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Electrocoagulation and ionic-liquid membrane-based microbial fuel cells for wastewater treatment: A critical comparative review

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ABSTRACT

Electrochemical and bioelectrochemical technologies are increasingly explored to address the coupled challenges of wastewater treatment and energy sustainability. Among them, electrocoagulation (EC) and microbial fuel cells (MFCs) represent fundamentally different yet potentially complementary approaches. EC removes pollutants through the in situ generation of coagulants from sacrificial metal electrodes, enabling rapid treatment of suspended solids, emulsified oils, dyes, and many dissolved metals. In contrast, MFCs use electroactive microorganisms to oxidize biodegradable organics at the anode and transfer electrons to a cathode, allowing simultaneous wastewater treatment and direct electricity recovery. Although both technologies have been widely studied independently, integrated comparisons addressing treatment performance, energy balance, material constraints, and scale-up remain limited, especially for MFC systems using ionic-liquid (IL)-based membranes. This critical comparative review evaluates EC and IL-membrane-based MFCs in terms of pollutant removal efficiency, operational flexibility, energy consumption versus recovery, by-product generation, long-term stability, and techno-economic feasibility. Particular attention is given to supported ionic liquid membranes and polymer/ionic-liquid composite separators as promising materials for reducing internal resistance, while also considering membrane fouling, oxygen crossover, and IL leaching. Overall, EC is highly effective for rapid depollution but remains energy- and material-intensive, whereas MFC deployment depends on stable, low-resistance, and environmentally safe IL-based membranes. Hybrid EC–MFC systems appear especially promising for robust, scalable, and resource-efficient wastewater treatment.

Keywords: electrocoagulation, microbial fuel cells, ionic liquid membranes, polymer inclusion membrane, wastewater treatment, energy recovery, membrane fouling.

INTRODUCTION

Wastewater treatment is increasingly shaped by three converging pressures: tightening discharge requirements, intensifying water scarcity, and rising energy costs. Climate-driven drought dynamics and the growing frequency of prolonged water-scarcity events are projected to amplify stress on freshwater systems, reinforcing the need for resilient treatment and reuse pathways (Ravinandrasana et al., 2025). In parallel, treated wastewater reuse is being positioned not only as a supply-augmentation strategy but also as a climate-adaptation measure; however, contaminants of emerging concern and risk-management challenges remain critical barriers to sustainable large-scale implementation (Khan et al., 2024). Energy constraints further complicate this landscape: wastewater treatment represents a significant electricity consumer within the urban water cycle, and recent assessments highlight both the opportunity and necessity for improved energy efficiency as treatment standards become more stringent (Cardoso et al., 2021). Spatially explicit global analyses confirm that water and wastewater treatment technologies account for a non-negligible share of total electricity demand, underscoring the urgency of developing processes that either reduce energy consumption or enable resource and energy recovery (Magni et al., 2025).

Within this context, electrochemical and bioelectrochemical technologies are attracting renewed attention due to their modularity, operational flexibility, and potential suitability for complex industrial matrices. Electrocoagulation (EC) is an electrochemical process in which sacrificial metal electrodes (commonly Fe or Al) generate coagulant species in situ; pollutant removal occurs through coagulation–flocculation, adsorption, and coprecipitation, making EC particularly effective for wastewaters containing suspended solids, emulsified oils, dyes, and metal contaminants. Recent reviews confirm the broad applicability of EC while emphasizing that performance is highly sensitive to pH, current density, electrode material, and conductivity—parameters that simultaneously influence sludge generation and energy consumption (Jo et al., 2024; Patel et al., 2025).

In contrast, microbial fuel cells (MFCs) are bioelectrochemical systems in which electroactive microorganisms oxidize biodegradable organics at the anode and transfer electrons to a cathode through an external circuit, enabling simultaneous wastewater treatment and direct electricity recovery. Despite sustained research activity, recent analyses consistently report that practical scale-up remains limited by low power densities, internal resistance, cathode durability, and sensitivity to wastewater composition and operational variability (Jafary et al., 2026).

