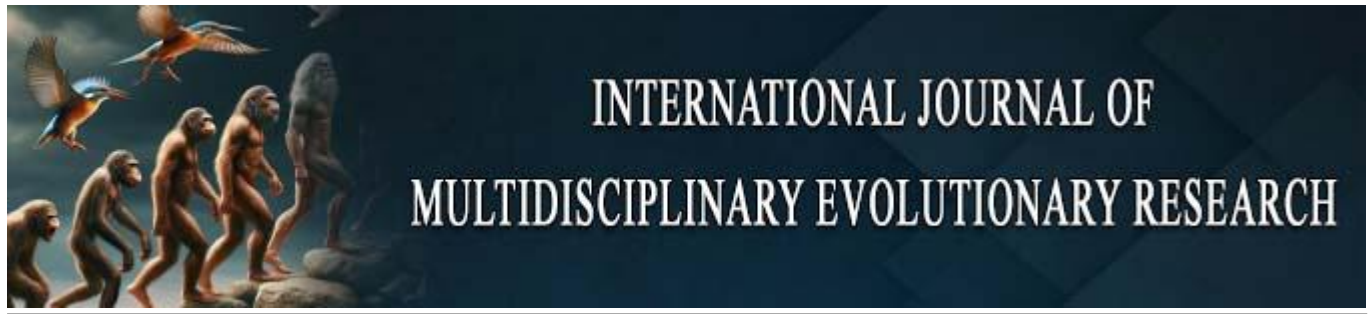




Two-Decade Review of Revolutionizing Wastewater Treatment

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Abstract

This research paper presents a two-decade review of the transformative journey in wastewater treatment, focusing on technological evolution and regulatory dynamics. Over the examined period, advancements in membrane technologies, decentralized systems, and smart, autonomous processes have significantly improved treatment efficiency. Integrating circular economy principles and nature-based solutions reflects a commitment to sustainability and resource recovery. Regulatory frameworks have evolved, setting stringent standards that drive innovation. Despite notable progress, challenges persist, including resource limitations and emerging contaminants. Future trends emphasize smart systems, circular economy integration, and community engagement. The sector's resilience, adaptability, and commitment to sustainability are vital for navigating ongoing challenges and contributing to a more efficient, environmentally friendly, and socially inclusive wastewater treatment future.

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1. Introduction

Wastewater treatment is a cornerstone in safeguarding environmental health and sustaining human well-being (Brusseau, Ramirez-Andreotta, Pepper, & Maximillian, 2019; Singh, Chakraborty, & Sehgal, 2023; Yang & Lo, 2021). Over the past two decades, the field has undergone a transformative journey marked by unprecedented technological advancements, regulatory landscape shifts, and a growing awareness of the need for sustainable practices. The importance of effective wastewater treatment cannot be overstated, given its role in mitigating pollution, preserving water resources, and protecting ecosystems (Hill, 2017; Inyinbor Adejumo *et al.*, 2018). The two-decade period under scrutiny has been characterized by an intensified focus on innovation and efficiency, driven by factors such as escalating urbanization, heightened environmental consciousness, and the imperative to meet increasingly stringent water quality standards. As we delve into this review, we will explore the technological evolution within the field, examining breakthroughs that have transcended conventional wastewater treatment methods. Additionally, the interplay between regulatory frameworks and technological advancements will be dissected, shedding light on how policy changes have acted as catalysts or impediments to progress. This exploration is not confined to the technical sphere alone; it extends to the broader socio-environmental context. Beyond the machinery and processes, we will scrutinize the industry's environmental impact, considering the unintended consequences and benefits of the revolutionary changes in wastewater treatment. The review also highlights the challenges that have surfaced during this period and the opportunities they present for further innovation. By addressing these challenges head-on, the wastewater treatment industry can pave the way for a more sustainable and resilient future. In essence, this paper seeks to provide a panoramic view of the dynamic landscape of wastewater treatment over the past two decades. By doing so, it aims to contribute to understanding the field's trajectory, current state, and potential paths it may tread in the future.

