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Microbial Cells Represent A Promising Technology For Industrial Wastewater Treatment.

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Abstract

Industrial wastewater contains various toxic chemicals, inorganic and organic, such as heavy metals, pharmaceuticals, dyes, oils, nutrients, and toxic solvents. Disposing of complex waste without adequate treatment is very detrimental to the environment, marine life, and social health. Conservative wastewater treatment approaches are often associated with high costs, high energy requirements, and the possible production of toxic byproducts. Microbial cells have gained immense popularity as environmentally friendly and sustainable tools for the bioremediation of chemically contaminated industrial wastewater. This review provides a comprehensive overview of the quality, sources, and impacts of industrial waste. It also seems that microorganisms (bacteria, fungi, algae, and other microbes) help to clean up polluted water. Microbial mechanisms used for treatment include biodegradation, biosorption, bioaccumulation, and bio-electrochemical processes, which use them to generate electricity. These methods are often used in systems like activated sludge and biofilm reactors. Recently, there has been progress in using specially designed groups of microbes, mixed systems that combine microbes with nanoparticles, and combined systems that use both biological and electrical processes. The review highlights the limitations and challenges of using microorganisms for treatment, what might happen when these methods are used on a larger scale, and how resources can be recovered. Microbial cell-based technologies offer an optimistic, eco-friendly option for effectively treating industrial wastewater containing a mix of chemicals.

INTRODUCTION

The use of water at the national and international levels is essential for human beings, sustaining ecological balance, supporting human life, and underpinning various industrial and agricultural endeavors. Demand for freshwater resources has always risen with the growth of the human population worldwide. Out of the water present on our planet, 97% is saline in nature, while only 3% is categorized as fresh water (Abbasi & Abbasi, 2012). Only 0.5% of the available fresh water is accessible for social use and is available in fluid form, including river water, groundwater, and other water resources (Kato & Kansha, 2024). The severity of water shortage has been portrayed by the (UNWWAP) United Nations World Water Assessment Program in 2018: currently, 3.6 billion people live under water insufficiency for 1 month each year, and may increases to 4.8-5.7 billion by 2050 (Koncagül *et al.*, 2018). The increasing global demand for freshwater and the generation of wastewater have led to a global water problem. Wastewater amount produced worldwide each year is estimated at 380 billion m^3, and it is estimated to rise by 51% by 2050 (Qadir *et al.*, 2020).

The pace of industrialization and urban development has accelerated, and a large volume of wastewater is being generated globally. On average, industries use 22% of total water consumption. An average of 80% of the total wastewater is wasted into water channels, creating pollution that threatens the health of human beings (Association, 2018). Effluents from industrial wastewaters are essentially the waste products from human activities related to the processing of raw materials and manufacturing. Industrial wastewater depends on different production processes and can be broadly categorized as manufacturing processes, non-process wastewater such as boiler blow-off water and cooling water, and industrial site drainage. Each of these water streams comprises different impurities, which need to be treated accordingly (Abdul Hameed M Jawad *et al.*, 2010; Silva *et al.*, 2021).

This included toxic organic solvents, various heavy metals like mercury, lead, chromium, and various organic compounds (drugs), various nutrients, high levels of BOD, ammonia, oils, and greases from food processing industries; various dyes, salts, plastics, organic or inorganic pigments, (Gadipelly *et al.*, 2014) and textile auxiliaries from textile industries; lignin, (Christian *et al.*, 2023) chlorinated organic compounds from pulp and paper industries; ferrous sulfate, hydraulic oils, and various metallic constituents such as cadmium, zinc, arsenic, nickel from iron, steel, and metal industries; cyanides, hydrocarbons, and acid mine drainage from mining and oil from natural gas industries; (Kadier *et al.*, 2022) and various petroleum hydrocarbons and phenols from the petroleum industries. Inorganic matter, such as grit, sand, metallic waste, and also rubber particles from various industries, is associated with this wastewater; various pH extremes from hydrochloric or sulfuric acids from metal industries (Farooq *et al.*, 2011; Helmer & Hespanhol, 1997; Khan *et al.*, 2022). Microbial cells are a promising green technique for industrial wastewater treatment, with considerable benefits over traditional methods (Saranya *et al.*, 2025). Photosynthetic bacteria can treat industrial wastewater without sludge formation and produce valuable by-products, such as bacterial biomass, algae suitable for use as animal and fish food, and organic fertilizers (Kobayashi & Tchan, 1973). Immobilized microbial cells are more resistant to harmful substances than their free-floating counterparts and are highly effective for removing contaminants from industrial effluents (Martins *et al.*, 2013). Modern bio-inspired technologies for wastewater treatment involve the use of a range of microorganisms in different bioreactors, where microbes serve a dual purpose: removing pollutants from wastewater and producing valuable outputs as bio-fertilizers and biofuels (Singh *et al.*, 2022). The inclusion of microbial nanotechnology in treatment processes further improves the process by allowing the production of eco-friendly nanomaterials, improving enzyme activity and reusability, thus reducing costs compared to conventional processes(Mandeep & Shukla, 2020). Microbial cells provide a safe, eco-friendly, and sustainable methods to treat chemically hazardous industrial wastewater by utilizing natural biodegradation processes to remove pollutants without producing harmful by-products (Kumar & Verma, 2025). Recent advancements include the use of engineered microbial associations, bio-electrochemical systems, and nanotechnology to further improve efficiency (Al-Rajhi & Abdelghany, 2025).