A comparative review of EC and MFCs is therefore timely for three reasons. First, the two approaches often target overlapping treatment goals (e.g., COD reduction and removal of specific contaminants), yet they rely on fundamentally different mechanisms: electrochemically induced coagulation chemistry for EC versus microbially catalyzed electron harvesting for MFCs, which leads to distinct by-product profiles (notably sludge in EC) and different sensitivities to wastewater matrix effects (Jo et al., 2024). Second, their energy balances diverge: EC is an electricity-consuming treatment process, while MFCs aim to recover a fraction of the chemical energy of wastewater as electrical power, though typically limited by electron losses to competing pathways and electrochemical inefficiencies (Patel et al., 2025). Third—and central to the originality of this review—MFC performance and feasibility are tightly linked to the separator/membrane, and ionic-liquid (IL)–based separators are emerging as a potentially lower-cost, tunable alternative to conventional membranes.

Accordingly, this review analyzes municipal and industrial wastewaters (e.g., agro-food, oily/refinery, and other high-strength effluents) and compares EC and IL-enabled MFCs using harmonized performance indicators. These include conventional treatment metrics (COD, turbidity/color, nutrients and metals where relevant), process metrics (specific energy consumption and sludge production for EC), and bioelectrochemical metrics (cell voltage, power density, coulombic efficiency, and stability for MFCs), alongside durability aspects such as electrode passivation (EC) and cathode/membrane fouling (MFC) (Jo et al., 2024; Patel et al., 2025).

A central objective is to evaluate whether advances in IL-based membranes—such as supported ionic liquid membranes and polymer inclusion membranes—can meaningfully reduce internal resistance and enhance operational stability to a degree that shifts the comparative sustainability balance between EC and MFC systems. Foundational work demonstrated that polymer inclusion membranes incorporating ionic liquids can operate as proton-exchange membranes under wastewater-treatment conditions (Hernández-Fernández et al., 2016). However, subsequent analyses indicate that long-term scalability critically depends on controlling oxygen crossover, fouling, resistance drift, and particularly IL leaching during extended operation (Rynkowska et al., 2018; Jafary et al., 2026).

By integrating performance, energy, material durability, and techno-economic dimensions within a unified analytical framework, this review seeks to clarify the conditions under which EC, IL-based MFCs, or hybrid configurations represent the most rational pathway toward scalable and resource-efficient wastewater treatment. We hypothesize that membrane stability and energy balance are the decisive parameters determining the practical competitiveness of IL-enabled MFCs relative to established electrochemical approaches.

FUNDAMENTALS AND TREATMENT MECHANISMS

Electrocoagulation (EC)

Principles: sacrificial electrodes (Fe/Al) and hydroxide formation

EC is an electrochemical treatment process in which the coagulant is generated in situ by the anodic dissolution of sacrificial metal electrodes, most commonly iron (Fe) or aluminum (Al). Under direct current, the anode releases metal ions (Fe^{2+}/Fe^{3+} or Al^{3+}) that undergo hydrolysis in water, forming a spectrum of hydroxo-complexes and, ultimately, metal hydroxide precipitates such as $Fe(OH)_2$/$Fe(OH)_3$ and $Al(OH)_3$. These freshly formed hydroxides act as reactive coagulant phases with high affinity for colloids and dissolved pollutants (Mollah et al., 2001; Mollah et al., 2004). In parallel, cathodic reactions reduce water and generate OH^- locally, shifting the micro-environment toward conditions that favor hydroxide precipitation and floc maturation (Chen, 2004).

A key advantage of EC over conventional chemical coagulation is that coagulant production and speciation are controlled by electrochemical conditions and by the wastewater matrix itself. As emphasized in major reviews, the identity, polymerization degree, and reactivity of the electro-generated species depend strongly on pH, ionic strength, and the presence of complexing anions; therefore, EC should be understood as a coupled electrochemical–hydrolysis–precipitation system rather than a simple "metal dosing" method (Chen, 2004; Jo et al., 2024). This dynamic generation of reactive hydroxide phases is central to EC's broad applicability across industrial effluents.

From a process-engineering perspective, the anodic dissolution step directly links pollutant removal to electrode consumption according to Faraday's law, establishing a material–energy coupling that distinguishes EC from biological systems. Consequently, removal efficiency, sludge production, and electricity demand are intrinsically interconnected through current density and treatment time. Moreover, electrode material selection (Fe vs Al) not only determines hydroxide speciation but also influences sludge characteristics, redox activity, and susceptibility to passivation, factors that become critical in long-term and large-scale applications.