As we stand at the cusp of a new era, the lessons learned from the past two decades will undoubtedly inform the strategies and technologies that will shape the next phase of the evolution of wastewater treatment.

2. Historical Context

To comprehend the revolutionary changes in wastewater treatment witnessed over the past two decades, it is imperative to trace the historical trajectory that laid the foundation for these transformative advancements. The roots of contemporary wastewater treatment practices can be found in the early to mid-20th century when the detrimental effects of untreated sewage on public health and the environment became increasingly apparent. The mid-20th century marked a crucial period in recognizing the urgent need for comprehensive wastewater management. The post-World War II era witnessed rapid industrialization and urbanization, resulting in a surge in wastewater generation (Brunn, Williams, & Zeigler, 2003; Gupta & Vastag, 2020). The environmental consequences of discharging untreated or poorly treated wastewater into rivers and water bodies became evident, leading to widespread pollution and public health crises. In response to these challenges, the 1970s saw the implementation of landmark environmental legislation in various parts of the world, including the Clean Water Act in the United States and the Water Framework Directive in the European Union. These regulations laid the groundwork for stringent standards for wastewater discharge, setting the stage for developing advanced wastewater treatment technologies (Haigh, 2015; Kallis & Nijkamp, 1999; Orth, 2002).

The late 20th and early 21st centuries gradually shifted from conventional treatment methods to more sophisticated and efficient technologies. Advances in microbiology, chemistry, and engineering played a pivotal role in enhancing our understanding of wastewater treatment processes. Membrane technologies, biological nutrient removal, and decentralized treatment systems began to gain prominence, offering alternatives to traditional activated sludge processes (Bitton, 2005; Daims, Taylor, & Wagner, 2006; Mowery & Rosenberg, 1999).

As the world entered the 21st century, sustainability and resource recovery emerged as critical considerations in wastewater treatment. The circular economy concept gained traction, prompting a reevaluation of wastewater as a valuable resource rather than a mere waste product. Innovations in energy recovery, nutrient recycling, and the application of artificial intelligence further propelled the field toward a more sustainable and integrated approach (Chojnacka & Chojnacki, 2023; Demirel & Rosen, 2023; M. O. Khan, 2023). The historical context underscores the evolutionary nature of wastewater treatment, shaped by a continuous interplay of scientific discoveries, regulatory frameworks, and societal demands. The journey from essential sewage disposal to the current era of advanced treatment technologies reflects a dynamic and adaptive response to the ever-growing challenges of urbanization, industrialization, and environmental degradation (Ahmad, Saeed, Shah, Gondal, & Mumtaz, 2022; Kumar, Kumar, & Pandey, 2021).

Understanding this historical context provides a critical lens through which we can appreciate the significance of the revolutionary changes observed in wastewater treatment over

the past two decades. The early to mid-20th century laid the groundwork for recognizing the environmental and public health impacts of untreated sewage, prompting the development of regulatory frameworks in the 1970s. These regulations, driven by a growing awareness of the consequences of pollution, set the stage for the adoption of advanced treatment technologies in the late 20th century (Board, National Academies of Sciences, & Medicine, 2019; Nadakavukaren & Caravanos, 2020). The shift from conventional to advanced treatment methods in the late 20th century was not merely a technological upgrade but a paradigm shift in how society viewed and approached wastewater (Armah *et al.*, 2021; Villarín & Merel, 2020; Wang *et al.*, 2018). Incorporating membrane technologies, biological nutrient removal, and decentralized systems signaled a departure from the traditional linear approach of treating wastewater as a problem to be disposed of. Instead, it emphasized the need to view wastewater as a potential resource that could contribute to sustainable development (Hai & Yamamoto, 2011; Janssen, Meinema, & Van der Roest, 2002).