Microbial fuel cells (MFCs) utilize electroactive bacteria to both remove organic and toxic pollutants and produce electricity, which addresses remediation and energy conversion simultaneously (Chatterji *et al.*, 2025). Microbial organisms remove toxins via their enzymatic mechanisms: cytochromes in bacteria that degrade organics, fungi harvest extracellular enzymes (laccase) to degrade lignin-derived compounds, and microalgae fix carbon dioxide while taking up metals (Guo *et al.*, 2023). Electroactive species, such as Geobacter, transmit electrons extracellularly, allowing microbial fuel cells (MFCs) to break down contaminants while also producing bioenergy (Álvarez-Ley *et al.*, 2025). These technologies surpass chemical oxidation by working at ambient temperatures, resulting in up to a 70% reduction in energy input (Aryanfar *et al.*, 2025; Strik *et al.*, 2011). Green microbiology includes sustainable microbial technologies that generate renewable biofuels, biodegradable plastic alternatives, nutritious food sources, and clean energy while breaking down harmful waste into less toxic compounds. It provides viable solutions for cleaner production and waste management across agriculture, manufacturing, and energy sectors (Akinsemolu, 2023). In this review article, we will discuss how industrial wastewater can be treated using various microorganisms like bacteria and fungi, through bioremediation, and we will review future strategies & advancements in treating industrial wastewater.

Industrial Wastewater Characteristics and Challenges

A significant environmental issue that is arising from global industrialization, urbanization, and a wide range of manufacturing processes is the industrial wastewater containing chemicals. Unlike municipal wastewater, industrial effluents vary greatly in terms of composition, concentration, and treatment on the basis of particular industrial sectors, procedures, and raw materials used, and generate wastewater containing lethal and toxic pollutants, directly discharging into the environment without treatment (Nikolić *et al.*, 2025). This untreated wastewater containing toxic chemicals poses a threat to the terrestrial and aquatic environment, even to human health. This problem requires urgent treatment and management for the protection of the environment and public health (Haq & Kalamdhad, 2022). Characterization of industrial wastewater is necessary to design efficient treatment strategies, but it also depends on the complexity of industrial developments and manufacture conditions. Among the major sources of chemical containing wastewater are the textile, pharmaceutical, and leather industries (Saxena *et al.*, 2020). Undoubtedly, the leather industry is contributing significantly to the nation's budget; it is among the major polluters, producing large volumes of wastewater with unpleasant odors, high pH, brownish color, and extreme toxicity to land (Saxena *et al.*, 2020).

Physical Characteristics

The color of industrial effluent varies greatly by industry and is a major indicator of pollution. The effluents from textile and dyeing industries are highly colored, ranging from dark reds and blues to blacks and browns, due to the use of synthetic dyes that are resistant to deterioration. Tannery wastewater contains visible suspended particles and appears to be brownish or blackish (Saxena *et al.*, 2016). The appearance of wastewater also helps in quantifying the pollutants present in it. Turbid water indicates large amounts of suspended particles, while oil sheens over wastewater indicates oil coming from industries. Some industries' wastewater may appear clear but contain large volumes of pollutants that are toxic in nature and also invisible to the human eye (Ullah *et al.*, 2024). Temperature is an important factor, as many industries release hot wastewater produced during processes, which can adversely affect the aquatic ecosystem. It can diminish oxygen levels and stress sensitive aquatic creatures. Additionally, hot wastewater hinders the biological treatment as microorganisms may thrive in extreme temperatures. Particularly hot effluents are produced by industries like chemical manufacturers, power plants, and steel mills (Han *et al.*, 2021; Mahmood *et al.*, 2019).

A major part of industrial effluent is unpleasant odors, which frequently indicate the presence of certain contaminants. For example, wastewater from tanning produces strong, unpleasant aromas because of sulfides, ammonia, and decomposing organic debris. Based on the materials and chemicals being used, wastewater from food processing and pharmaceuticals can also produce unique odors (Czarnota *et al.*, 2023). Fiber particles and dye solids are present in greater amounts in textile effluents. Grinding residues and suspended metal particles are generated during metal processing activities.

Organic Pollutants

The two most crucial markers of organic contamination in wastewater are COD (Chemical oxygen demand) and BOD (Biological oxygen demand). While BOD is the oxygen utilized by microbes breaking down biodegradable organic matter over a specific time period (typically 5 days), COD is the total amount of oxygen required to chemically oxidize organic matter in the water. Heavy organic contamination is indicated by high COD and BOD levels (Bezsenyi *et al.*, 2021). Some industrial wastewaters include high amounts of organic materials. Compared to regular dwellings' sewage, wastewater from chemical production processes can have COD values of over 10,000 mg/L, which is more than 100 times greater. Such high concentrations provide serious treatment problems since they may be harmful to the microorganisms used in biological treatment systems. Furthermore, exceptionally high quantities of BOD and COD are commonly seen in tanning effluents, indicating their high organic (Urbina-Suarez *et al.*, 2021). The COD to BOD ratio offers valuable insights into biodegradability. A significantly greater COD than BOD suggests the existence of organic substances that are either impossible or very difficult for microbes to decompose. Instead of using traditional biological treatment, these refractory organics need advanced procedures like chemical oxidation or membrane filtering (Bhandari *et al.*, 2016).

Discharge from the automobiles metal processing, food processing, and petroleum industries frequently contains oils and greases.

These pollutants can cover and kill aquatic organisms, clog treatment equipment, skim on water surfaces, and affect oxygen transport. Food processing industries release animal fats and vegetable fats that solidify and block the collection systems. Physical separation techniques like dissolved air flotation devices or oil-water separators are usually needed to remove oil and grease (Heponiemi & Lassi, 2012).

