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Sustainable Microbial Wastewater Treatment Technologies: A Review

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Abstract

Microbial wastewater treatment technologies play a central role in protecting public health and maintaining environmental sustainability by harnessing the metabolic capabilities of microorganisms to remove organic matter, nutrients, pathogens, and emerging contaminants. This review provides a comprehensive synthesis of eight major microbial treatment systems: Activated Sludge Process (ASP), biofilm reactors, anaerobic digestion, oxidation ponds, constructed wetlands (CWs), biologically activated carbon (BAC), microbial fuel cells (MFCs), and microbial desalination cells (MDCs). Each technology relies on specific microbial consortia including heterotrophic bacteria, nitrifies, denitrifiers, methanogens, exoelectrogens, algae, and rhizosphere microbes to drive processes such as organic degradation, nitrification, denitrification, methane generation, electricity production, nutrient uptake, and desalination. The review highlights core mechanisms, microbial community structure, operational features, advantages, and limitations for each treatment process. Collectively, these systems illustrate the versatility of microbial communities in addressing global wastewater challenges. Emerging bioelectrochemical technologies (MFCs and MDCs) show strong potential for energy-positive treatment and integrated water–energy systems, while nature-based solutions such as CWs and oxidation ponds remain valuable for low-cost, decentralized treatment. Understanding and optimizing microbial interactions across these systems is essential for advancing sustainable wastewater management in both developed and resource-limited regions.

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1. INTRODUCTION

Water is fundamental to life on Earth, and both its quality and availability significantly influence natural and human systems. However, rapid urbanization, climate change, and population growth have led to an unprecedented rise in the demand for freshwater resources, resulting in stress and shortages in many regions around the world (Amtul Bari et al., 2024). The adoption of practical and sustainable strategies is vital to promote global water sustainability and to avert the looming crisis of living without access to safe and clean water for drinking, agriculture, and industrial purposes (Mishra et al., 2021). Water lies at the heart of sustainable development and is vital for socio-economic progress, energy generation, food

production, healthy ecosystems, and human survival. It also plays a central role in climate change adaptation, acting as a critical link between society and the natural environment (UN, 2023). Sustainable water management is a holistic approach aimed at meeting the water needs of current and future generations while minimizing negative impacts on society, the environment, and the economy (Olley et al., 2024). It entails the implementation of policies and technologies that enhance water quality, reduce pollution, promote economic development, and protect public health, all within the framework of sustainability (Santos et al., 2023). By embracing such strategies, we can ensure the long-term availability and quality of water resources for generations to come.

The intensifying global water crisis marked by growing water scarcity and widespread pollution poses serious threats to human health, environmental sustainability, and economic stability (Omolere, 2024). This crisis refers to the diminishing availability of usable and accessible freshwater resources worldwide. Currently, around 703 million people roughly 1 in 10 globally lack access to water, while over 2 billion people are without safe drinking water services (Biswas et al., 2025). According to the United Nations, by 2025, an estimated 1.8 billion people will be living in countries or regions experiencing absolute water scarcity. Under current climate change projections, nearly half of the world's population could be living in areas facing high water stress by 2030. Moreover, water scarcity in arid and semi-arid regions is expected to displace between 24 million and over 700 million people by the same year (UNICEF & WHO, 2023).

Although traditional wastewater treatment methods have proven effective to a certain degree, they often fall short in dealing with emerging contaminants and typically demand high energy and resource inputs, revealing their limitations in achieving long-term sustainability (Bakare et al., 2020). Conventional systems frequently struggle to eliminate micropollutants such as pharmaceuticals and personal care products that pose serious risks to both aquatic ecosystems and human health. Additionally, these methods can be energy-intensive and may produce secondary pollutants, thereby compounding environmental challenges (Sharma et al., 2024). As a result, there is an urgent need for innovative, sustainable water management solutions that can efficiently tackle these issues while reducing ecological impact.

Microbial innovations present a promising pathway for sustainable water management by utilizing the natural abilities of microorganisms to remove pollutants, improve water quality, and facilitate resource recovery (Akinsemolu et al., 2024). These strategies exploit the diverse metabolic functions of microbes to break down or transform a variety of contaminants, including organic compounds, heavy metals, and emerging pollutants. Additionally, microbial processes can be optimized for nutrient removal, helping to prevent eutrophication and enhance the ecological health of aquatic systems (Glockow et al., 2024). Integrating microbial technologies into water management frameworks offers cost-effective, environmentally sustainable, and resilient solutions that support a more sustainable water future (Mallick & Poddar, 2025).

