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Review Article

Next-Generation Biological Processes in Wastewater Treatment and Resource Recovery

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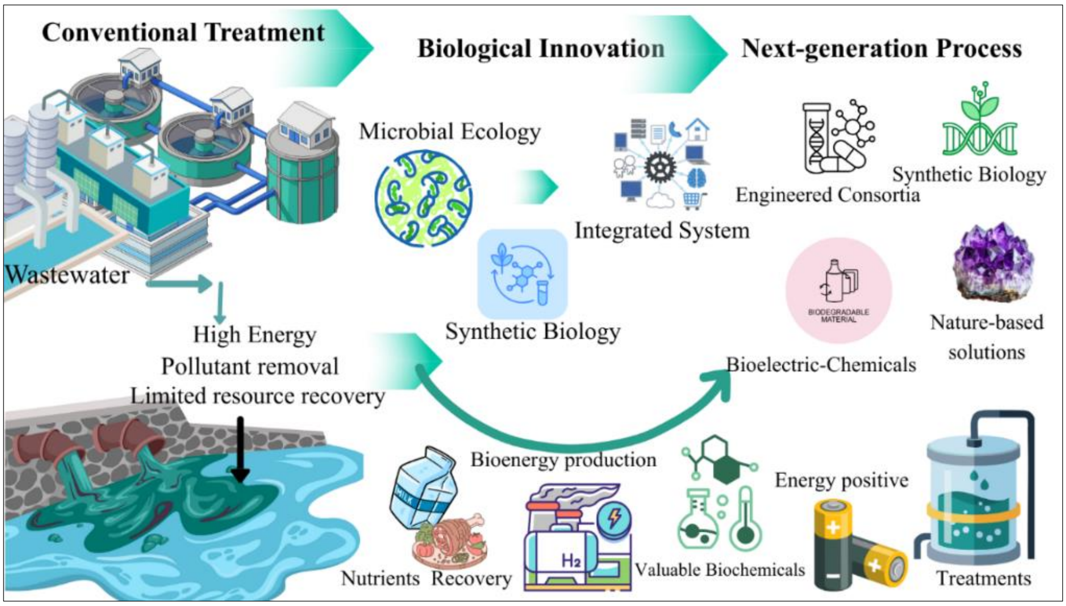
Abstract



Graphical Abstract

Traditional methods of wastewater treatment, in the past, have aimed at removing pollutants and compliance to regulations as a result of which have proven to be inefficiency and resource wastage. Nevertheless, growing demands of water scarcity, climate change, and requirements to adopt a circular economy have fuelled the shift into next-generation biological processes, which redefine the concept of wastewater as a resource, as opposed to a waste stream. This review assesses critically emerging paradigms in biological treatment that go beyond traditional activated sludge systems and incorporate the new developments in the fields of microbial ecology, synthetic biology and bioelectrochemical systems and nature-inspired engineering. Special focus is made on new microbial consortia, designed metabolic routes, and system-wide process advancement that allow the recovery of nutrients, generation of bioenergy, and the manufacture of value-added biochemicals in a better way. The article also assesses the role of hybrid biological systems in the treatment of wastewater under energy-neutral or energy-positive processes, including microbial electrochemical systems and algae-bacteria systems. The problem of techno-economic feasibility, operational resilience, and scalability are discussed systematically to reduce the gap between the innovation over the laboratory scale and its application in the real world. This article identifies the key gaps in knowledge, regulatory issues, and barriers to integration that may not be able to be easily adopted since they point to the recent advances in various fields. Finally, the review also provides a future-based structure of planning sustainable wastewater treatment processes in accordance with a circular bioeconomy, with future-generational biological processes being the core elements of the future water infrastructure in cities and industry.

Keywords: Circular bioeconomy, Microbial functional engineering, Nutrient valorization, Bioenergy recovery, Hybrid bioreactor systems, Metabolic pathway optimization, Sustainable water infrastructure.