Volatile organic compounds, including carbon-based substances, readily evaporate at room temperature. VOCs, such as solvents, degreasers, paints, and chemical intermediates, are used or produced in a variety of manufacturing procedures. Benzene, toluene, xylene, formaldehyde, and chlorinated solvents are common volatile organic compounds (VOCs) found in industrial effluent (Fatima *et al.*, 2022). In addition to being hazardous or carcinogenic to both humans and animals, VOCs (volatile organic compounds) also contribute to air pollution as they evaporate from wastewater, and some are challenging to eliminate using traditional treatment methods. The production of chemicals, pharmaceuticals, paint & protective coatings, and automobiles is among the industries that frequently release volatile organic compounds (VOCs) (Insam & Seewald, 2010). Air stripping, activated carbon adsorption, or advanced oxidation are examples of specialized methods for treatment that can be employed (Byliński *et al.*, 2019).

1.1. Inorganic Pollutants

The most hazardous substances found in industrial effluent include heavy metals, which are toxic, persistent, and have the capability to accumulate in living organisms. Heavy metals present in industrial effluent include lead, cadmium, nickel, copper, zinc, and chromium. Such companies use metal salts in plating baths, producing wastewater that contains chromium, nickel, copper, and zinc (Gao *et al.*, 2025).Wastewater treatment from chemical production, petroleum refining, and some food processing processes is greatly hindered by high salinity, or salt concentration. Total Dissolved Solids (TDS) are used to quantify salinity. Various wastewaters from chemical processes have salt concentrations above 3.5%, which is higher than that of seawater. It leads to osmotic stress, which harms or blocks the microorganisms used in biological purification (Srivastava *et al.*, 2021). Industrial wastewaters frequently have extreme pH values, which can be extremely acidic (low pH) or extremely alkaline (high pH). The toxicity and solubility of various contaminants, especially heavy metals, are influenced by pH. Since the majority of bacteria can only survive in a small pH range close to neutral (pH 6- 9), it also establishes whether biological treatment is feasible (Ganji *et al.*, 2024). Tanning effluents are often extremely alkaline (pH 9–12) due to the use of lime and other alkaline chemicals in the tanning process.

1.2. Nitrogenous Compounds as Pollutants

There are various kinds of nitrogen in wastewater like organic nitrogen, nitrate, nitrite, and ammonia (Bagherzadeh *et al.*, 2021). Although fertilizer manufacturing plants are the most visible source of nitrogen pollution, wastewaters containing nitrogen are also released by the food processing, pharmaceutical, and some chemical sectors (Mahmood *et al.*, 2019). Because ammonia is hazardous to aquatic organisms at relatively low concentrations and is problematic. Excessive algae growth (eutrophication) reduces the oxygen levels in water (Zhou *et al.*, 2023). Nitrification, the oxidation of ammonia to nitrate, and denitrification, the reduction of nitrate to nitrogen gas, are biological processes required for nitrogen removal (Bai *et al.*, 2023). However, some industrial wastewater may have nitrogen compounds that are difficult to treat, and excessive ammonia concentration may inhibit these biological reactions (Kasiński *et al.*, 2025). Industries that produce detergent, food processing, and fertilizer are the main sources of phosphorus contamination. Like nitrogen, phosphorus makes receiving waters eutrophic, and even trace levels can lead to an overabundance of algae. Wastewater usually contains phosphate compounds, which are phosphorus (Almanassra *et al.*, 2021; Comber *et al.*, 2013).

Sources by Industry Type

Wastewaters from the chemical industry are highly hazardous and complex, containing unreacted chemicals, organic solvents, and reaction byproducts (Manasa & Mehta, 2020). The textile and dyeing industry generate larger volumes of radiant effluent that contain chemicals, suspended particles, and synthetic dyes (Masum *et al.*, 2025). Wastewater from electroplating and metal finishing processes contains hazardous organics and heavy metals like zinc, nickel, copper, and chromium. Even at low quantities, the active pharmaceutical components, solvents, and intermediates found in pharmaceutical effluent remain persistent and biologically active. Advanced therapies, including combining ozone with activated carbon, and advanced oxidation, are required (Arora *et al.*, 2021). Biodegradable organic materials like carbohydrates, proteins, lipids, and oils, remain abundant in wastewater from food processing. Biological processes may usually handle high organic loads, but to avoid overloading, proper system design and efficient pretreatment are necessary (Juwarkar *et al.*, 2010). Tannery effluents are usually alkaline (pH 9–12), extremely contaminated, and contain high levels of chromium, salts, sulfides, and organic waste (Herazo *et al.*, 2021). Undoubtedly, the leather industry is contributing much to the nation's economy; it is amongst the major polluters producing large wastewater volumes with unpleasant odor, high pH, brownish color, and extremely toxic for land (Saxena *et al.*, 2020). Oils, solvents, paints, surfactants, and heavy metals are all present in automotive wastewater, which comes from painting, degreasing, and coating procedures. Biological and physicochemical processes are typically combined in treatment (Yuan *et al.*, 2022).

Microbial Cell in Wastewater Treatment

Microbial cells are present in animals, plants, air, soil, water and extreme conditions and known as the earliest forms of life on Earth, preceding multicellular organisms. Microbial cells are crucial to the treatment of wastewater. They eliminate the hazardous materials, break down the organic contaminants, and transform the trash into less hazardous and more useful goods (Zeng *et al.*, 2022). Wastewater treatment is required before it is disposed of because industrial wastewater frequently contains several complicated pollutants that are harmful to both the environment and human health. Consequently, a critical step before disposing of wastewater is treatment, which transforms it into an effluent that can be recycled or used otherwise. It was determined that the best way to get rid of the extra sludge and energy problems in traditional wastewater treatment systems was to directly convert waste into clean electricity, high-value energy, or chemical goods (Zhang *et al.*, 2018). Bio-electrochemical systems (BESs) are biological systems that transform chemical energy (found in wastewater as organic substrate) into electrical energy or other valuable products (Kumar *et al.*, 2023). BES made of two electrodes: one anode and one cathode. The anode is used for the oxidation of organic matter and release electrons & carbon dioxide that move through the electrolyte towards the cathode for reduction reaction. It enables the production of bioelectricity and the generation of valuable chemicals, like hydrogen gas (H_2) illustrated in the Figure 1.