2. ADVANTAGES OF MICROBIAL TECHNOLOGIES

2.1 Natural and Environmentally Friendly

Microbial treatment methods utilize naturally occurring microbes to clean water without the need for strong chemicals or energy-intensive technologies (Lakhani et al., 2022; Sanchez-Rosario et al., 2024). Systems like constructed wetlands combined with microbial fuel cells

replicate natural wetland environments, employing plants and bacteria to eliminate pollutants while also producing electricity in a sustainable cycle (Arliyani et al., 2024). These approaches rely on indigenous microbial populations to improve water quality, support biodiversity, and reduce chemical use. As nature-based solutions, they contribute to sustainable development by minimizing environmental impact and preventing the creation of secondary waste (Jacobs et al., 2024)

2.2 Effective Removal of a Wide Range of Contaminants

Microorganisms are capable of breaking down and transforming a wide variety of pollutants including organic substances, heavy metals, excess nutrients, and emerging contaminants through their metabolic activities.(Ayilara & Babalola, 2023; Bala et al., 2022). Biological approaches such as biofilms and microalgae consortia demonstrate high efficiency in removing chemical oxygen demand (COD), nitrogen, phosphorus, and trace-level toxins that often resist traditional treatment methods (Vo et al., 2024). Integrated systems that pair microbial degradation with membrane filtration or adsorption technologies broaden the range of contaminants that can be treated (Mathew et al., 2022). This adaptability allows microbial solutions to be effectively applied to municipal, industrial, and agricultural wastewater.

2.3 Low Energy and Resource Requirements

Biological treatment methods typically function under normal temperature and pressure conditions, significantly lowering energy requirements compared to high-temperature or high-pressure alternatives (Narayanan & Narayan, 2019). Technologies like microbial desalination cells and microbial fuel cells can purify water while generating energy, cutting overall energy consumption by more than 40% compared to processes like reverse osmosis or thermal desalination (Farahani et al., 2024; Odunlami et al., 2023) Additionally, engineered microbial reactors can utilize the organic content in wastewater as both an energy source and nutrient supply, removing the need for external chemicals or energy inputs (Apollon et al., 2025)

2.4 Cost-Effective Solutions

After setup, microbial treatment systems generally have lower operational and maintenance expenses compared too many conventional physicochemical methods (Patel et al., 2021). For example, constructed wetlands integrated with microbial fuel cells not only cleanse water but also produce modest amounts of electricity, helping to lower treatment costs and reduce dependence on external energy sources (Kesarwani et al., 2023). Innovations in electrode materials like graphene and the integration of automated processes can lead to capital and operational savings of up to 20% in microbial fuel cell applications. Additionally, the scalable and modular design of these systems makes them particularly suitable for use in settings with limited resources (Roy et al., 2023b)

2.5 Adaptability and Resilience

Microbial communities are highly adaptable, capable of adjusting to changes in pollutant concentrations, pH levels, and temperature. As part of climate-resilient agricultural and water treatment practices, these robust microbes are increasingly employed to ensure consistent performance during environmental stresses such as droughts or heavy rainfall (Iqbal et al., 2023; Philippot et al., 2021). By selecting or engineering microbial strains tailored to specific

local conditions, both centralized and decentralized treatment systems can maintain effective contaminant removal even amid environmental fluctuations. This flexibility helps safeguard water quality and availability in a changing climate (Etsuyankpa et al., 2024; Sharma et al., 2023)

2.6 Nutrient Recovery and Resource Recycling

Biological treatment systems are capable of capturing and reclaiming essential nutrients especially nitrogen and phosphorus from wastewater (Rahimi et al., 2020). Technologies like bio electrochemical systems and osmotic membrane bioreactors can selectively extract these nutrients, producing fertilizers such as struvite with low energy requirements. This nutrient recovery not only helps prevent eutrophication in downstream ecosystems but also reduces reliance on fertilizers derived from fossil fuels (Siciliano et al., 2020; Zhan et al., 2025). By transforming wastewater into a valuable resource, these approaches support a circular economy and promote sustainable agricultural practices.