Mechanisms: coagulation-flocculation, adsorption, coprecipitation, flotation

Pollutant removal in EC results from several mechanisms that typically occur simultaneously, explaining its effectiveness for diverse contaminant classes. The first core pathway is coagulation–flocculation, where electro-generated hydroxides destabilize colloids by charge neutralization and sweep-flocculation, leading to rapid aggregation into separable flocs (Mollah et al., 2001; Jo et al., 2024). A second major mechanism is adsorption onto the newly formed hydroxide surfaces. Because these flocs are often amorphous and rich in active sites, they can bind suspended particles, natural organic matter, dyes, and various inorganic species through surface complexation and electrostatic interactions (Ullah et al., 2025). A third pathway is coprecipitation, where dissolved pollutants become incorporated into the growing hydroxide matrix or precipitate concurrently with it, enhancing removal for metals and some anionic contaminants under favorable pH conditions (Mollah et al., 2004; Chen, 2004).

Finally, EC often includes an electroflotation contribution: hydrogen microbubbles produced at the cathode attach to flocs and promote their buoyant separation. This mechanism is particularly relevant for waters containing emulsified oils or low-density flocs and is widely recognized as a key contributor to solid–liquid separation in EC/ECF configurations (Barakat et al., 2025). Importantly, these mechanisms should not be presented as strictly sequential "steps"; rather, they form a coupled network whose dominant pathway depends on wastewater composition and operating regime (Ullah et al., 2025; Jo et al., 2024).

Collectively, these concurrent mechanisms explain the versatility of EC across contaminant classes but also underpin its intrinsic material intensity. Because pollutant capture occurs predominantly through phase transfer into hydroxide flocs, sludge generation is not a side effect but a mechanistic consequence of the treatment principle. This distinguishes EC from oxidative or biologically mineralizing systems and has direct implications for downstream handling, cost, and environmental footprint.

Key operating parameters (pH, current density, conductivity, time)

EC performance is governed by a small set of tightly coupled operating parameters. pH is arguably the most influential because it controls metal speciation, hydroxide solubility, floc surface charge, and the balance between soluble hydroxo-complexes and precipitated phases. Reviews consistently report an optimal pH window for many applications, while extreme acidic or alkaline conditions can reduce efficiency by shifting speciation and limiting stable floc formation (Mollah et al., 2004; Jo et al., 2024). In real industrial waters, EC can also induce gradual pH drift due to cathodic OH^- generation and secondary electrode reactions, which changes precipitation pathways over time and may affect effluent stability (Al-Ajmi et al., 2024).

Current density controls the rate of coagulant generation (anodic dissolution), bubble production (electroflotation), and overall electrical demand. Increasing current density generally accelerates pollutant removal but may raise energy consumption, intensify electrode consumption, and in some cases exacerbate operational issues such as passivation or excessive sludge production; hence, optimization is essential to balance kinetics and cost (Mollah et al., 2001; Jo et al., 2024). Conductivity (often adjusted with supporting electrolytes in low-conductivity waters) affects ohmic losses, current distribution, and process energy efficiency; insufficient conductivity can limit the effective current and increase voltage requirements, whereas higher conductivity typically improves electrical efficiency but may alter removal selectivity depending on ion composition (Chen, 2004; Jo et al., 2024).

Finally, treatment time (or hydraulic residence time in continuous systems) integrates the above variables: at a given current density, it determines the total coagulant dose generated, the degree of floc maturation, and the separation outcome. However, longer times do not always translate into proportional gains because secondary reactions and changing water chemistry may reduce marginal benefits; therefore, time must be optimized together with pH, conductivity, and current density (Al-Ajmi et al., 2024; Ullah et al., 2025). Overall, modern syntheses converge on the view that EC should be managed as a multiparameter system, with performance and cost emerging from the coupled control of pH–current density–conductivity–time, tailored to the specific wastewater matrix and treatment objective (Jo et al., 2024; Ullah et al., 2025).

Importantly, because EC performance scales directly with applied current, the process behaves like a controllable electrochemical dosing system in which removal kinetics are accelerated by increasing electrical input. While this provides operational flexibility and rapid treatment capability, it also ties performance linearly to electricity demand and electrode consumption. This current-driven architecture fundamentally contrasts with bioelectrochemical systems, where electron flux is constrained by microbial metabolism and internal resistance rather than externally imposed current density.