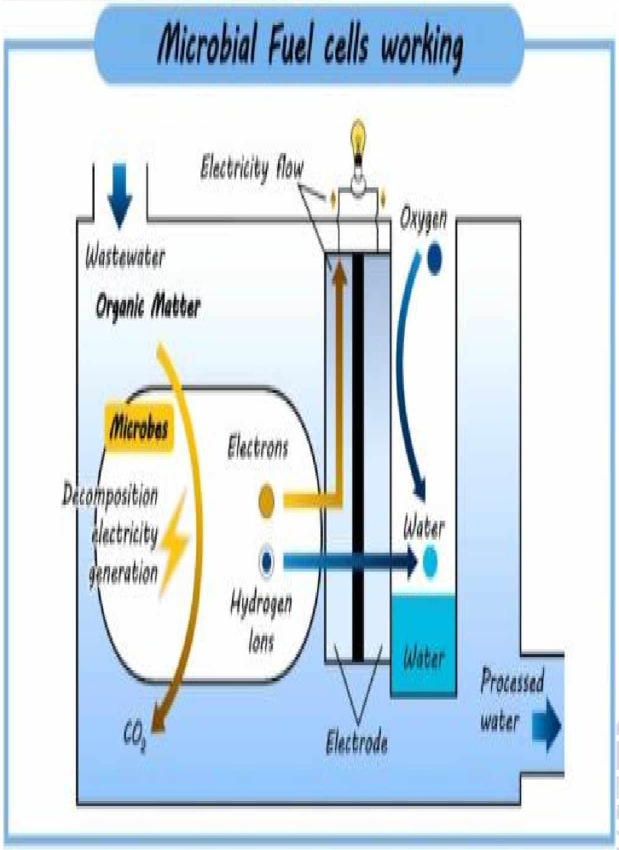

Figure 1. Working of a Typical Microbial fuel cell for electricity generation and wastewater treatment (Nawaz *et al*., 2022).

Over the past few decades, humanity has attempted to maintain equilibrium in every manner conceivable, but we require some more effective and environmentally friendly techniques (Kumar *et al*., 2023). Industrial wastewater can be treated using a variety of techniques, including chemical, biological, and mechanical processes. With extracellular enzymes, cellular metabolism, and community interactions, microbial cells function as active biocatalysts that transform, sequester, or mineralize chemical pollutants in wastewater. In the literature, microorganisms are presented as more ecologically friendly or "green" treatment methods since these processes frequently take place in situ with fewer chemical inputs and lower energy needs (Raper *et al*., 2018). Numerous applications of biotechnological processes shown in Figure 2, which use microorganisms to break down wastewater contaminants, have been made for wastewater treatment (Zhang *et al*., 2018). Practical application spans bacteria, fungi, algae, and engineered consortia across textile, pharmaceutical, petrochemical, and metal-laden effluents. In integrated designs, microbial systems can be connected to energy recovery processes such as biomass valorization or biogas (Udaiyappan *et al*., 2017).

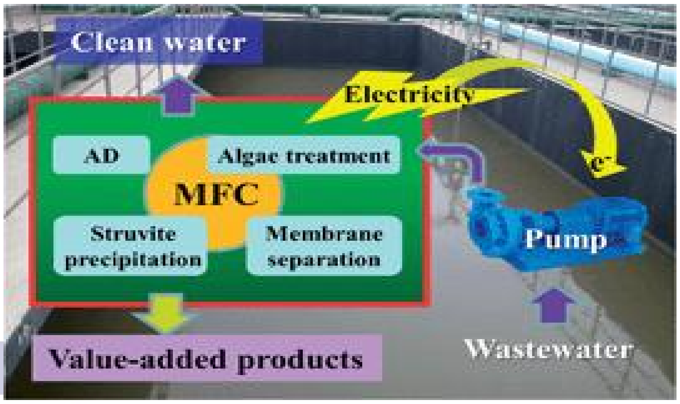

Figure 2. Sustainable wastewater treatment by using microbial fuel cells (Li *et al*., 2014).

Organism type

The organisms involved in water treatment include bacteria, fungi, algae, and other microorganisms as summarized in table 1.

Table 1.Types of Microorganisms used for Bioremediation

Specie Name	Primary Role	Secondary Role	Target Contaminant	References
Pseudomonas aeruginosa	Decomposition of organic	Production of bio-surfactants	Hydrocarbon (crude oil, diesel, petrol), phenols,	(Thanh *et al*., 2017)