2.7 Reduced Production of Secondary Pollutants

In contrast to many chemical treatments that create waste by-products or sludge requiring additional disposal, microbial processes often break down organic pollutants into benign substances such as carbon dioxide and water (Maglione et al., 2024; Sadiq et al., 2025). These biological systems generally produce 30–50% less excess sludge compared to chemical coagulation, reducing the burden of waste management (Alaidaroos, 2023). Moreover, since toxic chemicals are not used, the risk of forming harmful disinfection by-products is minimized, offering greater protection for both aquatic environments and public health (Kumar et al., 2023).

3.1 Microbial Technologies for Sustainable Wastewater Management

Microbial technologies offer innovative approaches to tackling both water scarcity and pollution. These solutions leverage the power of microorganisms, like bacteria and fungi, to purify water, remove pollutants, and even create new water resources. By harnessing the power of microorganisms, scientists and engineers are developing innovative solutions to address water scarcity and pollution, paving the way for a more sustainable and equitable future. Microbes are being used for sustainable wastewater management through different microbial processes:

3.1 Activated Sludge Process (ASP)

The activated sludge process (ASP) represents the most extensively applied aerobic wastewater treatment technology (Khudhair et al., 2023). In this system, wastewater is introduced into aeration tanks containing a dense suspension of microorganisms, known as activated sludge, where continuous aeration provides oxygen to support microbial metabolism. During treatment, organic pollutants are biologically oxidized into carbon dioxide, water, and new microbial biomass. The resulting microbial aggregates, or flocs, are subsequently separated from the treated water in secondary clarifiers (Roman et al., 2022). To maintain optimal biological activity, a portion of the settled sludge is recycled back into the aeration tank, while the excess sludge is withdrawn for further processing or disposal (Chinedu Agu et al., 2024)

In the activated sludge process (ASP), various microorganisms perform distinct but complementary functions that drive efficient wastewater treatment (Diehl & Farås, 2013). Heterotrophic bacteria such as *Pseudomonas*, *Bacillus*, and *Zoogloea ramigera* are primarily responsible for decomposing dissolved and particulate organic matter, with *Zoogloea* playing a key role in forming stable flocs essential for sedimentation. Autotrophic nitrifying bacteria, including *Nitrosomonas* and *Nitrobacter*, facilitate the oxidation of ammonia to nitrate, contributing to nitrogen removal (Yang et al., 2020). Protozoa such as *Vorticella* and *Paramecium* help regulate bacterial populations and enhance the clarity of the treated effluent by consuming dispersed bacteria. Additionally, fungi like *Aspergillus* and *Penicillium* contribute to the degradation of complex organic compounds, particularly under low-oxygen conditions, supporting the overall stability and efficiency of the ASP system (Shchegolkova et al., 2016).

3.2 Biofilm Reactors

Biofilm-based wastewater treatment systems serve as a robust alternative to conventional suspended growth processes. In these reactors, microorganisms adhere to solid surfaces such as rocks, plastic media, or membranes, where they develop structured biofilms through which wastewater continuously flows (Espinosa-Ortiz et al., 2023). Within the biofilm matrix, pollutants diffuse inward and are degraded by diverse microbial populations inhabiting microenvironments with varying oxygen gradients. This stratified structure enhances the efficiency and stability of treatment (Abera et al., 2024). Biofilm reactors come in several designs that promote microbial attachment and pollutant degradation. Trickling filters use rock or synthetic media coated with biofilms, rotating biological contactors (RBCs) rotate discs alternately exposed to air and wastewater, and moving bed biofilm reactors (MBBRs) use mobile plastic carriers for biofilm growth (Saini et al., 2023).

Autotrophic nitrifiers such as *Nitrosomonas* and *Nitrobacter* facilitate the oxidation of ammonia, while heterotrophic denitrifiers including *Paracoccus* and *Pseudomonas* convert nitrate into nitrogen gas under anoxic conditions (Sehar & Naz, 2016). Additionally, the coexistence of fungi and algae alongside bacteria contributes to greater metabolic flexibility and ecological resilience. Although biofilm reactors typically generate less sludge and exhibit higher resistance to hydraulic and organic shock loads compared to the activated sludge process, their performance depends on adequate surface area availability and precise reactor design to ensure optimal biofilm development and nutrient removal efficiency (Gullicks et al., 2011).

