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Editorial

Advanced Wastewater Treatment Technologies with the Potential to Achieve Resource Recycling—From Pollutant Removal to Circular Water Systems

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1. Introduction

Rapid industrialization, urbanization, climate change, and population growth have all contributed to a global water crisis, increasing the need for resource-efficient water management strategies and sustainable wastewater treatment technologies. Historically, wastewater treatment has focused mainly on safe disposal of treated wastewater and removal of pollutants. However, increasing demand for fresh water, nutrients, and critical resources is driving a paradigm shift towards recovery and reuse of wastewater and its valuable materials. Thus, this Special Issue, "Advanced wastewater treatment technologies with the potential to achieve resource recycling", brings together recent advances in innovative treatment processes and resource recovery approaches and highlights their potential to promote environmental sustainability and circular resource recovery.

These contributions cover a broad range of technological and research perspectives, including those covered in this specific issue. These include a critical review of environmental nanotechnology, which identified a persistent gap between laboratory performance and real-world implementation [Contribution 1], and a comprehensive assessment of 15 nature-based solutions for decentralized wastewater treatment, which showed savings of up to 66% in construction costs and energy savings of more than 40% compared to conventional activated sludge systems [Contribution 2]. A comprehensive evaluation of an anaerobic methane-driven membrane biofilm reactor achieving nitrogen removal at approximately 0.51 mg/L·h^{-1} without detectable denitrifying anaerobic methane oxidation (DAMO) microorganisms [Contribution 3]. In addition, the mechanistic review examines different methods of treatment of high-salinity effluents, including physicochemical, biological, and integrated approaches [Contribution 4]. In addition, an experimental study will examine the use of Arundo donax, Typha latifolia, Pistia stratiotes, and Eichhornia crassipes in built-up wetlands to treat waste from paper recycling. These studies showed a remarkable 68.83–88.18% reduction in COD and a remarkable reduction in heavy metals up to 80.09% [Contribution 5].

Collectively, these studies provide valuable insights into the development and implementation of advanced wastewater treatment technologies and highlight several critical directions for future research. First, improving the translation of laboratory-scale findings into practical applications requires greater emphasis on treatment performance under complex wastewater conditions, long-term operational stability, and field-scale validation. Second, integrating nanotechnology, biological processes, and nature-based solutions offers promising opportunities to enhance treatment efficiency, reduce energy consumption, and improve resource recovery. Third, the successful implementation of sustainable wastewater

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management strategies requires comprehensive evaluation frameworks that incorporate technical performance, economic feasibility, environmental safety, resource recovery potential, and social acceptance. Addressing these interconnected challenges will be essential for advancing wastewater treatment beyond conventional pollutant removal toward integrated resource recovery and circular water management.

2. Main Contributions to This Special Issue

2.1. The Study of Environmental Nanotechnology Aims to Bridge the Gap Between the Laboratory and Reality

Elsakhawy et al. [Contribution 1] provide a timely and critical review of nanotechnologies in wastewater treatment, arguing that the continued optimism in the sector, based on extraordinary bench-scale removal efficiency, masks a fundamental disconnect with the operational reality on the ground. In genuine wastewater matrices, reactive oxygen species are competitively scavenged from natural organic matter and background ions, active sites are passivated, and electrical double-layer compression is induced, resulting in a rapid degradation of performance. The authors critically assess each class against the thermodynamic and hydrodynamic constraints of actual liquids and systematically categorize nanomaterials according to their functionalities—reactive interfaces, selective barriers, signal generators, and bio-modulators.

The most important contribution of the review is its six-dimensional framework for assessment—effectiveness under real conditions, stability, scalability, costs, environmental safety, and compatibility of the system. To assess what is really important in practice, the framework goes beyond material-based metrics (e.g., maximum adsorption capacity of deionized water) to assess energy demand (through electrical energy per order (EEO)), matrix-tolerability, and long-term structural resilience. The authors also point out that predictive models trained on idealized data sets often fail under stochastic conditions in real wastewater, underlining the potential of artificial intelligence and machine learning for intelligent wastewater treatment and adaptive control of processes. In conclusion, the review provides practical recommendations for researchers, industry engineers, and policymakers to take action by standardizing complex matrix testing, favoring hybrid integration over isolated nano-units, and developing regulatory frameworks specific to nanomaterials. This contribution is essential reading for anyone seeking to translate nanomaterial innovation into field-ready solutions.

2.2. Decentralized Treatment Can Be Achieved Through Nature-Based Solutions, Which Offer Multidimensional Viability

Heyberger and Rodríguez-Chueca [Contribution 2] provide a comprehensive, technical, economic, environmental, and socially acceptable assessment of 15 nature-based solutions (NBS) for decentralized wastewater treatment. According to their analysis, NBS can offer significant economic and environmental benefits while achieving a pollutant removal efficiency comparable to conventional systems, in particular for organic matter (COD, BOD) and, in some cases, emerging contaminants. In general, energy savings are in excess of 40%, and the construction costs reported are 66–96% lower than those of systems activated by the sludge.