	contaminants	(Rhamnolipids)and co-metabolism.	dyes, solvents.	
Bacillus subtilis	Enzymatic degradation.	Formation of biofilms and biosorption.	Dyes, oils, heavy metals (Hg, Zn, Cu).	(Al Disi *et al.*, 2022)
Geobacter sulfurreducens	Degradation by Bio-electrochemical means.	Generation of Electricity (MFC).	Organic matter, heavy metals (Hg, Zn).	(Ramzan *et al.*, 2025)
Acinetobacter calcoaceticus	Degrades Hydrocarbons (lubricating oils, benzene, paraffins).	Produce Bio-surfactants (Emulsan, Alasan).	Oils, petroleum hydrocarbons.	(Tabares *et al.*, 2020)
Shewanella oneidensis	Electron Transfer, Redox Reactions	Reduces Metals (Fe, Mn)	Heavy metals (lead, uranium), organic pollutants.	(Tabares *et al.*, 2020)
Phanerochaete chrysosporium	Produces ligninolytic enzymes (Lignin peroxidase, Manganese peroxidase)	Biosorption	Dyes (Azo Dyes, Triphenyl methane), phenols(Cresols, Pentachlorophenol)	(Tien, 1987)
Aspergillus niger	Biosorption	Enzymatic Degradation	Heavy metals (lead, copper), dyes (Congo red, Malachite green, Crystal violet	(Liu, 2025)
Trametes versicolor	Oxidation mediated by laccase.	Detoxification of intermediates (Aromatic amines, quinone derivatives, Phenoxy radicals, Reactive phenolic metabolites)	Textile dyes, pharmaceuticals	(Bhatnagar & Kim, 2010)
Penicillium chrysogenum	Metal biosorption	Degrades organic pollutants (Phenol, catechol, Remazol Brilliant Blue R, Chlorinat	Pb, Cd, Cu, dyes	(Xu *et al.*, 2015)

		ed aromatic compounds, Organochlorine pesticides, Phenolic herbicides)		
Rhizopus arrhizus	Bioaccumulation	Enzyme secretion (lipase, protease, amylase)	Chromium, dyes, phenols	(Mazzoli *et al.*, 2017)

Treatment Processes and Mechanisms

Different reactor types and biochemical processes are used in biological wastewater treatment to break down contaminants into simpler chemicals, biomass, and, in certain systems, useful electricity. The mechanistic and technological advancements of immobilized-cell reactors, bio-electrochemical systems, and activated-sludge and biofilm reactors are highlighted in reviews and comparative studies (Gupta *et al.*, 2026; Li *et al.*, 2014).

Activated sludge is a biological wastewater treatment process which practices aeration and microbial communities to eliminate organic pollutants and suspended solids from wastewater. It depends upon a suspended growth system where microbes metabolize organic pollutants under aerobic conditions, altering them into CO_2, H_2O, and microbial biomass (flocs) whereas alleviating the sludge for disposal. Biofilm procedure employs microbial groups to reduce pollutants through biotransformation, bioaccumulation, biomineralization, and biosorption. Biofilms consist of extracellular polymeric substances (EPS) used for pollutant sorption. These are the principal methods used in conventional municipal facilities to remove bulk organic matter and nutrients, and they are backed by recognized operating and control procedures. Heavy metals, hydrocarbons, dyes, and high-strength organics common to businesses are handled by specialized reactors, immobilized cells, and customized microbial consortia for industrial effluents (Aiyer & Vijayakumar, 2019). With experimental designs showing viability at limited scales, MFCs applied to food-and-beverage wastewater and small-scale industrial streams in bio-electrochemical systems can achieve significant COD removal while producing power (Asai *et al.*, 2017). Combined wastewater treatment and desalination have been demonstrated in lab-scale three-chamber configurations in microbial desalination cells, including investigations employing algae in cathodes as an oxygen source (Venkatramanan *et al.*, 2021). Bed reactors that are immobilized and packed are used to extend the retention time, reduce sludge generation, and increase the removal efficiency of nutrients and recalcitrant substances.

Tools for Wastewater Treatment Analysis and Optimization

Diagnostic Tools are essential to evaluate microbial populations and to optimize wastewater treatment systems. Advanced sequencing techniques, such as 16S rRNA sequencing, metagenomics, and multi-omics, provide insights into microbial diversity, the abundance of functional genes, and the response of microbes to stress (Zeng *et al.*, 2022). Quantitative PCR (qPCR) allows the quantification of functional genes (amoA and nirK). In addition, biosensors, such as microbial fuel cells (MFCs), can be used for real-time BOD and toxicity measurements. Moreover, they can even produce electricity from wastewater (Mishra *et al.*, 2025). Flow cytometry is used to evaluate microbial viability, while the use of omics information in metabolic models can predict microbial dynamics (Nyika & Dinka, 2022).

Factors Affecting the Efficiency of Microbial Cells as Green Tools in Industrial Chemically Mixed Wastewater Treatment

The efficacy and stability of microbial processes in the treatment of industrial chemically mixed wastewater are influenced by a multitude of factors. It is essential to understand these factors to optimize treatment efficiency and ensure stability in the face of the varied and toxic nature of industrial pollutants(Kumar & Verma, 2025).

Physicochemical Factors Affecting Microbial Performance

The physicochemical composition of chemically mixed industrial wastewater is of great significance for the survival of microorganisms, enzyme kinetics, and the effectiveness of pollutant degradation.

pH, temperature, dissolved oxygen concentration (DO), salinity, and nutrient availability, particularly the carbon, nitrogen, and phosphorus ratio, are of prime importance. Inhibitors such as cyanides, phenols, heavy metals (copper, zinc, chromium, and lead), and organic micro-pollutants (agrochemicals and pharmaceuticals) also play important roles (Khan *et al.*, 2022). These parameters directly affect microbial physiology, enzyme activity, and the efficiency of pollutant degradation, and hence, their control is necessary for effective wastewater treatment. High salinity can lead to osmotic stress in microbes, arising from disequilibrium and cell turgor pressure, while low concentrations of DO favor denitrification and Anaerobic Ammonium Oxidation but inhibit the aerobic degradation of organics.