1. INTRODUCTION

Biological wastewater treatment has been one of the essential elements of environmental protection strategies since it allows the effective extraction of organic substances, nutrients, and suspended solids of municipal and industrial effluents using both attached and suspended growth systems (Machineni *et al.,* 2019). Traditional biological treatment systems, the most popular of which are activated sludge systems, were initially developed to guarantee the discharge control and to protect the receiving ecosystems. Though the systems have proven to be reliable in the decades of operation, the design philosophy of such systems is based on the period when the efficiency of treatment was valued more than sustainability, resource recovery, and energy optimization (Matheri *et al.,* 2022). This limited perspective has become very inadequate in the context of contemporary water stress on the global level, climate changes, and resource loss. Wastewater has now been managed as a highly resourceful stream with recoverable carbon, nutrients as well as energy entrenched within the organic and inorganic compounds (Qasim *et al.,* 2025). Nevertheless, conventional biological treatment processes are still ill adapted to capturing the same value (Guieysse *et al.,* 2014). The energy consumption is mostly associated with aeration intensive operations and nutrients like nitrogen and phosphorus are usually transformed into inert or deprived of circulation. Overproduction of sludge also increases the disposal problems and costs. The treatment plants of wastewater are, therefore, often net energy consumers and resource dissipators, and thus, there exists a discrepancy between the environmental goals and the performance of the systems (Maktabifard *et al.,* 2018).

The progress in microbial ecology has largely transformed the concept of biological treatment processes (Rittmann *et al.,* 2006). Instead of operating as homogenous biomass, treatment systems support complex microbial communities, which are made up of functionally diverse populations, which compete and cooperate with each other through metabolism. The interactions determine stability of the system, the efficiency of the treatment, and the destiny of carbon and nutrients (Carey *et al.,* 2009). Although this is known, traditional treatment designs have minimal control over microbial functionality and most commonly depend on indirect measures of operation like dissolved oxygen or sludge age. This inability to control biological processes to achieve desired resource recovery outcomes is limited by this functional imprecision. Innovative developments in functional microbiology and metabolic engineering have broadened the opportunities of biological treatment of a wastewater beyond the elimination of contaminants. By means of engineered microbial consortia and pathway level optimization strategies carbon and nutrient fluxes can be diverted to the synthesis of bioenergy carriers, biopolymers and other value add products (Long *et al.,* 2025). These strategies are a radical change in the stabilization of waste to biochemical manufacture. Nevertheless, the transfer of these advances into a working system of treatment needs novel reactor designs, adaptive control approaches and a shift toward infrastructure that has been developed with the sole purpose of pollutant removal (Satyam *et al.,* 2025).

The energy efficiency has become a much-needed key to innovation of the next generation of biological treatment processes. The traditional aerobic system is an energy-consuming one, primarily, owing to the constant aeration demand (Skouteris *et al.,* 2020). Conversely, anaerobic and bioelectrochemical systems utilize the metabolism of microorganisms to extract energy directly out of wastewater in the form of methane, hydrogen or electrical power. Photosynthetic-assisted bioremediation also creates possibilities to combine wastewater treatment with carbon capture and biomass production (Shen *et al.,* 2014). Although these systems show significant potential, issues of process stability, start-up times, operational strength and sensitivity to the variability of the influent still hamper their large-scale application. The next-generation biological treatment is another important dimension, which is called nutrient recovery and valorization. Nitrogen and phosphorus are vital to the world food supply, but are being limited by environmental and geopolitical forces (Cordell *et al.,* 2014). Nutrient loops can be closed with biological pathways that allow selective uptake of nutrients, storage within the cell, or their use to generate reusable products. These pathways need to be balanced with conflicting aims such as effluent quality, ease of operation, and financial viability to implement such pathways into full-scale treatment systems (Singh *et al.,* 2025). This balance is one of the most significant research and engineering issues.

Even with the recent development of technology, numerous new biological processes are still limited to pilot and laboratory research (Wynn *et al.,* 2016). Such obstacles as high capital requirements, regulatory risks, scarcity of long-term performance information and multi-functional system complexity are barriers to full-scale adoption. Also, the literature used tends to focus on specific technologies separately, which lacks deeper information about how various biological processes can be combined into integrated systems of treatment. This decentralized model blurs the trade-offs across the entire system, and stems out the creation of resilient and scalable solutions (Arnaud *et al.,* 2024). The increased focus on the principles of a circular bioeconomy requires the reconsideration of the wastewater treatment systems. Biological processes in the future should be designed to both be effectively treated, recover resources, be energy neutral, and resilient to the environment. The challenges can be resolved by means of interdisciplinary synthesis of microbiology, process engineering, systems analysis, and sustainability evaluation, and regional and socio-economic contexts (Fagunwa *et al.,* 2020). This review will critically discuss next-generation biological processes to treat wastewater under the focus of microbial functional innovation, energy and nutrient recovery, as well as the integration of the system. It also aims to determine the main gaps in knowledge and give strategic information on the way forward of incorporating sustainable and resource-efficient wastewater treatment systems.