However, the review does not shy away from NBS limitations. Land requirements range from 0.45 to 840 m^2 per population (PE), and the load factor is significantly lower than in conventional systems, limiting their applicability in dense areas. The presence of performance variability is apparent in some technologies, such as rapid soil infiltration systems, where the removal of TN ranges from 10 to 93%. This underlines the important impact of site-specific factors. In addition, the authors propose a decision support

framework and decision tree to guide the choice of technologies based on land availability, energy requirements, wastewater type, and loading rate, stressing that social acceptance and governance are key factors for long-term success. This contribution provides a practical plan for implementation and a summary of current knowledge.

2.3. A New Pathway for Energy-Efficient Nitrogen Elimination: Methane-Driven Denitrification

Zhang et al. [Contribution 3] address the most urgent wastewater treatment challenges: achieving nitrogen removal while reducing greenhouse gas emissions. Their work shows that the membrane biofilm reactor (MBfR) is capable of maintaining stable, methane-driven denitrification for 250 days. This remarkable achievement allows nitrate removal at a rate of approximately 0.51 mg/L·h^{-1}, while keeping NO^{2-}-N effluents at less than 0.5 mg/L. Critically, microbial community analysis revealed that neither DAMO archaea nor DAMO bacteria were detected; instead, *Methylocystis* (a type II methanotroph) acted as the dominant methane oxidizer, in synergy with heterotrophic and autotrophic denitrifies such as *Hyphomicrobium*, norank_f__Caldilineaceae, Clostridium_sensu_stricto_12, and *Lentimicrobium*.

This finding offers a more tractable and engineer-friendly way to simultaneously remove nitrogen and reduce methane emissions, challenging the prevailing assumption that methane-associated microorganisms are necessary for methane denitrification. The study also provided valuable operational data: shorter HRT durations (8 h) resulted in nitrite accumulation above 2.0 mg/L. In comparison, longer durations of hydraulic retention (20 h) favored slow-growing methanotrophs and increased the diffusion of substrates in the biofilm. The authors are keenly aware that in future research direct measurements of methane uptake efficiency will be required, and that functional assignments based on 16S rRNA gene sequencing are only tentative. However, the study provides strong evidence for methane-based denitrification as a method to remove low-carbon nitrogen.

2.4. The Study Explores the Mechanisms, Technologies, and Integrated Solutions of High-Salinity Wastewater

Dai et al. [Contribution 4] address the complex problem of high-salinity organic wastewater produced by sectors ranging from petrochemicals and food processing to textiles and leather. High concentrations of salts (1–3.5% inorganic salts) interfere with biological processes, inhibit enzyme activity, and cause serious osmotic stress to the microbial cells. Each of these physicochemical methods—coagulation, membrane separation, and advanced oxidation processes—has its advantages and disadvantages, including membrane fouling, high energy consumption, and deactivation of catalysts under saline conditions.

The emphasis of the review on integrated processes and its systematic benchmarking of treatment outcomes are two of its strengths. For example, increasing biodegradability (increasing BOD5/COD from 0.065 to 0.165) and increasing subsequent nitrogen removal may be achieved by pre-treatment with catalytic ozone in the case of biological methods. At operating costs of USD 1.18/m^3, electro-Fenton and electro-adsorption in combination achieved COD, TN and salinity removal rates of 96.5%, 98.2% and 46.2% respectively. Methane recovery is a potential result of anaerobic technologies, especially those enhanced with conductive materials such as magnetite, which facilitate direct interspecies electron transfer (DIET). The authors concluded that the circular economy objectives of resource recovery and zero liquid discharge should be closely aligned with future research, with priority given to salt-tolerant catalysts, antimicrobial membrane materials, microbial consortia and smart hybrid systems.

2.5. Constructed Wetlands for Industrial Wastewater: Phytoremediation and Synergistic Effects

Iftikhar et al. [Contribution 5] provide a convincing case study of a pioneering water treatment project for paper recycling in Pakistan based on built-up wetlands. The study used four macrophytes—Arundo donax, Typha latifolia, Pistia stratiotes, and Eichhornia crassipes— to illustrate the range of contaminant removal abilities across species. In particular, the removal of COD (88.2%) and nitrate (86.6%) was achieved by the species Arundo donax, whereas the species Typha latifolia had the highest BOD (87.4%) and solid removal (71.0%). Pistia stratiotes showed higher removal of heavy metals, including Cr (71.8%), Cd (74.0%), and Hg (61.8%), and higher phosphate (80.9%). The most important factors for pollutant removal were retention time, the soil itself, and the wetland system itself, with synergistic interactions between the soil and the wetland being crucial, according to the analysis of the Response Surface Method (RSM).

The study also highlights the importance of removing heavy metals due to their persistence and bioaccumulation potential in the effluent of paper mills. Although the study provides valuable empirical evidence of the efficacy of built-up wetlands as a low-cost and environmentally friendly option for treating industrial wastewater, it is limited to an experimental period of 30 days and a single wastewater source. To increase the resilience and biodiversity of the system, the authors propose to continue research into optimizing hydraulic retention times, examining the impact of seasonal variations and introducing mixed-species measures.