Microbial fuel cells (MFCs)

Principles: anodic bio-oxidation and cathodic reduction (O_2 and alternative electron acceptors)

MFCs are bioelectrochemical reactors that convert the chemical energy stored in biodegradable substrates directly into electricity through the catalytic activity of electroactive microorganisms. The core concept relies on a spatial separation of redox reactions: anodic bio-oxidation occurs under anaerobic (or anoxic) conditions, while cathodic reduction proceeds at a physically separated cathode (Logan et al., 2006; Franks and Nevin, 2010). At the anode, electroactive bacteria oxidize organic matter (e.g., acetate, volatile fatty acids, and soluble organics in wastewater), releasing electrons and protons while forming CO_2 and biomass. A fraction of the released electrons is transferred to the anode either by direct contact (outer-membrane cytochromes and conductive pili), by redox mediators, or via hybrid pathways depending on the microbial community and electrode properties (Franks and Nevin, 2010).

At the cathode, electrons arriving through the external circuit are consumed by a reduction reaction. In air-cathode MFCs, the most common terminal electron acceptor is oxygen, reduced to water (or hydroxide), making oxygen reduction kinetics and cathode catalytic activity critical determinants of performance (Gude, 2016). However, MFCs can operate with alternative electron acceptors (e.g., nitrate, ferricyanide, metal oxides, or other oxidants) depending on the design goals (enhanced kinetics, nutrient removal, or specific remediation functions). The use of biological cathodes is also an important development pathway: bio-cathodes can facilitate electron acceptor reduction and enable functions such as nutrient transformations, but they introduce additional biological constraints and can change the overall rate-limiting steps (Song et al., 2019). Overall, the "treatment + energy recovery" promise of MFCs arises from coupling microbial oxidation of wastewater organics to cathodic reduction in a controlled electrochemical architecture (Logan et al., 2006; Gude, 2016).

Transfers: electrons (external circuit) and ions (membrane/separator)

The operation of an MFC depends on two coupled transport pathways: electron transfer through the external circuit and ion transfer within the electrolyte (and across the membrane/separator if present). Electrons harvested from anodic oxidation are conducted through the anode material, pass through an external load (where electrical power is delivered), and reach the cathode to sustain the reduction reaction (Logan et al., 2006). In parallel, electroneutrality must be maintained: positively charged species (often H^+ but more commonly other cations in real wastewaters such as Na^+, K^+, and NH_4^+) and/or anions migrate to balance charge. These ionic fluxes strongly influence pH gradients and internal resistance, and thus have direct consequences for power output and stability (Logan et al., 2006; Roy et al., 2023).

In systems using a membrane/separator, the separator is not simply a physical barrier—it is a functional element that controls ionic conductivity and crossover phenomena, especially oxygen back-diffusion from the cathode to the anode. Oxygen crossover is detrimental because it creates competing electron sinks at the anode and lowers coulombic efficiency by enabling aerobic oxidation that does not contribute to current generation (Roy et al., 2023). Therefore, an effective separator should provide low ionic resistance while limiting oxygen and substrate crossover. This has motivated continued research into next-generation proton-exchange or ion-selective membranes designed to reduce internal losses and sustain stable biofilm activity; recent membrane-focused analyses emphasize that preventing oxygen crossover and maintaining electrochemical neutrality are central functions of PEMs in MFCs (Sharma et al., 2024). At the same time, the selection of membrane/separator interacts with reactor hydrodynamics and the cathode architecture (e.g., air-cathodes), meaning that optimizing transport often requires system-level design rather than "membrane-only" tuning (Roy et al., 2023; Gude, 2016).

Key parameters (*substrate, inoculum, external resistance, pH, temperature*)

MFC performance is governed by a set of interdependent biological and electrochemical parameters. The substrate determines both the maximum available energy and the achievable electron recovery. Simple substrates such as acetate typically yield more predictable performance, while real wastewaters contain complex organics that may be partially fermented, diverted to biomass synthesis, or consumed through competing pathways (e.g., methanogenesis), lowering coulombic efficiency even when COD removal is high (Gude, 2016). Substrate concentration and loading rate can enhance current up to a point, but excessive loading may lead to mass-transfer limitations, acidification, or unstable community dynamics (Gude, 2016).