2. MICROBIAL FUNCTION–DRIVEN TREATMENT PARADIGMS

2.1. Advanced Microbial Functional Guilds

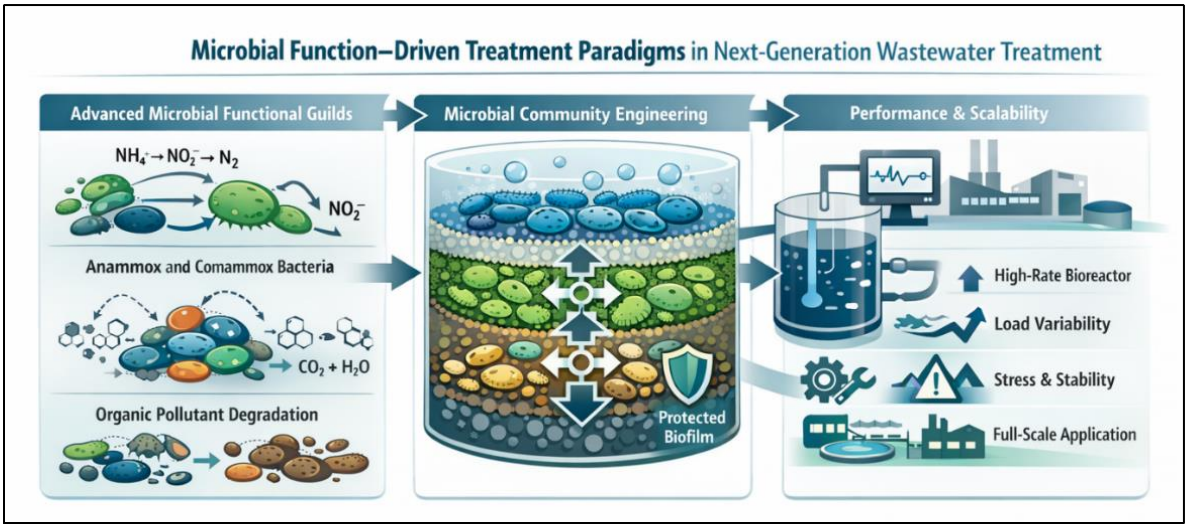
There is an ever-growing shift in the direction of next-generation biological wastewater treatment, which is increasingly mediated by the active utilization of specialized microbial functional guilds with the ability to conduct specific biochemical transformations and do so with high efficiency. Among them, anaerobic ammonium-oxidizing and complete ammonia-oxidizing systems constitute a paradigm shift in the elimination of nitrogen, whereby a system that regenerates the energy state achieves energy-favorable and space-efficient pathways into the biochemical and biological frameworks of a system. In addition to nitrogen cycling, consortia highly adapted to degrade carbon have developed that respond with selective affinity to complex and recalcitrant organic matter, which allows better industrial and high-strength wastewater decontamination (Lü *et al.,* 2024). These guilds can be ecologically adaptable, redundant in metabolic functions, and capable of surviving inhibitory compounds, all of which dictate the functional robustness of such guilds. The functional stability of influent change and operational stress: It is important to remember that sustaining treatment performance under variable influent composition and operational stress is the key to increased loading rates and reduced hydraulic retention times (Santillan *et al.,* 2020).

2.2 Microbial Community Engineering

Innovations in microbial community engineering have facilitated rational engineering of structured systems of biomass to facilitate functional specialization and metabolic cooperation. Granular sludge and structured biofilms have the advantage of offering a spatially stratified microenvironment, and therefore, aerobic, anoxic, and anaerobic bio-transformations can occur simultaneously in the same reactor volume (Rosa-Masegosa *et al.,* 2024). These architectures improve on the transfer of masses and also safeguard the delicate populations of microbes against temporary fluctuations in the environment. Optimization of metabolic pathways is also done by selective enrichment and operational control tactics, which further focus microbial activity on the desired treatment outcomes, pathways and recovery of resources. No less significant is the management of interaction networks of microbes, in which synergetic and competitive relationships are used to maintain and assemble communities, resilience, and efficiency of processes in general. Control and decontamination of these interactions are becoming a vital control tool to stabilize complex biological systems in realistic settings (Pezzulo *et al.,* 2016).