Optimal microbial growth occurs at mesophilic temperatures of 20-35°C and near-neutral to slightly alkaline pH ranges of 6.5-8.5, which favor enzymatic activity, cell membrane integrity, and efficient metabolic processes. However, extreme conditions can lead to enzyme denaturation, inhibition of metabolism, or the dominance of stress-tolerant but inefficient microbes (Sharma *et al.*, 2023). Moreover, toxic compounds, including heavy metals, can inhibit enzymes and DNA, induce oxidative stress, and decrease the effectiveness of nutrient removal, while nutrient deficiencies can limit the growth of microbes and the co-metabolism of hard-to-treat organics (Sharma *et al.*, 2023).

Microbial Characteristics and Their Role

The structure of microbial communities and their functions are essential for the effective management of challenging industrial wastewater. The combination of different microbes provides functional redundancy, metabolic complementarity, and increased resistance to shock and changes in the environment. This is often associated with enhanced degradation of complex pollutants compared to what any individual pure culture can do (Mishra *et al.*, 2025). Supplementing microbes or microbial populations through bio-augmentation, such as *Pseudomonas* spp. for the degradation of organic compounds or metal-tolerant bacteria, can enhance the efficiency of xenobiotic removal while aiding in the preservation of the resident microbes during stressful periods such as high toxicity or low temperatures (Saeed *et al.*, 2022). In biofilms, microbes are protected by extracellular polymeric substances (EPS), which enhance adhesion, transfer, and protection against toxins. Consequently, biofilm-based systems such as the moving bed biofilm reactor (MBBR) are often superior to suspended growth systems when the process is subjected to industrial stress (Mishra *et al.*, 2025).

Operational Parameters and Treatment System Design

The operational parameters, including Hydraulic Retention Time (HRT) and Solid Retention Time (SRT), are crucial in determining microbial adjustment, biomass stability, and removal capability of pollutants in bioreactors (Dvořák *et al.*, 2016). High HRT and SRT help in the degradation of recalcitrant, non-biodegradable organics and help in maintaining microbes that are not yet adapted. Biofilm reactors, like moving bed biofilm reactor (MBBRs) and integrated fixed film activated sludge (IFAS), have better performance than conventional suspended growth systems because of their superior solid-liquid separation, shock resistance, and mass transfer properties (Lin *et al.*, 2012). In addition, the combination of biological treatment with physicochemical processes, such as advanced oxidation processes (AOPs) or electrochemical processes, can make non-biodegradable pollutants more biodegradable compounds, thereby increasing the effectiveness of treatment (Saeed *et al.*, 2022).

Limitations of Microbial Cells as Sustainable Tools for Treating Chemically Mixed Industrial Wastewater

The microbial cells that have been cited as effective green technologies in the bioremediation of chemically mixed industrial waters include bacteria, fungi, yeasts, algae, and mixed microbial consortia. The benefits associated with microbial cells are low cost, environmental friendliness, and the ability to eliminate or detoxify contaminants by use of biodegradation, biosorption, bio-accumulation, and co-metabolic reaction (Singh *et al.*, 2022). Nevertheless, microbial cells cannot be used in complex industrial effluents containing recalcitrant organic materials (including PAHs, dyes, and pharmaceuticals), heavy metal ions (including Cu, Zn, Cr, and Pb), phenols, cyanides, and high salinity due to various reasons. These are caused by the inability to attain the total elimination of contaminants, long treatment durations, and the inability to implement laboratory processes at full industrialization (Silva *et al.*, 2021).

Low Bioavailability and Recalcitrant Pollutant Degradation

High molecular weight aromatics, dyes, pharmaceuticals, hydrocarbons, and some other common persistent industrial pollutants are usually poorly soluble, chemically stable, and unavailable to microorganisms (Kumar & Verma, 2025). This contributes to either partial or slow biodegradation, the formation of toxic intermediates, and delayed degradation. The incompatibility of the microbial enzymatic activity with the pollutant structure frequently leads to the appearance of the inhibitory byproducts or a deceleration of the degradation process (da Silva, 2022).

Instability in Microbial Consortia

Although microbial consortia are susceptible to instability due to interspecies competition and preferential substrate utilization, they remain beneficial due to their capacity to thrive under stress conditions. However, poor colonization efficiency and washout of inoculated strains remain major challenges .The bio-augmentation may not be effective in large-scale practices due to the inability of the microorganisms introduced to acclimate, compete with the indigenous populations, or survive longer (Saleem *et al.*, 2021).

Sensitivity to Environmental and Physicochemical Fluctuations

Several factors, such as pH, temperature, dissolved oxygen, salinity, osmotic pressure, and nutrient ratio (C: N: P), common in chemically mixed industrial effluents, are very sensitive to microbial systems. Such variations can inhibit important microbial degraders, alter the microbial composition, and reduce the overall effectiveness of treatment z(Sharma *et al.*, 2023). Bioremediation is more economical than physicochemical processes, as it requires less energy, no costly chemicals, and simple operational systems (Wu *et al.*, 2021).

Mass Transfer and Biofilm Constraints

Mass transfer constraints of nutrients, oxygen, and substrates are likely to happen in biofilms. The other problems are the stagnation of the reactors and entrapment of toxic products that may be detrimental to the survival and treatment of the microbes in the high-strength mixed industrial wastewater in the long-term (Haripriyan *et al.*, 2022).