The 21st century saw an even more profound transformation in wastewater treatment philosophy. Sustainability and resource recovery became central to discussions around wastewater management (Ashley, Cordell, & Mavinic, 2011; Buck, 2020). Once considered a burden, wastewater was now seen as a reservoir of valuable resources – energy, nutrients, and water. Innovations in energy recovery from wastewater, nutrient recycling, and the integration of artificial intelligence for process optimization exemplified this paradigm shift. The emergence of the circular economy concept played a pivotal role in reshaping wastewater treatment. Instead of a linear model where wastewater is treated and discharged, the circular economy envisions a closed-loop system where the by-products of wastewater treatment become inputs for other processes (Sharafat & Zahoor). This holistic approach aligns with the broader sustainability goals of minimizing waste and maximizing resource efficiency.

The revolutionary changes in the past two decades reflect technological advancements and a fundamental shift in mindset. Wastewater treatment is not solely about compliance with regulations but embracing opportunities for innovation, resource recovery, and environmental stewardship. The integration of advanced technologies and a deeper understanding of the interconnectedness of environmental, social, and economic factors has propelled wastewater treatment into a new era (Sánchez-García, Martínez-Falcó, Marco-Lajara, & Manresa-Marhuenda, 2023; Shrivastava, 1995).

In conclusion, the historical perspective provides a rich tapestry against which the transformative changes in wastewater treatment can be appreciated. From the early recognition of environmental and public health challenges to the adoption of stringent regulations and the subsequent shift toward advanced treatment technologies, the journey has been dynamic and responsive to the evolving needs of society. The recent focus on sustainability, resource recovery, and the circular economy marks a paradigm shift that positions wastewater as a valuable asset rather than a liability. As we navigate the challenges of the future, the lessons from the past remind us of the ongoing need for adaptability, innovation, and a holistic approach to wastewater management.

3. Technological Evolution in Wastewater Treatment

Over the past two decades, wastewater treatment technologies have undergone a profound transformation fueled by scientific breakthroughs, engineering innovations, and an increasing commitment to sustainability (Bradú *et al.*, 2022; Diallo *et al.*, 2013). This evolution has enhanced the efficiency of wastewater treatment, substantially reduced environmental impact, and promoted resource recovery. Traditional methods, while effective, are now being complemented and, in some cases, replaced by a new generation of technologies that promise a more sustainable future.

A key milestone in this technological evolution is the widespread adoption of membrane-based processes, particularly reverse osmosis (RO) and ultrafiltration. These technologies have revolutionized contaminant removal, establishing a more robust barrier against pollutants and pathogens (Anis, Hashaikh, & Hilal, 2019; Fane, Wang, & Jia, 2011). Membrane bioreactors (MBRs) have emerged as a noteworthy advancement, seamlessly integrating biological treatment with membrane filtration. This hybrid approach results in smaller treatment footprints and yields higher quality effluents, meeting or exceeding stringent water quality standards (Hai, Yamamoto, & Lee, 2018; Mora-Sánchez, Serna-García, Bouzas, Seco, & Ruano, 2023; Truong & Bui, 2023).

Biological Nutrient Removal (BNR) is a cornerstone in modern wastewater treatment practices. The optimization of microbial processes within treatment plants allows for the efficient removal of nitrogen and phosphorus, addressing concerns related to nutrient pollution in receiving water bodies. This strategic shift aligns with increasingly stringent environmental regulations. It contributes significantly to restoring ecosystems that have been adversely affected by the detrimental impacts of excess nutrients (Hasan *et al.*, 2021; Qiu, Shi, & He, 2010; Robles *et al.*, 2020).