3.3 Anaerobic Digestion

Anaerobic digestion (AD) is used for sludge stabilization and treating high-strength industrial wastewater. In oxygen-free conditions, microorganisms convert organic matter into biogas (methane and CO_2) and stabilized sludge, reducing waste volume and generating renewable energy (Prasanna Kumar et al., 2024). Although AD offers energy recovery and low sludge production, its microbial communities grow slowly and are sensitive to environmental fluctuations, requiring longer retention times for stable operation (Huang, 2024). The process occurs in four stages: (1) Hydrolysis**:** hydrolytic bacteria (*Clostridium*, *Bacteroides*) break down complex polymers into monomers; (2) Acidogenesis**:** fermentative bacteria (*Enterobacter*, *Lactobacillus*) produce volatile fatty acids, alcohols, H_2, and CO_2; (3) Acetogenesis**:** *Syntrophomonas* and *Syntrophobacter* oxidize these products into acetate, H_2, and CO_2; and (4)

Methanogenesis**:** methanogenic archaea (*Methanobacterium*, *Methanosaeta*, *Methanosarcina*) generate methane from acetate or H_2/CO_2 (Ali Shah et al., 2014).

3.4 Oxidation Pond

Oxidation ponds, or waste stabilization ponds (WSPs), are extensive, shallow basins designed for the biological treatment of domestic and certain industrial wastewater. They are especially effective in warm climates, as they rely on natural sunlight and microbial processes to achieve purification. The treatment process involves a complex interplay among bacteria, algae, protozoa, and solar energy, providing a low-cost, energy-efficient, and sustainable wastewater management solution, particularly in developing regions (Alam, 2018; Ali et al., 2019). In operation, wastewater enters the pond where heavier solids settle and organic matter undergoes biological degradation. Algae within the pond perform photosynthesis, releasing oxygen into the water, which aerobic bacteria then use to oxidize organic matter into carbon dioxide, ammonium, and other by-products (Ho & Goethals, 2020). The carbon dioxide produced is subsequently utilized by algae, maintaining a symbiotic oxygen-carbon cycle that sustains microbial activity. Pathogen reduction occurs through a combination of sunlight exposure (ultraviolet radiation), elevated pH, protozoan predation, and natural die-off mechanisms (Djarot et al., 2024).

The microbial communities within oxidation ponds are diverse and functionally specialized. Algae such as *Chlorella*, *Scenedesmus*, and *Spirulina* generate oxygen through photosynthesis, supporting aerobic degradation (Abate et al., 2024). Heterotrophic bacteria including *Pseudomonas*, *Bacillus*, and *Escherichia coli* metabolize organic matter, while nitrifying bacteria like *Nitrosomonas* and *Nitrobacter* facilitate ammonia oxidation to nitrate. Denitrifying bacteria (*Paracoccus*, *Pseudomonas denitrificans*) operate in anoxic zones to convert nitrate into nitrogen gas, reducing nitrogen pollution. In anaerobic zones, methanogenic archaea (*Methanosaeta*, *Methanobacterium*) produce methane during the final stages of organic degradation (Salazar et al., 2023). Protozoa such as *Vorticella* and *Amoeba* prey on free bacteria, thereby enhancing effluent clarity (Gad et al., 2024).

3.5 Microbial Fuel Cells

Microbial fuel cells (MFCs) are an innovative wastewater treatment technology that simultaneously removes organic pollutants and generates electricity. In these systems, electrogenic microorganisms oxidize organic matter in wastewater and transfer the resulting electrons to an anode, producing a usable electric current (Nawaz et al., 2022). Mechanistically, the anode chamber operates under anaerobic conditions, where wastewater serves as the electron donor substrate. Electrogenic bacteria degrade organic compounds such as glucose and acetate, releasing electrons and protons. Rather than transferring electrons to oxygen, these microbes deliver them to the anode either through direct electron transfer using conductive pili or nanowires or through mediated electron transfer via secreted redox-active compounds (Roy et al., 2023a). Protons generated during oxidation migrate through a proton exchange membrane (PEM) into the cathode chamber. In the aerobic cathode chamber**,** electrons flow from the anode through an external circuit and combine with oxygen and protons at the cathode surface, producing water and completing the electrical circuit (Bazina et al., 2023).

A diverse microbial community supports MFC function. Exoelectrogenic bacteria such as *Geobacter sulfurreducens* (direct electron transfer via conductive pili), *Shewanella oneidensis* (nanowires and soluble mediators), and *Pseudomonas aeruginosa* (phenazine-mediated electron shuttling) drive electricity generation (Shajid et al., 2025). Fermentative bacteria including *Clostridium* and *Enterobacter* break down complex substrates into simpler molecules and hydrogen, providing additional substrates for electrogens. Methanogenic archaea such as *Methanosaeta* and *Methanobacterium* compete for acetate and electrons, often reducing power output. In systems employing biocathodes, organisms like *Nitrobacter* and *Desulfovibrio* may participate in catalyzing oxygen or nitrate reduction at the cathode (Dakal et al., 2025).

