

Advanced Biological Wastewater Treatment and Nutrient Removal

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1. Introduction to the Special Issue

The traditional activated sludge process, developed more than a century ago, remains the cornerstone of biological wastewater treatment worldwide owing to its reliability and adaptability [1]. Nevertheless, increasing wastewater generation, increasingly stringent discharge regulations, and the global transition toward carbon neutrality have exposed several inherent limitations of conventional biological treatment systems, including high energy consumption, limited volumetric loading capacity, and insufficient resource recovery [2,3]. These challenges have driven the development of next-generation biological wastewater treatment technologies that aim to achieve higher treatment efficiency while simultaneously reducing energy demand and environmental impacts [4–6].

Against this background, this Special Issue, Advanced Biological Wastewater Treatment and Nutrient Removal, was launched to showcase recent advances in innovative biological processes, microbial mechanisms, reactor engineering, and practical applications for sustainable wastewater treatment. The Special Issue particularly encouraged contributions on emerging biological nitrogen and phosphorus removal pathways, stable operation of the anammox process, aerobic granular sludge, biofilm-based technologies, and other advanced treatment strategies with engineering significance.

Following a rigorous peer-review process, eight high-quality papers were accepted for publication. Rather than simply representing individual technological advances, these contributions collectively illustrate several emerging trends in biological wastewater treatment, including process intensification, mechanism-guided reactor design, functional microbial regulation, and the transition from pollutant removal toward resource recovery. In this closing editorial, we summarize these developments, discuss the knowledge gaps they help address, and outline future research priorities that may accelerate the evolution of biological wastewater treatment toward low-carbon, resource-efficient, and intelligent water resource recovery systems.

2. Overview of the Contributions to This Special Issue

A major focus of this Special Issue is the development of low-carbon nitrogen removal technologies. Jagenteufel et al. investigated the transition of deammonification from sidestream to mainstream treatment by comparing moving bed biofilm reactor and integrated fixed-film activated sludge configurations using cubic polyurethane foam carriers (Contribution 1). Their long-term study demonstrates the importance of reactor configuration, dissolved oxygen control, pH regulation, and aeration strategy for maintaining



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anammox activity while suppressing nitrite-oxidizing bacteria. Gong et al. further explored the integration of anammox with iron-based autotrophic denitrification (Contribution 2). By coupling anaerobic ammonium-oxidizing bacteria with zero-valent iron-mediated denitrification, their work improved nitrate removal and reduced ammonium byproduct accumulation, while also identifying iron passivation and cell encrustation as important limitations for long-term operation. Together, these contributions show that future nitrogen removal will increasingly depend on autotrophic pathways, microbial retention, electron donor management, and precise operational control.

Functional materials and interfacial regulation also emerged as important themes. Sun et al. demonstrated that iron–carbon micro-electrolysis can enhance nitrogen and phosphorus removal in constructed wetlands treating low-pollution water (Contribution 3). The superior performance of the Fe-activated carbon system highlights the role of conductive materials in accelerating iron corrosion, promoting electron transfer, and enriching functional microorganisms. Similarly, Zhan et al. developed a *Chlorella* biofilm-loaded ZnO–NiO@rGO carbon-fiber composite cathode for photosynthetic algae–microbial fuel cells (Contribution 4). Their study linked cathode interfacial engineering with algal biofilm assembly, stable electricity generation, and light-enhanced ammonium removal. These studies suggest that biological treatment performance is increasingly shaped not only by reactor operation but also by the design of functional interfaces that regulate microbial attachment, electron transfer, and local microenvironments.

Several contributions further emphasize the value of biological synergy and resource-oriented treatment. Ortega-Blas et al. investigated microalgae–bacteria consortia for nitrogen and phosphorus removal from municipal wastewater and developed a mathematical model to describe biomass generation and nutrient consumption (Contribution 5). Their findings demonstrate the potential of algal–bacterial systems as low-cost and sustainable treatment platforms, while also revealing the complexity of nitrogen transformation in mixed microbial communities. Takaya et al. examined the Enzyme Biofilm Method for high-strength food industry wastewater and verified that microbial hydrolytic enzymes can degrade starch into simpler compounds (Contribution 6), thereby supporting endogenous microbial growth and biofilm activity. These studies indicate that exploiting microbial cooperation, enzymatic hydrolysis, and biomass-based assimilation can provide new routes for improving treatment efficiency under different wastewater conditions.

The Special Issue also includes studies addressing sludge management and intelligent wastewater treatment. Chen et al. explored the co-dewatering of aerobic granular sludge and alum sludge, showing that the inorganic components and residual coagulants in alum sludge can improve the dewatering behavior of aerobic granular sludge (Contribution 7). This work provides a practical example of coupling sludge treatment with resource utilization and waste minimization. Zhou et al. presented a bibliometric analysis of machine learning applications in wastewater treatment, revealing the rapid expansion of artificial intelligence-assisted research and identifying hybrid modeling, influent prediction, advanced data acquisition, and process optimization as future priorities (Contribution 8). This contribution highlights the growing role of data-driven methods in managing the nonlinear and dynamic characteristics of wastewater treatment systems.

3. Conclusions and Future Perspectives

The contributions collected in this Special Issue provide a representative snapshot of the rapid evolution of advanced biological wastewater treatment and nutrient removal. Collectively, these studies demonstrate that the development of next-generation wastewater treatment technologies is extending beyond the optimization of individual treatment processes toward the establishment of integrated, sustainable, and resilient systems. Emerging

strategies increasingly rely on the synergy among microbial ecology, reactor engineering, functional materials, resource recovery, and intelligent process control to achieve efficient pollutant removal while reducing energy consumption and environmental impacts.

Despite substantial progress, several challenges remain before these innovative technologies can be widely implemented. Long-term operational stability, effective microbial regulation, material durability, and performance under fluctuating real wastewater conditions remain critical issues requiring further investigation. Moreover, bridging the gap between laboratory-scale innovation and full-scale engineering application will require more comprehensive pilot-scale validation, life-cycle assessment, and techno-economic evaluation. Future research should also strengthen the integration of multi-omics, mechanistic modeling, and artificial intelligence to establish predictive and adaptive treatment systems capable of responding to dynamic wastewater characteristics.

Looking ahead, biological wastewater treatment is expected to evolve from conventional pollutant removal facilities toward intelligent water resource recovery systems that simultaneously achieve nutrient removal, energy recovery, carbon emission reduction, and resource circularity. The integration of advanced biological processes with emerging materials, digital technologies, and systems-level engineering approaches will be essential for realizing sustainable wastewater management. We hope that the studies presented in this Special Issue will inspire further interdisciplinary collaboration and contribute to the development of low-carbon, resource-efficient, and intelligent wastewater treatment technologies.

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