Advantages of Microbial Cells as Green Tools in Industrial Chemically Mixed Wastewater Treatment

Among the most efficient, eco-friendly, and sustainable green technologies for treating chemically mixed industrial wastewater are microbial cells such as bacteria, fungi, yeasts, algae, and mixed microbial populations. Industrial effluents are reported to have a complicated blend of recalcitrant matters such as hydrocarbons, dyes, phenols, pharmaceuticals, pesticides, heavy metals such as Cu, Zn, Cr, Pb, Cd, salts, and other toxic compounds (Al Disi *et al.*, 2022; Qattan, 2025). Compared to traditional physicochemical wastewater treatment, e.g., coagulation, membrane filtration, or advanced oxidation processes, microbial bioremediation makes use of natural metabolic processes to degrade, detoxify, bio-sorb, bio-accumulate and bio-transform pollutants (Kumar & Verma, 2025).

Environmentally Friendly and Sustainable:

The microbial treatment process automatically breaks down pollutants into non-hazardous by-products such as CO2, water, and microbial mass. The process does not generate secondary toxic by-products or chemical sludge. The process adheres to green chemistry, which reduces environmental effects and helps in restoring the ecosystem by not generating toxic by-products associated with chemical treatment processes (Li *et al.*, 2014).

Effective for Complex and Mixed Pollutants:

The microbial consortia have synergistic degradation capabilities, where different microbial strains work in a complementary manner to utilize the enzymatic pathways for the complete mineralization of recalcitrant compounds, such as organic compounds and heavy metals. The microbial consortia are more efficient than pure cultures in dealing with a combination of wastewater, with removal efficacy of 80-95% by biosorption, enzymatic oxidation, and co-metabolic processes (Bala *et al.*, 2022).

Adaptability and Versatility

Bacterial cells can be made to resist difficult environmental conditions like pH, temperature, salinity, or toxic shock by acclimation, biofilm formation, or the production of extracellular polymeric substances (EPS). Biofilm-based reactors, like MBBRs, also offer defense against shock loads, while bio-augmentation with specific strains enables the separation of particular pollutants like pharmaceuticals or heavy metals (Arora *et al.*, 2024).

Resource Recovery and Energy Production

Some microbial engineering, such as microbial fuel cells (MFCs) and microbial electrolysis cells (MECs), enables the treatment of wastewater and the production of electricity, hydrogen gas, or bio-methane by anaerobic digestion. This is in line with the regenerative economy concept and decreases the energy demand in comparison to traditional methods (Pikaar *et al.*, 2022).

Minimal Secondary Pollution and On-Site Feasibility

Microbial technologies can be applied in-situ or ex-situ with less disturbance. This eliminates the need for excavation and transportation of waste (Saxena *et al.*, 2020). The technology prevents the transfer of pollutants to other media in the environment, hence facilitating site restoration. The technology can be applied in dispersed or distant industrial sites, as it favors site restoration and prevents the transfer of pollutants to other media in the environment (Mazzoli *et al.*, 2017). The successful treatment of industrial effluents containing harmful chemicals requires the application of precise control of physicochemical factors, resilient microbial communities, and appropriate operational methods. Flexible microbial consortia and biofilms improve the stability of the system and pollutant degradation, even in extreme industrial conditions. Although microbial cells provide a sustainable and eco-friendly approach to traditional technologies, their use can be hampered by toxicity, recalcitrant compounds, environmental variability, and scalability (Mantis *et al.*, 2005). Tackling these hurdles demands the use of holistic strategies, such as hybrid pre-treatment technologies, adapted microbial consortia, bio-augmentation, and sophisticated monitoring technologies. By adopting these approaches, high treatment efficiency, system reliability, and resource recovery can be ensured, thus making microbial technologies applicable for industrial-scale wastewater treatment (Martins *et al.*, 2013).

Prospects of Microbial Wastewater Treatment Technologies

Microbial technologies like bio-electrochemical systems (BES), engineered consortia, and nano-enhanced bioremediation are moving the treatment of complex industrial wastewaters from burden to beneficial use and production. Tapping their full potential will require targeted investment in reactor development, innovative materials, integrated hybrid systems, and complementary pilot-scale techno-economic validation (ADEYEMI *et al.*, 2026).

Emerging Microbial Technologies

The wastewater treatment industry is transitioning from the conventional activated sludge technology into emerging biofilm and granular-based biotechnologies for contaminant degradation as well as resource recovery. New-generation applications combine contaminant degradation with value creation, by energy generation or by-product formation, both improving sustainability and reducing the amount of waste (Saxena *et al.*, 2020).

Bio-electrochemical systems (BESs) are appealing because they use electrogenic microorganisms to degrade organic pollutants, with power density in the tens of watts per cubic meter range and >85% removal efficiency under industrial effluent conditions (Selvasembian *et al.*, 2022). Bacterial-microalgal consortia, through the combination of their metabolic capabilities, microalgae and bacteria can consume and break down dyes and difficult-to-degrade organic material while recovering nutrients and creating biomass for biofuels or bio-fertilizers to support a circular economy (Srivastava, 2019). While Nano-microbial hybrid systems that incorporate Nano-adsorbed and Nano-catalytic properties deliver enhanced microbial metabolism for the removal of heavy metals or pharmaceutical compounds by improving electron transfer rates and the interactions between surfaces (Mandeep & Shukla, 2020). And Enzymatic, fungal, and immobilized-cell technologies Various anaerobic/aerobic sequencing technologies, such as enzymatic, fungal, and immobilized-cell technologies, including fluidized-bed bioreactors [FBB](Nelson *et al.*, 2017) and membrane bioreactors [MBR] (Lin *et al.*, 2012), offer practical and efficient methods of degrading hydrophobic and hard-to-degrade organic contaminants when paired with a carefully optimized anaerobic/aerobic sequence for the treatment of mixed industrial wastewater (Dvořák *et al.*, 2016).