The inoculum and microbial community structure are equally decisive. Start-up strategies, enrichment conditions, and prior exposure to electrochemical environments determine whether a robust electroactive biofilm develops and whether electron transfer proceeds primarily via direct mechanisms or mediated pathways (Franks and Nevin, 2010; Logan et al., 2006). In practice, the "best" community is highly context-dependent and sensitive to inhibitory compounds and salinity typical of industrial wastewaters (Gude, 2016).

From the electrochemical side, external resistance is a first-order control on current, voltage, and electron allocation. Operating at a non-optimal external load can suppress power output and alter the balance between electricity generation and competing metabolic sinks. Notably, real-time optimization of external resistance has been shown to improve power performance and coulombic efficiency while reducing methane production, highlighting that electrical loading is not merely a measurement choice but an operational lever shaping bioelectrochemical function (Pinto et al., 2011).

Finally, pH and temperature regulate both microbial metabolism and electrochemical kinetics. pH gradients between anode and cathode (often driven by ionic transport limitations) can inhibit biofilm activity, increase cathode losses, and reduce overall stability; consequently, membrane/separator selection and buffering capacity are critical in wastewater applications (Roy et al., 2023; Sharma et al., 2024). Temperature influences reaction rates, community composition, and internal resistances; many MFCs perform best under mesophilic conditions, while departures from this range can slow kinetics and destabilize the system (Logan et al., 2006; Gude, 2016). In synthesis, MFCs must be viewed as integrated bioelectrochemical systems in which substrate composition, microbial ecology, and transport through the separator, and external circuit conditions jointly determine treatment efficiency and energy recovery.

Comparison of depollution pathways: EC vs. MFCs

Target pollutants (TSS, COD, dyes, nutrients, metals, micropollutants)

Although EC and MFCs are sometimes positioned under the broad umbrella of "electro-driven" wastewater treatment, they are typically selected for different pollutant families and different performance priorities. EC has a long-standing reputation for its ability to rapidly remove suspended solids (TSS/MES) and turbidity by destabilizing colloids and forming sweep flocs, which makes it especially relevant for industrial effluents rich in particulate matter, emulsified phases, or color bodies (Jo et al., 2024; Patel et al, 2025). In the same operational window, EC often achieves substantial reductions in COD—particularly when COD is linked to colloidal/particulate organics, emulsified oils, and high-molecular-weight fractions that are readily captured by hydroxide flocs (Jo et al., 2024; Patel et al, 2025). For dyes and colored effluents, EC is widely reported as effective, largely because dye molecules can adsorb onto freshly formed hydroxides and become entrapped within growing flocs, while electroflotation enhances separation (Jo et al., 2024). EC is also frequently emphasized for metal removal, as metals can be removed by hydroxide precipitation and coprecipitation or by adsorption/complexation onto the floc matrix (Patel et al., 2025). Regarding nutrients, EC can be particularly strong for phosphate because Al/Fe species readily bind phosphate and form low-solubility precipitates; recent studies and reviews highlight near-complete phosphate removal in optimized systems (Ma et al., 2025; Reza et al., 2024).

MFCs, by contrast, are inherently suited for streams where the dominant target is biodegradable organic matter, because anode-respiring microorganisms convert part of the substrate's chemical energy into electrical current while reducing COD (Logan et al., 2006; Gude, 2016). Their treatment "footprint" extends beyond COD: depending on design and electron acceptors, MFCs can support removal/transformation of nitrogen species (e.g., nitrate reduction at the cathode or in bio-cathode systems) and contribute to phosphorus removal when integrated with adsorption media or coupled wetland configurations (Jacobs et al., 2024; Tao et al., 2025). For metals, MFCs can be used in specialized modes where cathodic reactions drive metal reduction (e.g., Cr(VI) to Cr(III) or metal deposition) or where bioelectrochemical conditions promote immobilization routes; recent reviews frame this as a promising niche at the interface of remediation and energy recovery (Akagunduz, 2025).