2.3 Performance and Scalability Considerations

The microbiological design and operational configuration of the reactor strongly determine the practical application of function-driven microbial systems, including hydrodynamic behavior, substrate availability and biomass retention. The reactor designs should be designed with the ability to maintain the stratification of microbes and avoid functional washout, especially in a high-rate treatment case (Skiadas *et al.,* 2003). The ability to withstand changing loads in organic and nutrient is another characteristic performance parameter, since full-scale facilities are prone to strong temporal variations. Although laboratory and pilot-scale experiments indicate promising performance in terms of efficiencies, there are challenges involved in long-term operation associated with the degradation of biomass, changes in the population of microorganisms and a decreasing performance. To overcome such limitations, there is a need to have integrated strategies to incorporate process monitoring, adaptive control, and resilient microbial communities designed to make next-generation wastewater treatment systems scalable and sustainable in functionality (Renganathan *et al.,*2025).



3. Synthetic Biology and Engineered Bioprocesses

3.1. Genetically Engineered Microorganisms

The use of genetically engineered microorganisms (GEMs) has added the transformative aspect of biological wastewater treatment since it allows a much more specific interaction with recalcitrant contaminants. With the use of accurate genome editing and pathway reconstructions, microbial hosts can be engineered to secrete catalytic modules with selective mineralization of persistent organic contaminants, pharmaceuticals, and novel micropollutants which cannot be degraded by traditional methods (Yaashikaa *et al.,* 2022). These types of specific biodegradation plans would much greater contribute towards treatment selectivity and minimization of unintended by-products. In addition to the removal of pollutants, synthetic metabolic rewiring has made it possible to amplify nutrient assimilation pathways, especially the pathways controlling nitrogen and phosphorus fluxes. Designer regulatory circuits enable rapid assimilation and internalization of nutrients, as well as efficiency and polishing of effluents at the same time. The changes enhance the efficiency of the systems with variable influent profiles, which is essential in the decentralized and industrial wastewater usage scenario. Simultaneously, the incorporation of the biosensing and self-regulatory capabilities in GEMs has improved the autonomy in processes (Sharma *et al.,* 2023). Engineered strains can dynamically respond to environmental signals by altering metabolic activity via genetic logic gates and inducible promoters in response to environmental signals like the concentration of contaminants, redox conditions, or the presence of nutrients. It is inherently flexible and minimizes the dependence of external control mechanisms and improves the operational robustness in complex treatment settings.

3.2 Synthetic Microbial Consortia

The case of synthetic microbial consortia is a paradigm shift of the single-strain engineering models to collaborative, multi-species engineering models with functional specialization. Division-of-labor structures allocate metabolic activities into different populations of microbes and reduce the intracellular load and maximize collective efficiency of processes (Tsoi *et al.,* 2018). These are especially beneficial when there are sequential or parallel transformation pathways, whereby the intermediate metabolites produced by one population act as substrates by another population. Innovations in programmable metabolic coordination have made interspecies interactions in designed consortia precisely regulated. Synthetic signaling networks, Quorum-sensing modules and metabolite responsive feedback loops promote synchronized activity, which guarantees stable operation under different conditions of operation. Such collective action increases resilience to environmental disturbances and minimizes competition which is usually a limitation to natural microbial communities. The issues of containment and biosafety have been the main focus of the consortium design leading to the introduction of genetic protection and ecological control systems. Auxotrophy, kill-switch mechanisms, and reliance on artificial nutrients are some of the strategies that limit uncontrolled growth outside the envisioned settings. These design principles solve the problems of biosafety and provide the ability to control the use in open or semi-open wastewater treatment systems (Pérez *et al.,* 2023).

3.3 Implementation Barriers

Although there have been immense achievements in the laboratory scale, the translation of bioprocesses that have been developed due to synthetic biology into practical wastewater treatment is still limited by regulation and institutional structures (Renganathan *et al.,*2025). Currently, biosafety policies do not cover engineered microorganisms in environmental infrastructure, and as a consequence, they have long approval periods and uncertainty on large-scale use. The effect of environmental risk management on deployment is also an additional reason why it is complex, since the dynamics of long-term ecological interactions and horizontal gene transfer have not been adequately described at operational scales. Effective risk evaluation techniques, as well as monitoring plans after the deployment, should be in place to make sure that the environment is intact and the people can take the change. There are further technical challenges in the shift between the controlled laboratory conditions to pilot-scale systems. Scale-up in competitive microbial environments is usually associated with performance instability, loss of engineered characteristics and less functional dominance. The solutions to these limitations require an integrative design of reactor, a control of processes by adaptability, and an interdisciplinary cooperation between synthetic biologists, environmental engineers, and regulatory agencies (Butean *et al.,* 2025).