In response to the evolving landscape, decentralized wastewater treatment systems have emerged as a viable and flexible alternative to traditional centralized approaches. Systems such as constructed wetlands, decentralized membrane units, and package plants provide adaptability in design and application. Particularly relevant in areas with low population density or where the installation of extensive sewer networks is economically unfeasible, these decentralized systems mark a paradigm shift in wastewater treatment planning and implementation. Moreover, integrating advanced monitoring and control systems, facilitated by incorporating sensors and automation, has significantly improved the operational efficiency of wastewater treatment plants (Ahmad *et al.*, 2022; Martínez *et al.*, 2020; Olsson, Nielsen, Yuan, Lynggaard-Jensen, & Steyer, 2005). Real-time data collection and analysis empower operators with the tools for proactive decision-making, enabling the optimization of treatment processes while minimizing energy consumption. This contributes to operational cost savings and ensures treatment facilities operate efficiently, reducing their environmental footprint.

The advent of these transformative technologies is not without challenges. While membrane-based processes offer unparalleled contaminant removal capabilities, they require careful consideration of maintenance and replacement costs. Biological nutrient removal, though effective, demands a nuanced understanding of microbial processes and necessitates regular monitoring to ensure optimal

performance. Decentralized systems, while flexible, may face challenges related to the scalability of their application and the need for standardized design and operation protocols (Antal, Cioara, Anghel, Antal, & Salomie, 2021).

As we navigate the future of wastewater treatment technologies, sustainability is paramount. Achieving a delicate balance between technological innovation and environmental stewardship is critical. These cutting-edge technologies must be integrated by a commitment to responsible and ethical usage, ensuring their benefits are maximized while potential drawbacks are mitigated. Looking forward, the evolution of wastewater treatment technologies is poised to continue. Research and development efforts will likely focus on improving these technologies' efficiency, affordability, and environmental sustainability. Advancements in materials science, nanotechnology, and artificial intelligence may further revolutionize wastewater treatment processes, offering new avenues for addressing emerging contaminants and optimizing resource recovery.

In conclusion, the technological evolution in wastewater treatment over the past two decades marks a significant leap towards a more sustainable and efficient approach to managing water resources. From membrane-based processes to decentralized systems and advanced monitoring, each innovation contributes to a comprehensive and adaptable toolkit for addressing the challenges of contemporary wastewater treatment. As these technologies evolve, the prospect of a future where wastewater is not just treated but transformed into a valuable resource becomes increasingly tangible, paving the way for a more sustainable and water-secure world.

4. Regulatory Landscape

Over the last two decades, the regulatory landscape of wastewater treatment has profoundly evolved, reflecting a global commitment to environmental protection and sustainable water management. This transformative journey has been spurred by heightened awareness of emerging contaminants, the need for stricter discharge limits, and a growing emphasis on energy efficiency and carbon footprint reduction. Environmental agencies and legislative bodies worldwide have responded to these challenges by revising and augmenting existing regulations, shaping the trajectory of wastewater treatment, and driving the adoption of revolutionary technologies.

One of the significant shifts in wastewater treatment regulations has been prompted by the increased awareness of emerging contaminants, such as pharmaceuticals and personal care products (Chaturvedi *et al.*, 2021; Parida *et al.*, 2021). Regulatory agencies globally have acknowledged the potential risks associated with these substances and have undertaken a reassessment of water quality standards. In response, new regulations have been introduced, necessitating the development and implementation of advanced treatment technologies capable of removing or mitigating these pollutants. This marks a departure from traditional wastewater treatment methods, requiring innovative approaches to effectively address the challenges of emerging contaminants (S. Khan, Naushad, Govarthan, Iqbal, & Alfadul, 2022).

The evolution of wastewater treatment regulations is evident in imposing stricter discharge limits for conventional pollutants. Biochemical oxygen demand (BOD), suspended solids, and nutrients are among the parameters subject to

more stringent standards to protect aquatic ecosystems (Bhateria & Jain, 2016; Sun *et al.*, 2021). The enforcement of these regulations has acted as a catalyst for adopting innovative treatment processes. Wastewater treatment facilities must surpass conventional methods, embracing cutting-edge technologies to meet and exceed these heightened standards. This shift represents a commitment to maintaining water quality and restoring ecosystems impacted by wastewater discharges.