Technology Integration and Hybrid Platforms

The combination of microbial treatment processes with nanotechnologies, genetic engineering, and synthetic biology will result in the development of multifunctional treatment systems with accelerated degradation kinetics and selective and effective resource recovery. Nano-enhanced electrodes are made up of composites such as titanium dioxide and carbon nanotubes; graphene-based anodes can increase the rate of electron transfer, oxidize pollutants more effectively, and produce larger amounts of electricity through bio-electrochemical systems (Strik *et al.*, 2011). Genetic and synthetic biology tools can be used to create optimized biodegradation pathways, improve xenobiotic metabolic tolerance, and develop rationally designed synthetic consortia that provide compatible metabolism. Omics-guided strain selection and pathway engineering will assist in developing the best strain for the application (Mishra *et al.*, 2025). Furthermore, hybrid biological-physical-chemical systems that integrate bio-electrochemical components with membrane separation and adsorption devices are more effective in treatment capabilities over the range of possible variable loadings (Thalla & Devika, 2024). There are many technical and economic barriers that will have to be overcome to transition from laboratory demonstration to implementation in an industrial setting, but solutions to engineering these issues are becoming available. Efforts directed at cost-effective material development, scalable reactor configurations, and operation stability are of primary importance (Udaiyappan *et al.*, 2017).

The major challenges include the high cost of capital expenditures for specialized equipment, membrane fouling, limited trust in long-term operational reliability, and sensitive performance to variations in the composition of wastewater (Udaiyappan *et al.*, 2017). Stacked configurations of modular reactors or multiple anodes, with a shared cathode configuration, provide the ability to incrementally add capacity with simplified construction and maintenance. Integrated processes using bio- electrochemical modules and existing reactor technologies (MBRs, FBBs, Bio-filters) (Nelson *et al.*, 2017) utilize established operational frameworks to provide additional treatment capabilities and load level fluctuations (Patel, 2025). The Operational optimization systems, including immobilized biofilm systems, stress-tolerant engineered consortia, and adaptive process control, have increased the effectiveness of start-up times and stability throughout sustained industrial operations. Pilot- scale testing at real industrial effluent facilities demonstrated technical feasibility with organic removal rates of 85%+ and power output of tens of watts per meter^3 (Venkatramanan *et al.*, 2021).

Economic, Environmental, and Policy Considerations

The economic feasibility of commercially sustainable bioprocessing depends upon balancing both capital (start-up) and operational costs against the return on investment (revenue), and environmental benefits and regulatory policies influencing commercial adoption (Bhattacharya & Sachdev, 2026). Current literature reflects that while the sustainable advantages of bioprocesses appear promising, they are also plagued by major regulatory and economic uncertainties that require resolution.

Current economic viability is limited by high fixed (capital) costs associated with purpose-built reactors and electrode materials, but can be improved with revenue generation through electricity generation, nutrient recovery, and biomass valorization, pending further rigorous techno-economic feasibility studies (Wu *et al*., 2021). As bioprocesses are predicted to produce less (smaller amount) sludge, require fewer chemical inputs (more chemically efficient), and to recover energy while simultaneously removing many pollutants, resulting in measured greater overall sustainability than those associated with traditional physio-chemical processes (Jabin *et al*., 2026). Regulators have been concerned about the safety and risks associated with genetically engineered organisms or modified organisms (GMOs) systems; therefore, regulators require containment methods to restrict the possible spread of GMOs in the environment or implement "kill switches" to allow for the complete removal of engineered organisms from the environment (ADEYEMI *et al*., 2026). Containment Methods also address regulatory approval of GMOs and engineered systems. With limited guidance available on biosafety protocols, effluent quality standards for hybrid engineered systems, and regulatory pathways for engineered systems, it is anticipated that an effective policy framework to govern the commercial release of engineered systems will be in place as the technology advances (Noordover *et al*., 2002). There still exists a substantial time lag between technological advancement and the development of an effective policy framework to support the release of new technologies.

Critical Research Priorities and Future Directions

To advance these technologies toward the broad-scale application within industry, research agendas must be identified in order to address the technical, economic, and regulatory knowledge gaps in the area of biosafety. It is expected that there will be multiple disciplines working together to obtain a complete understanding of best practices to meet the safety standards (Kumar & Verma, 2025).

It will be important to conduct extended pilot demonstrations of variable industrial wastewater for a minimum of 12 months to determine maintenance requirements, fouling characteristics, life cycles of components, and costs of the systems under actual operating conditions (Zhang *et al*., 2018). Material innovations that focus on the design and production of electrode and membrane systems from waste-derived carbon products and Nano-enabled composites will lower the initial capital cost of developing or retrofitting engineered systems; therefore, increasing the economic viability of these products in the marketplace (Saranya *et al*., 2025). The Industrial applications of comprehensive techno-economic and lifecycle analyses, considering treatment performance, potential revenues from resource recovery, and potential environmental impacts, will provide insight into realistic commercial viability as well as inform investment decisions (Zheng *et al*., 2015). The development of robust, high-performance synthetic consortia through omics-guided microbiome engineering should create consortia that are more tolerant to biotic stresses and carry lower ecological risks, with consideration given to genetic containment strategies when regulatory concerns exist (Patel *et al*., 2025). Standardization and regulatory research establishing protocols for biosafety assessments, establishing quality guidelines for effluent from hybrid systems, and creating clear pathways for the permitted use of engineered organisms remains a critical gap requiring immediate attention (Corominas *et al*., 2010).

Conclusion

Microbial cells provide a green, sustainable, and efficient means of treating industrial effluents containing various chemicals. They reduce toxic contaminants by utilizing natural biological processes and require less energy, which also helps in preventing further pollution. Although there are constraints, modern microbial technologies and hybrid approaches provide a favorable means of sustainably treating wastewater.

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