Table 1: This table synthesizes state-of-the-art synthetic biology and engineered bioprocess strategies for wastewater treatment, emphasizing mechanistic design principles, functional performance, and system-level outcomes. Particular focus is given to scalability, biosafety governance, and the translational challenges that constrain the transition from laboratory-scale innovation to operational wastewater infrastructure

Strategy / Sub-Domain	Engineering Approach / Design Principle	Targeted Pollutants / Process Function	Key Functional & Process-Level Outcomes	Implementation Constraints & References
Genome-edited GEMs	CRISPR-Cas genome editing; heterologous pathway insertion	Pharmaceuticals, POPs, micropollutants	High substrate specificity; accelerated mineralization; reduced toxic by-products	Genetic instability; regulatory uncertainty (Yaashikaa *et al.,* 2022)
Pathway reconstruction GEMs	Synthetic metabolic pathway assembly	Recalcitrant organic compounds	Expanded biodegradation spectrum; enhanced treatment selectivity	Metabolic burden; scale-up performance loss (Sharma *et al.,* 2023)
Metabolic rewiring for nutrient recovery	Amplified N and P assimilation pathways	Nitrogen and phosphorus removal	Simultaneous effluent polishing and nutrient recovery	Growth–storage trade-offs; reactor integration limits (Renganathan *et al.,* 2025)
Intracellular nutrient storage GEMs	Polyphosphate and PHA overexpression	Phosphate, carbon recovery	Improved resource recovery potential; circular bioeconomy alignment	Downstream harvesting complexity (Butean *et al.,* 2025)
Biosensing GEMs	Genetic logic gates; inducible promoters	Process monitoring and adaptive control	Autonomous metabolic regulation; reduced external control demand	Signal interference in real wastewater (Sharma *et al.,* 2023)
Self-regulatory GEMs	Feedback-controlled gene circuits	Variable influent and redox conditions	Enhanced operational robustness under fluctuating loads	Circuit failure under long-term operation (Pérez *et al.,* 2023)
Synthetic microbial consortia	Division-of-labor architecture	Complex and sequential pollutant degradation	Reduced cellular burden; higher collective efficiency	Community instability at pilot scale (Tsoi *et al.,* 2018)
Sequential consortia design	Metabolic task partitioning	Multi-step transformation pathways	Improved degradation completeness	Spatial coordination challenges (Tsoi *et al.,* 2018)
Quorum-sensing consortia	Programmable interspecies signaling	Coordinated pathway activation	Synchronized activity; resilience to perturbations	Signal dilution in large reactors (Pérez *et al.,* 2023)
Cross-feeding consortia	Engineered metabolite exchange	Intermediate detoxification	Improved thermodynamic efficiency; stable performance	Dependency collapse risk (Pérez *et al.,* 2023)
Ecological containment strategies	Auxotrophy; synthetic nutrient dependency	Biosafety assurance	Restricted proliferation outside reactors	Reduced competitiveness in mixed systems (Renganathan *et al.,* 2025)
Genetic kill-switch systems	Conditional lethality circuits	Environmental risk mitigation	Enhanced biosafety compliance	Reliability concerns under mutation pressure (Butean *et al.,* 2025)

Strategy / Sub-Domain	Engineering Approach / Design Principle	Targeted Pollutants / Process Function	Key Functional & Process-Level Outcomes	Implementation Constraints & References
Reactor–strain co-design	Integrated bioreactor optimization	Process stability and scalability	Improved lab-to-pilot translation	Capital and operational cost escalation
Pilot-scale deployment	Adaptive process control integration	Real wastewater matrices	Partial retention of lab-scale gains	Performance decline under competition
Regulatory and monitoring frameworks	Risk assessment and post-release surveillance	Environmental deployment	Improved public acceptance and governance	Lack of standardized approval pathways