3.6 Microbial Desalination Cells (MDCs)

Microbial Desalination Cells (MDCs) are an emerging bioelectrochemical technology that combines wastewater treatment, electricity generation, and desalination within a single integrated system (Alabi, 2025). In MDCs, electroactive bacteria in the anode chamber oxidize organic matter in wastewater, releasing electrons that flow to the cathode through an external circuit. This electron flow creates an electrical potential that drives the migration of ions across ion-exchange membranes, enabling the removal of salts from saline or brackish water without the need for external energy input (Odunlami et al., 2023) Unlike conventional desalination methods such as reverse osmosis or electrodialysis which require substantial energy and high-pressure systems, MDCs utilize the metabolic activity of exoelectrogenic microorganisms to generate the electrical current necessary for salt separation. Within the anode chamber, these electrogenic bacteria oxidize organic substrates and transfer electrons to the anode, establishing the potential difference between electrodes (Aidan et al., 2015).

A typical MDC consists of an anode chamber, a cathode chamber, and a central desalination compartment equipped with cation- and anion-exchange membranes. As electrons move from the anode to the cathode, cations migrate toward the cathode through the cation-exchange membrane, while anions move toward the anode through the anion-exchange membrane (Aber et al., 2023). This coordinated ion movement effectively extracts salt ions from the desalination chamber, achieving simultaneous pollutant removal, energy recovery, and water desalination (Alhimali et al., 2019).

3.7 Constructed Wetlands (CWs)

Constructed wetlands (CWs) are engineered ecosystems designed to imitate natural wetlands for treating wastewater, stormwater, and agricultural runoff. Built with vegetation, soil, and shallow water channels, they operate as artificial marshes that filter, degrade, and transform pollutants through natural processes (Ravikumar et al., 2022). Because they require minimal energy and maintenance, CWs are widely used in community and environmentally sustainable wastewater treatment systems.(Rahman et al., 2020). Treatment in CWs occurs through a combination of physical, biological, and chemical mechanisms. As water flows slowly through the wetland, solids settle out, while plant roots introduce oxygen into localized zones that support aerobic microbial degradation of organic matter (Vymazal, 2022). Deeper anaerobic zones facilitate denitrification, and plants absorb nutrients such as nitrogen and phosphorus, preventing downstream eutrophication. Additional removal of metals and pathogens occurs via adsorption and microbial action, enabling CWs to treat moderate wastewater volumes depending on their design (Saroj & Dutta, 2019). Microorganisms are central to the effectiveness of CWs. They break down organic pollutants, reducing

biochemical oxygen demand (BOD) and chemical oxygen demand (COD). They also drive nutrient cycling through nitrification in oxygen-rich regions and denitrification in oxygen-poor areas (Rajan, 2019). Microbes in the root zone help suppress pathogens through degradation and antimicrobial activity, while others contribute to the transformation of various emerging contaminants. Through these combined microbial functions, constructed wetlands achieve efficient and sustainable wastewater purification (Shravani et al., 2025).

3.1.8 Biologically Activated Carbon (BAC)

Biologically Activated Carbon (BAC) is a treatment method that integrates the adsorption capacity of activated carbon with microbial biodegradation to remove organic contaminants from water (Kalkan et al., 2011). In this system, microorganisms colonize the surface of activated carbon and form a biofilm capable of degrading both the organic compounds trapped on the carbon and those remaining dissolved in the water. This combined action makes BAC more effective than conventional activated carbon filtration alone, allowing for the removal of a broader spectrum of organic pollutants while offering an environmentally friendly and cost-efficient treatment option (Mądrecka-witkowska et al., 2023).The process operates through two key mechanisms. First, adsorption occurs as the highly porous activated carbon captures organic pollutants from the water onto its extensive surface area. Second, biodegradation takes place as bacteria and other microorganisms metabolize these adsorbed contaminants, thereby regenerating the carbon surface and enhancing long-term treatment efficiency (Korotta-Gamage & Sathasivan, 2017). The mechanisms, dominant microbial communities, and performance characteristics of conventional and emerging microbial wastewater treatment technologies are comparatively summarized in Table 1.