A notable paradigm shift within regulatory frameworks is the increasing emphasis on water reuse. Recognizing the scarcity of water resources and the imperative for sustainable water management, policies promoting water reuse have gained prominence. This shift has encouraged the development of technologies that facilitate safe and efficient water recycling. Wastewater is no longer viewed solely as a waste product but as a valuable resource that can be treated and reused for various purposes, reducing the demand for freshwater sources (Salgot & Folch, 2018; Smol, Adam, & Preisner, 2020; Verstraete, Van de Caveye, & Diamantis, 2009). This evolution aligns with broader sustainability goals and represents a fundamental reorientation of the role of wastewater in the more general water cycle.

The evolving regulatory landscape has also brought energy efficiency and carbon footprint reduction to the forefront of wastewater treatment considerations. Environmental agencies increasingly recognize the environmental impact of energy-intensive treatment processes. Consequently, regulations now emphasize reducing energy consumption and exploring renewable energy sources within wastewater treatment facilities. This shift has spurred the exploration of energy recovery from wastewater and the implementation of energy-efficient treatment technologies. By integrating sustainability principles into regulatory frameworks, authorities drive the wastewater treatment sector towards a more environmentally conscious and resource-efficient future.

5. Challenges and Opportunities in Wastewater Treatment

The revolutionary journey in wastewater treatment over the past two decades has brought forth a myriad of challenges that underscore the complexities of the field, necessitating ongoing innovation and strategic planning. Resource limitations pose a significant hurdle, particularly in developing countries, where stretched budgets impede the adoption of advanced wastewater treatment technologies. Aging infrastructure in urban centers further complicates the landscape, requiring substantial engineering and financial investments to retrofit facilities for new technologies.

The persistent presence of emerging contaminants, such as pharmaceuticals and microplastics, demands continuous research to understand and develop effective treatment methods. Climate change introduces uncertainties, impacting the efficiency of wastewater treatment processes, with extreme weather events posing risks of untreated discharges. Additionally, public awareness and acceptance of advanced wastewater treatment technologies remain challenging, hindering the widespread implementation of water recycling initiatives. Keeping pace with evolving regulatory standards also poses a continuous challenge for wastewater treatment facilities, requiring ongoing investment in technology and process optimization (Li, Yu, & He, 2014; Qasim, 2017).

Amidst these challenges, a landscape of opportunities has emerged, offering prospects for further advancements and

sustainable solutions. The necessity to overcome challenges has spurred a culture of innovation, with continued research and development presenting opportunities to discover novel treatment technologies, improve existing processes, and lower implementation costs. Decentralized wastewater treatment systems offer opportunities to provide effective treatment solutions without extensive centralized infrastructure, especially in rural and remote areas (Capodaglio, 2017).

The paradigm shift in viewing wastewater as a resource rather than waste has given rise to opportunities for resource recovery. The recovery of energy, nutrients, and other valuable by-products from wastewater presents economic and environmental opportunities. Fostering community engagement and education is a crucial opportunity to enhance public acceptance of advanced treatment methods, promoting transparent communication about the benefits and safety of treated wastewater. Collaboration between the wastewater treatment sector, academia, industry, and policymakers is also identified as a crucial opportunity, accelerating the translation of research into practice and facilitating the implementation of innovative solutions. Adopting a circular economy approach in wastewater management opens doors to sustainable practices, promoting holistic and regenerative solutions by integrating water, energy, and nutrient cycles (Sharma *et al.*, 2021; Varma *et al.*, 2023).

