footprint. The table also shows that circular economy-based wastewater management provides long-term benefits by converting waste into usable resources, although full sustainability must be verified through life cycle assessments.

Table 3: Environmental Impacts of Advanced Wastewater Technologies

Category	Positive Impacts	Potential Concerns
Water Quality Improvement	Reduced pollutant load, removal of micropollutants & pharmaceuticals	Risk of incomplete oxidation products in AOPs
Resource Conservation	Recovery of nutrients, energy, reusable water	High cost of recovery technologies may limit adoption
Energy & Emissions	Lower sludge production, renewable energy from biogas	Membrane systems & AOPs may require high energy input
Circular Economy Benefits	Waste converted to valuable products, reduced reliance on raw materials	Need for life cycle assessment to confirm long-term sustainability

Looking ahead, the trajectory of advanced wastewater treatment is marked by an ongoing convergence of research areas addressing both technological and global water management challenges. Continued innovation in integrated systems combining biological, chemical, and physical techniques promises to increase adaptability and resilience against fluctuating influent qualities and varied pollutant

loads. Expanding the use of biocatalytic processes, especially those leveraging microbial enzymes for the breakdown of persistent contaminants, is expected to deliver greener and more energy-efficient solutions that complement current physicochemical approaches (Kumar *et al.*, 2022) ^[9]. Nevertheless, the field must contend with issues such as operational costs, sensitivity to input

variability, and the potential for secondary pollutant formation, placing emphasis on optimization and interdisciplinary collaboration. Given increasing environmental pressures and freshwater scarcity, future advances will likely focus not only on technical efficacy but also on holistic sustainability, driving global adoption of treatment practices that align with evolving resource protection and public health objectives (Kumar *et al.*, 2022) [9].

Conclusion

The analysis presented in this essay demonstrates the considerable evolution of advanced wastewater treatment technologies driven by a combination of regulatory demand, public scrutiny, and environmental necessity. Central themes such as the adoption of membrane-based techniques, advanced oxidation processes, and innovative biological systems illustrate the breadth of technical progress achieved in recent years. Efforts to integrate resource recovery and circular economy strategies further expand the role of wastewater treatment beyond pollution control, emphasizing the generation of renewable resources and sustainable operational models. Environmental impact assessments, including comprehensive life cycle approaches, have highlighted both the advantages and trade-offs inherent in adopting these advanced technologies, underscoring the need for ongoing optimization. Reflecting on these developments, it is clear that modern wastewater management will remain a cornerstone of sustainable water use, supporting ecological integrity and societal well-being as future challenges emerge.

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