The most delicate category is micropollutants (pharmaceuticals, pesticides, PFAS, etc.). EC can remove some micropollutants by sorption onto hydroxide flocs or by co-removal with natural organic matter, but performance is compound-specific and often limited for highly persistent molecules; the PFAS literature, for instance, shows that conventional coagulation/flocculation is usually weak for many PFAS, prompting modified/coagulant-aided strategies (Maroli et al., 2024). Nonetheless, electro-driven coagulation variants and integrated approaches continue to be explored for difficult micropollutants, including PFAS-related treatment trains where electrochemical steps play a targeted role (Hassan et al., 2025). In MFCs, micropollutant attenuation is typically discussed as a combined outcome of biodegradation/biotransformation, sorption onto biofilm/electrodes, and redox transformations, but the removal of persistent compounds remains highly variable and often slower than bulk COD removal (Boas et al., 2022; Hossain, 2025). In short, EC is most naturally aligned with rapid physicochemical removal of particulates, metals, oils, and phosphate, whereas MFCs are primarily aligned with biodegradable COD removal with potential energy recovery, with conditional extensions to nutrients, metals, and selected organics depending on configuration (Jo et al., 2024; Patel et al., 2025; Logan et al., 2006).

Kinetics and contaminant transformation trajectories

A meaningful comparison between EC and MFCs requires moving beyond "percent removal" and examining kinetics and contaminant fate. In EC, treatment kinetics are often fast because coagulant generation is immediate once current is applied, and pollutant removal can occur within minutes to tens of minutes through destabilization, sweep flocculation, and flotation-assisted separation. For many industrial applications, EC's competitive advantage is precisely this rapid clarification and decontamination, which can make it suitable for shock loads or high-strength streams (Jo et al., 2024; Patel et al., 2025). However, the dominant trajectory is frequently a phase transfer rather than a chemical destruction:

contaminants are concentrated into an EC sludge stream via adsorption/capture/coprecipitation. This is highly beneficial for meeting discharge standards quickly, but it shifts the sustainability challenge toward sludge handling, dewatering, and safe disposal or valorization (Patel, 2025). For pollutants such as phosphate and metals, EC can be closer to "chemical immobilization" than mere transfer, because stable mineral phases can form—yet these still end up in the solid phase (Ma et al., 2025). For persistent micropollutants (e.g., PFAS), literature trends emphasize that conventional coagulation often yields incomplete removal and that kinetic limitations are linked to weak interactions with flocs unless modified strategies are implemented (Maroli et al., 2024; Hassan et al., 2025).

In MFCs, kinetics are typically governed by biological reaction rates (hydrolysis/fermentation of complex substrates, biofilm electron transfer) and electrochemical losses (internal resistance, cathode kinetics), so stable treatment may require longer residence times than EC—often hours to days depending on wastewater strength and configuration (Logan et al., 2006; Gude, 2016). The transformation trajectory is also different: MFCs tend to promote biotransformation and partial mineralization of organics (conversion to CO_2 and biomass), while only a fraction of electrons is harvested as current. Consequently, COD can decrease substantially even when power output is modest, because electrons can be diverted to competing sinks (e.g., methanogenesis, sulfate reduction, biomass synthesis), reducing coulombic efficiency (Logan et al., 2006; Gude, 2016). For nutrients and metals, "trajectory" depends heavily on cathode chemistry and electron acceptors: nitrate removal, for example, can be driven by cathodic reduction pathways, while metal removal may involve reductive transformations or precipitation under locally altered pH (Akagunduz, 2025). For micropollutants, MFCs often generate transformation products rather than complete mineralization, and the risk-benefit assessment must therefore consider toxicity and persistence of intermediates (Boas et al., 2022; Hossain, 2025).

Thus, EC is commonly characterized by short kinetics + solid-phase capture, whereas MFCs are characterized by longer kinetics + biological transformation, with energy recovery as an additional but often limited output (Patel et al., 2025; Logan et al., 2006).

Role of chemistry (EC) versus role of the microbiome (MFC)

At the mechanistic core, EC is dominated by inorganic aqueous chemistry and physicochemical separation. The controlling "actors" are the electro-generated Fe/Al hydroxo-species, their polymerization and precipitation behavior, and the interactions between flocs and pollutants (charge neutralization, adsorption, coprecipitation). Operational control—pH, current density, conductivity—essentially acts as a lever to shape coagulant speciation, floc properties, and gas bubble production, thereby shaping removal efficiency (Jo et al., 2024; Patel et al., 2025). Even when EC is combined with other processes (adsorption, membranes, and oxidation), the conceptual foundation remains chemical: pollutants are removed because the system creates a reactive sorbent/coagulant continuum in situ (Hassan et al., 2025).