6. Environmental Impact

The revolutionary transformations in wastewater treatment witnessed over the past two decades have bolstered pollutant removal efficiency and significantly altered the environmental footprint associated with wastewater management. Understanding the nuanced ecological impacts of these changes is imperative for evaluating the overall sustainability of wastewater treatment practices. Advanced treatment technologies have played a pivotal role in enhancing water quality in receiving water bodies. The improved removal of pollutants, ranging from nutrients and pathogens to emerging contaminants, has minimized adverse effects on aquatic ecosystems and public health. This marks a crucial step towards mitigating the environmental consequences traditionally associated with untreated or inadequately treated wastewater.

Moreover, these advancements have contributed to ecosystem restoration by reducing nutrient discharges, mainly through innovations in biological nutrient removal. This reduction has addressed issues such as eutrophication, fostering the restoration of ecosystems by maintaining nutrient balance and preserving biodiversity. Simultaneously, adopting energy-efficient technologies and exploring renewable energy sources have led to a noticeable reduction in the environmental footprint of wastewater treatment. This aligns with global efforts to minimize carbon footprints and mitigate the impacts of climate change, demonstrating a commitment to sustainable practices in wastewater management.

The shift towards resource recovery from wastewater, encompassing energy, nutrients, and water, exemplifies a transition towards a circular economy. Extracting valuable resources not only diminishes the reliance on external inputs but also promotes a sustainable and efficient utilization of resources. Furthermore, advanced treatment methods producing effluents with lower concentrations of contaminants contribute to minimizing potential harm when

discharged into water bodies. This reduction in downstream disposal impact supports aquatic ecosystems' resilience. It aligns with the intention to reduce anthropogenic effects on natural environments (O. Akpor, 2011; O. B. Akpor, Otohinoyi, Olaolu, & Aderiye, 2014).

The mitigation of emerging contaminants, facilitated by the evolving understanding of these substances, underscores the proactive nature of contemporary wastewater treatment practices. Advanced treatment processes, specifically designed to target and remove these contaminants, contribute to preventing the accumulation of potentially harmful substances in water bodies. In parallel, promoting water reuse practices has become a significant environmental benefit. The acceptance and implementation of water reuse practices help alleviate the demand for freshwater sources. When repurposed for non-potable purposes such as irrigation or industrial processes, treated wastewater becomes valuable in preserving natural water sources and fostering a more sustainable water cycle (Choukr-Allah & Hamdy, 2005; M. M. Khan *et al.*, 2022).

Additionally, preserving aquatic habitats is a notable outcome of stringent discharge standards in wastewater treatment practices. By reducing the concentration of pollutants in effluents, these practices contribute to safeguarding the health of rivers, lakes, and coastal areas, supporting diverse ecosystems. Despite these advancements, the dynamic challenge remains to balance the need for effective treatment with preserving ecosystems and promoting sustainable practices. Continuous monitoring and assessment of the long-term consequences of these changes are essential. The ongoing commitment to innovation and integrating environmental considerations into wastewater management strategies remains crucial for ensuring a positive and lasting environmental impact (Ross & Dovers, 2008). As we navigate this intricate balance, the field remains poised to meet the evolving environmental challenges with resilience and sustainability at its core.

7. Future Trends in Wastewater Treatment

As the wastewater treatment landscape continues to evolve, several key trends are shaping the industry's future, reflecting a collective drive towards sustainability, resilience, and efficiency in addressing the complex challenges associated with water management. One anticipated trend involves the integration of artificial intelligence (AI) and the Internet of Things (IoT), poised to revolutionize wastewater treatment. Incorporating smart sensors, predictive analytics, and autonomous control systems will optimize processes, enhance efficiency, and enable real-time monitoring, facilitating proactive decision-making. Another significant trend is the growing adoption of the circular economy concept in wastewater treatment. Strategies for resource recovery, such as extracting energy, nutrients, and other valuable by-products, will become more integral, aligning with broader sustainability goals and minimizing waste generation (Krishnan, Agarwal, Bajada, & Arshinder, 2020; Udugama *et al.*, 2020).