4. Bioelectrochemical and Electrobiological Systems

4.1. Microbial Electrochemical Technologies

Microbial electrochemical technologies can be regarded as a paradigm shift in the area of wastewater treatment in which the direct association between microbial metabolism and electrochemical energy conversion is made. In microbial fuel cells, electroactive microorganisms oxidize organic materials and pass electrons to an anode to directly generate electricity, and at the same time reduce organic load (Garbini *et al.,* 2023). These systems take advantage of extracellular electron transfer pathways, unlike conventional biological reactors, which enable the collection of energy without any intermediary steps. Microbial electrolysis cells build on this idea and use a small external voltage to force thermodynamically unfavorable reactions in order to promote greater hydrogen evolution from biodegradable material. Microbial electrosynthesis systems have more recently become a platform disruptive technology in which cathodic biofilms can accept electrons provided by electrodes to reduce inorganic carbon or simple organics to value-added products, replacing wastewater systems with biochemical synthesis systems.

4.2 Coupling Treatment with Energy Recovery

The integration of wastewater purification with energy recovery is a defining advantage of bioelectrochemical and electrobiological systems. Electricity generation arises from the spatial separation of oxidation and reduction reactions, governed by microbial electron donation at the anode and terminal electron acceptance at the cathode. Beyond power production, these systems enable the biological generation of hydrogen, methane precursors, and reduced organic intermediates through carefully controlled electrochemical conditions (Mirea *et al.,* 2025). However, the efficiency of such conversions is constrained by limitations in electron flux between microbial cells and electrode surfaces, as well as internal resistances within reactor configurations. Addressing these constraints requires optimization of biofilm conductivity, redox mediator dynamics, and reactor hydrodynamics to ensure effective coupling between biological activity and electrochemical performance.

4.3 Engineering and Scale-Up Challenges

Despite promising laboratory-scale outcomes, the translation of bioelectrochemical systems to full-scale applications remains technically demanding. Electrode composition and structural integrity critically influence long-term performance, as materials must simultaneously support microbial attachment, maintain electrical conductivity, and resist fouling under variable wastewater conditions. Additionally, relatively low power densities limit the practical deployment of these technologies in energy-intensive treatment scenarios (Guo *et al.,* 2019). System-level complexity further complicates scale-up, as integrating electrobiological units with existing treatment infrastructure introduces challenges related to operational control, maintenance, and cost efficiency. Overcoming these barriers will require interdisciplinary advances in materials science, reactor engineering, and process optimization to enable stable, economically viable implementation of electrobiological wastewater treatment systems.

5. Resource Recovery and Circular Bioeconomy Integration

5.1. Nutrient Valorization Pathways

Advanced biological wastewater treatment systems are increasingly being redesigned to function as nutrient recovery platforms rather than end-of-pipe removal units. Phosphorus reclamation has progressed toward biologically mediated recovery strategies that promote intracellular accumulation and subsequent controlled release, enabling downstream crystallization into reusable mineral forms. Such approaches reduce dependency on finite phosphate reserves while minimizing secondary pollution risks. In parallel, biologically driven nitrogen capture mechanisms are being refined to enable selective assimilation, transformation, and retention of reactive nitrogen species, facilitating their reintegration into agricultural and industrial nutrient cycles (Grzyb *et al.,* 2021). Controlled mineral precipitation processes, guided by microbial activity and physicochemical regulation, allow precise recovery of nutrient-rich compounds with consistent quality, thereby enhancing the economic feasibility and operational reliability of nutrient valorization within integrated treatment systems.

5.2. Carbon and Biomass Utilization

Beyond nutrient recovery, next-generation biological treatment frameworks prioritize the strategic conversion of organic carbon into energy carriers and value-added biomaterials. Enhanced anaerobic and fermentative bioprocesses enable efficient transformation of wastewater-derived substrates into biogas and biohydrogen, contributing to on-site energy generation and reduced operational energy demand. Simultaneously, the valorization of microbial biomass has gained prominence, with harvested cells serving as feedstock for biofertilizers, protein-rich additives, or precursor materials for downstream bioprocessing (Narayanasamy *et al.,* 2024). Recent advances further extend biomass utilization toward the biosynthesis of biodegradable polymers and bio-based materials, positioning wastewater treatment systems as contributors to sustainable manufacturing supply chains rather than solely environmental remediation infrastructures.