3. Cross-Cutting Themes and Emerging Research Directions

The five contributions in this Special Issue converge on several overarching themes that define the future of advanced wastewater treatment:

3.1. Matrix Tolerance to Idealized Performance

The same message is often conveyed by publications claiming that laboratory performance under ideal conditions is not a good predictor of success in a particular field. Elsakhawy al. el. [Contribution 1] quantify this gap between the lab and the real world for nanomaterials, while Heyberger and Rodríguez-Chueca [Contribution 2] document a large range of NBS performance under real-world conditions of operation. Clearly, the development of standardized multi-component test matrices simulating realistic wastewater conditions at an early stage of material or system development should be a priority for future research.

3.2. Integration, Not Addition

Real wastewater is a complex and multi-polluting problem that no technology can solve. The most promising routes are: hybrid systems: built wetlands with multiple macrophytes to remove pollutants synergistically [Contribution 2]; nanotechnology integrated in membrane bioreactors or in advanced oxidation processes [Contribution 1]; NBS in combination with complementary compounds [Contribution 3]; catalytic oxidation in pretreatment with biodegradable nitrogen [Contribution 4]; and heterotrophic denitrification [Contribution 3,5]. The main challenge is to achieve thermodynamic and hydrodynamic compatibility during subsequent unit operations under temporary load conditions.

3.3. Resource Recovery as a Design Objective

The central issue is the shift from linear destruction of polluting substances to circular resource recovery. Methane has the potential to act as a carbon source and energy carrier [Contribution 2]. It can be used as a mineral or in agriculture [Contribution 3]. It can also be used to extract rare metals from industrial effluents [Contribution 1]. It is also used for the

production of acids, bases, and mixtures of methane from salt water [Contribution 4]. However, the scale of operations, recovery costs, and value of recovered products—all of which require careful technical analysis—are critical to the economic viability of resource recovery.

3.4. Data-Enabled and Intelligent Systems

Artificial intelligence, machine learning, and real-time nano-sensing can be used to anticipate errors, control adaptive processes, and manage smart frictions in a transformative way [Contribution 1]. Modern predictive models often fail under stochastic conditions in the real world and are primarily trained with idealized static laboratory datasets. The way forward is to develop closed-loop, multi-objective control algorithms that can make autonomous decisions and to build large-scale datasets of authentic, multi-substance flows.

3.5. Social Acceptance and Governance

Successful implementation is not guaranteed only by technical performance. According to the Heyberger and Rodriguez-Chueca study [Contribution 2], NBS needs to maintain its long-term sustainability by involving the community, involving stakeholders, and establishing a proper governance framework. Acceptance is affected by cultural attitudes towards reuse of wastewater, perceived nuisances (odor, mosquitoes), the impact on tourism, and the willingness to pay. It is essential that these social aspects be integrated into the decision-making process from the earliest planning stages onwards.

4. Conclusions

All five papers in this Special Issue refer to a paradigm shift in advanced water treatment from a pollutant-removal approach to a systems-based approach integrating resource recovery, energy efficiency, environmental protection and social inclusion. The main findings are as follows.

In order to move environmental nanotechnologies from discovery by material to engineering at the system level, a multi-dimensional assessment framework is needed to assess stability, scalability, cost, environmental safety, compatibility, and performance in real-world conditions [Contribution 1].

Nature-based solutions offer a low-cost and efficient alternative to decentralized management, but their effectiveness is highly site-specific and depends on careful design, community engagement, and management [Contribution 2].

Methane-mediated *Methylocystis*-mediated denitrification and co-existing heterotrophic and autotrophic denitrifiers can achieve stable removal of nitrate without detectable microbial DAMO [Contribution 3].

Integrating physicochemical and biological processes is crucial to the formation of high-salinity wastewater. Future studies will focus on salt-tolerant catalysts, anti-fouling membranes, and microbial halophiles [Contribution 4].

Complex industrial wastewater can be efficiently treated by combining macrophytes in a built-up wetland, where interaction between plants and wetlands increases the removal of pollutants [Contribution 5].

If the field is to adopt an interdisciplinary framework that is machine-driven, data-driven, and regulatory-oriented, it must adopt this approach in the future, incorporating the following priorities:

1. Standardized test protocols that have been developed to take into account validated matrices and operational conditions of wastewater.
2. Hybrid treatment architectures that combine the strengths of natural processes, advanced oxidation, biotechnology, and nanotechnology.

3. Intelligent control systems that use artificial intelligence, machine learning, and real-time sensing to enable adaptive and resilient operation.
4. Life-cycle and techno-economic assessments that account for long-term stability, costs of regeneration, and the fate of the environment.
5. Participatory governance models that engage communities, stakeholders and policy-makers in the design and long-term management of wastewater.

These efforts are based to a large extent on the contributions of this Special Issue. We hope that they will inspire further research, innovation and collaboration towards a circular economy in which wastewater treatment is not only a cost center, but also a resource-creating, resource-efficient component.

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