Furthermore, an increasing emphasis on nature-based solutions, such as constructed wetlands and green infrastructure, is expected to enhance the ecological integration of wastewater treatment. These systems provide effective treatment and contribute to biodiversity conservation, flood control, and the creation of resilient, multifunctional landscapes. Continued advancements in

membrane technologies, including nanofiltration and forward osmosis, are anticipated to improve wastewater treatment efficiency further. These technologies offer enhanced contaminant removal and can be instrumental in addressing emerging pollutants and achieving higher water quality standards. Additionally, decentralized wastewater treatment systems, characterized by modular and scalable designs, are expected to become more prevalent, offering flexibility in areas with low population density or where centralized infrastructure is impractical (Bair, 2016; Ranzato, 2011).

Electrochemical treatment processes, such as electrocoagulation and electrooxidation, hold promise for removing specific pollutants and microbial contaminants, providing environmentally friendly alternatives that can be integrated into existing treatment plants to enhance performance. The exploration of microbial fuel cells, harnessing the energy produced during wastewater treatment, is expected to increase, aligning with efforts to improve energy efficiency and promote sustainable practices. Wastewater treatment facilities are also anticipated to incorporate resilience planning to address the impacts of climate change, preparing for extreme weather events, changing precipitation patterns, and rising sea levels to ensure the continued effectiveness of treatment processes under varying conditions.

Engaging communities in wastewater management and treatment processes will become more integral. Social innovation, including public education campaigns, participatory decision-making, and citizen science initiatives, will foster a sense of ownership and environmental stewardship. Lastly, with water-related challenges transcending geographic boundaries, there will be a growing emphasis on global collaboration and knowledge sharing (Wehn *et al.*, 2021). International partnerships, joint research initiatives, and the exchange of best practices are expected to accelerate progress and address shared water management issues. In summary, these future trends in wastewater treatment reflect a dynamic and interconnected approach to water management, incorporating technological innovation, sustainability, and community involvement. The wastewater treatment industry can proactively address emerging challenges and contribute to a more resilient and sustainable water future by staying attuned to these trends (Abdelfattah & El-Shamy, 2024).

8. Conclusion

The two-decade review of revolutionizing wastewater treatment presented in this paper unveils a dynamic and transformative journey characterized by technological innovation, regulatory evolution, and a growing commitment to environmental sustainability. The advancements witnessed in wastewater treatment over this period have not only elevated the efficiency of pollutant removal but have fundamentally reshaped the industry's approach to water management. From adopting membrane technologies and decentralized systems to integrating smart, autonomous systems powered by artificial intelligence, the industry has embraced various solutions to address the evolving challenges. These changes have improved the quality of treated water and contributed to the preservation and restoration of ecosystems, setting the stage for a more resilient and sustainable future.

The regulatory landscape, marked by increasingly stringent standards, has played a pivotal role in steering the industry

toward cleaner and more responsible practices. The focus on circular economy principles, resource recovery, and integrating nature-based solutions underscores a commitment to holistic and sustainable water management. However, amidst the successes, challenges persist. Resource limitations, the aging of infrastructure, and the continual emergence of new contaminants require ongoing attention and innovative solutions. Public perception and acceptance of advanced treatment methods remain critical, emphasizing the need for effective communication and community engagement.

Looking ahead, the identified future trends suggest a path toward greater efficiency, adaptability, and integration of cutting-edge technologies. The convergence of these trends promises a wastewater treatment sector that meets regulatory standards and goes beyond, actively contributing to environmental conservation, climate resilience, and community well-being. As we stand on the threshold of a new era in wastewater treatment, the lessons learned from the past two decades serve as a foundation for informed decision-making. The industry's commitment to innovation, sustainability, and collaboration will be paramount in addressing the complex and interconnected challenges that lie ahead. By fostering a continued spirit of exploration, embracing technological advancements, and engaging communities, the wastewater treatment sector can play a pivotal role in shaping a water-secure and environmentally sustainable future.

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