5.3. Circular Economy Frameworks

The integration of resource recovery within a circular bioeconomy paradigm requires system-level redesigns that align biological treatment processes with value chain development and market dynamics. Waste-to-resource conversion models emphasize closed-loop operation, wherein recovered nutrients, energy carriers, and biomaterials are continuously cycled back into productive use. Effective market integration of these recovered products depends on quality standardization, regulatory acceptance, and techno-economic competitiveness relative to conventional alternatives (Udugama *et al.,* 2017). From a sustainability perspective, lifecycle-based evaluations are increasingly employed to quantify environmental benefits, resource efficiency gains, and trade-offs associated with circular biological treatment systems. Such holistic assessments are essential for guiding policy, investment, and large-scale implementation of biologically driven circular economy solutions in wastewater management.

6. Integrated Hybrid and Smart Treatment Systems

6.1. Hybrid Biological Treatment Architectures

Integrated hybrid treatment configurations represent a paradigm shift in wastewater management by strategically combining complementary biological processes within unified system architectures. Anaerobic–aerobic coupling has emerged as a highly efficient approach, enabling the sequential exploitation of reductive and oxidative metabolic pathways to enhance organic matter conversion while minimizing energy demand. In such configurations, anaerobic units facilitate primary carbon transformation and energy recovery, whereas downstream aerobic stages polish residual contaminants and ensure regulatory compliance (Zhang *et al.,* 2024). Beyond dual-stage coupling, multi-stage bioreactor arrangements have gained attention for their capacity to spatially separate microbial functions, thereby reducing metabolic competition and improving process stability under variable influent conditions. Modular process design further strengthens system flexibility by allowing individual treatment units to be independently optimized, upgraded, or scaled. This architectural adaptability supports rapid technological integration and site-specific customization, positioning hybrid biological systems as robust solutions for diverse wastewater streams.

6.2 Digitalization and Process Control

The incorporation of digital technologies into biological wastewater treatment has redefined operational oversight and decision-making frameworks. Sensor-driven monitoring platforms now provide high-resolution, real-time insights into physicochemical parameters and biological activity, enabling proactive rather than reactive process management. Advanced analytics and artificial intelligence tools are increasingly employed to interpret complex datasets, identify performance trends, and autonomously adjust operational variables such as loading rates, aeration intensity, and hydraulic retention times. These AI-assisted optimization strategies enhance treatment efficiency while reducing operational variability and energy consumption (Rojek *et al.,* 2025). Moreover, data-guided microbial management has introduced a new level of biological control, where shifts in community structure and functional gene expression are anticipated and steered through informed operational interventions. Such digitally enabled governance transforms biological treatment systems into adaptive, self-optimizing infrastructures.

6.3 Techno-Economic and Deployment Constraints

Despite their technological promise, integrated hybrid and smart treatment systems face several constraints that influence real-world deployment. Capital investment requirements and operational expenditures often present complex cost–benefit tradeoffs, particularly when advanced sensors, control algorithms, and modular components are incorporated. Long-term operational reliability remains a critical concern, as system complexity can increase susceptibility to component failure or data inaccuracies if not properly managed. Additionally, infrastructure adaptability poses challenges in regions with aging treatment facilities or limited technical capacity, where retrofitting advanced hybrid systems may require substantial redesign (Scialpi *et al.,* 2023). Addressing these limitations necessitates comprehensive techno-economic assessments, standardized design frameworks, and capacity-building initiatives to ensure that smart hybrid treatment solutions achieve both economic viability and operational resilience at scale.

CONCLUSION

Next-generation biological processes are redefining wastewater treatment by transitioning engineered systems from pollutant removal units into multifunctional platforms for resource generation and environmental resilience. Emerging strategies emphasize functional integration, where advanced microbial consortia, hybrid reactor configurations, and digitally enabled control frameworks collectively enhance process efficiency and adaptability. Rather than optimizing individual treatment steps, current developments focus on system-level performance, enabling simultaneous recovery of energy, nutrients, and value-added bioproducts under increasingly variable operational conditions. The convergence of biological innovation with automation, artificial intelligence, and modular design has further strengthened the capacity of treatment infrastructures to respond dynamically to influent fluctuations and regulatory pressures. Nevertheless, the large-scale translation of these technologies requires careful alignment of biological complexity with economic feasibility and infrastructural compatibility. Addressing scalability, long-term stability, and knowledge gaps in microbial behavior under integrated operation will be pivotal. Ultimately, next-generation biological wastewater treatment systems hold substantial potential to support circular economy objectives and contribute meaningfully to sustainable water and resource management.

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