Table 1. *Comparative overview of microbial wastewater treatment processes, dominant microbial groups, and key functions.*

Treatment Process	Main Mechanism	Key Microbial Groups	Primary Outputs/Benefits	Limitations	References
Activated Sludge Process	Aerobic degradation of organic matter; formation of microbial flocs; aeration-driven oxidation	Heterotrophs (*Pseudomonas*, *Bacillus*, *Zoogloea*), nitrifiers (*Nitrosomonas*, *Nitrobacter*), protozoa, fungi	High removal of BOD/COD; effective nitrification; well-established technology	High energy demand for aeration; large sludge production; sensitive to toxic shocks	(Gad et al., 2024; Khudhair et al., 2023; Roman et al., 2022)
Biofilm Reactors	Wastewater flows over surfaces coated with biofilms; pollutants diffuse into biofilms with aerobic–anoxic microzones	Nitrifiers, denitrifiers (*Paracoccus*, *Pseudomonas*), fungi, algae	Stable under shock loads; lower sludge production; efficient nitrification	Requires large surface area; potential clogging; slower biofilm development	(Espinosa-Ortiz et al., 2023; Saini et al., 2023; Sehar & Naz, 2016)
Anaerobic Digestion	Four-stage anaerobic breakdown (hydrolysis, acidogenesis, acetogenesis, methanogenesis) producing biogas	Hydrolytic bacteria, fermenters, syntrophic bacteria, methanogenic archaea (*Methanosaeta*, *Methanobacterium*)	Biogas (CH_4) production; low sludge volume; energy recovery	Slow microbial growth; sensitive to pH, temperature, and toxins; long retention times	(Akinsemolu et al., 2024; Huang, 2024; Nabaterega et al., 2021; Sravan et al., 2024)
Oxidation Ponds	Symbiotic algae–bacteria interactions; sunlight-driven oxygenation; settling and natural degradation	Algae (*Chlorella*, *Scenedesmus*), heterotrophs (*Bacillus*, *E. coli*), nitrifiers, denitrifiers, protozoa	Low-cost, low-energy; high pathogen removal; suitable for warm climates	Large land area; odors in anaerobic ponds; slow treatment rates	(Alam, 2018; Ho & Goethals, 2020)

Microbial Fuel Cells	Electrogenic bacteria oxidize organics and transfer electrons to an anode; electricity generation	Exoelectrogens (*Geobacter*, *Shewanella*), fermenters (*Clostridium*), competing methanogens	Simultaneous wastewater treatment + electricity generation	Low voltage output; sensitive to competing microbes; expensive electrode materials	(Bazina et al., 2023; Dakal et al., 2025; Kesarwani et al., 2023)
Microbial Desalination Cells	Bioelectrochemical oxidation in anode drives ion migration across membranes for desalination	Exoelectrogens; fermenters; optional cathodic bacteria	Wastewater treatment + electricity + desalination with no external energy	Membrane fouling; complex reactor design; limited large-scale application	(Aber et al., 2023; Alhimali et al., 2019; Odunlami et al., 2023)
Constructed Wetlands	Physical settling + microbial degradation + plant uptake; aerobic–anaerobic zones around roots	Heterotrophs, nitrifiers, denitrifiers, rhizosphere microbes, algae	Low-energy, natural system; strong pathogen removal; nutrient uptake by plants	Requires large land area; performance varies with climate; slow processes	(Arliyani et al., 2024; Kesarwani et al., 2023; Saroj & Dutta, 2019; Shravani et al., 2025)

4. CONCLUSION

Microbial wastewater treatment technologies continue to form the foundation of modern environmental management by exploiting the diversity and metabolic capabilities of microorganisms to remove pollutants from water. Across the systems reviewed, microbes function as the primary drivers of organic matter degradation, nutrient transformation, pathogen removal, and biogas or electricity generation. Innovative technologies, including Biologically Activated Carbon, Microbial Fuel Cells, and Microbial Desalination Cells, demonstrate the expanding potential of microbial processes to address emerging treatment needs, such as the removal of recalcitrant contaminants, energy recovery, and desalination. Although challenges persist such as land requirements for nature-based systems, sensitivity of anaerobic processes, and technological immaturity of bioelectrochemical systems, continued research into microbial ecology, reactor optimization, and integrated hybrid systems promises to enhance performance, resilience, and sustainability. Overall, microbial treatment technologies represent a powerful and adaptable toolkit for achieving safe water, environmental protection, and resource recovery, positioning microorganisms as key contributors to the future of sustainable wastewater management.

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