MFCs, in contrast, are governed by the microbiome–electrode partnership. The microbiome is not simply a "biological black box"; it is the functional engine that controls electron release, extracellular electron transfer routes (direct contact, cytochromes, conductive pili, or mediators), biofilm architecture, and resilience to toxicity and salinity. In this setting, electrochemical parameters (external resistance, electrode potential, cathode kinetics) feedback into microbial community selection and metabolic partitioning between current generation and competing sinks (Logan et al., 2006; Gude, 2016). In other words, MFC performance emerges from the co-evolution of microbial ecology and electrochemical constraints—so the same wastewater can yield different outcomes depending on inoculum, acclimation, and electrode materials (Boas et al., 2022; Hossain, 2025).

This difference has practical consequences for process design and risk management. In EC, "failure modes" are often chemical/physical (passivation, suboptimal pH window, high energy use, sludge accumulation). In MFCs, failure modes are frequently biological-electrochemical (biofilm inhibition, cathode fouling, unstable community structure, oxygen crossover) and can manifest as gradual voltage decay or reduced electron recovery even when COD removal remains acceptable (Logan et al., 2006; Hossain, 2025). Therefore, comparing EC and MFCs is not merely a comparison of technologies; it is a comparison of dominant control paradigms: engineered inorganic chemistry versus engineered microbial ecology integrated with electrochemical architecture (Jo et al., 2024; Boas et al., 2022).

MEMBRANES AND SEPARATORS: ROLE, REQUIREMENTS, AND FAMILIES

Critical role of the membrane/separator (internal resistance, crossover, stability)

In MFCs, the membrane/separator is not a passive "divider" but a core electrochemical component that largely determines whether the reactor operates as an efficient bioelectrochemical system or devolves into a low-yield bioreactor with high parasitic losses. Its first critical function is controlling internal resistance, particularly the ohmic contribution associated with ion transport. Because practical MFC voltages are typically low, even modest increases in membrane resistance can cause a disproportionate drop in cell voltage and power output (Sharma et al., 2024; Mahendiravarman et al., 2025). Second, the membrane modulates crossover, notably oxygen diffusion from the cathode to the anode in air-cathode architectures. Oxygen crossover lowers coulombic efficiency by enabling aerobic oxidation at the anode that bypasses current generation, and it can shift microbial ecology away from electroactive metabolism (Yuan et al., 2013; Sharma et al., 2024). Third, the separator must remain stable under real wastewater conditions—chemically, mechanically, and biologically—because fouling, scaling, swelling, or material leaching can progressively increase resistance, promote pH splitting, and alter long-term performance (Pasternak et al., 2022; Jenani et al., 2024).

In contrast, in EC, membranes/separators are not intrinsic to the process: EC's primary treatment mechanism is the in situ generation of coagulant species via sacrificial electrodes. Nonetheless, membranes can become important in hybrid EC–membrane systems, where the membrane step is introduced to intensify separation, reduce residual turbidity, control sludge carryover, or produce high-quality permeate for reuse; in such cases the membrane's role becomes decisive for polishing performance and overall process economics (Aladily et al., 2025). This distinction—membranes as a fundamental necessity in many MFC designs versus membranes as an optional intensification step in EC—is essential when comparing the two technologies.

Membranes in MFCs: PEM, AEM, alternative membranes, and porous separators

The most widely discussed membrane class in MFCs remains ion-exchange membranes (IEMs), especially proton exchange (cation exchange) membranes (PEM/CEM) historically represented by Nafion. PEMs reduce intermixing between anode and cathode compartments while allowing ionic charge balance, but they can be costly and may suffer from oxygen/substrate crossover, pH splitting, and biofouling in long-term wastewater operation (Sharma et al., 2024; Mahendiravarman et al., 2025).

Anion exchange membranes (AEMs) are increasingly examined in MFC contexts, often motivated by different ion-transport selectivity and the possibility of mitigating some pH-gradient issues depending on operating mode. However, AEMs face durability and conductivity trade-offs related to their ionic functional groups and chemical stability, and the broader AEM literature emphasizes these limitations even in conventional fuel-cell applications (Das et al., 2022). In MFCs specifically, comparative assessments commonly highlight that membrane choice alters not only ionic resistance but also pH evolution, nitrogen species transport, and the extent of oxygen/substrate crossover, making the "best membrane" strongly configuration-dependent (Mahendiravarman et al., 2025).

Beyond classical IEMs, a major trend is the exploration of alternative low-cost membranes and porous separators, driven by scale-up and techno-economic constraints. These include polymeric alternatives (e.g., PVA, PVDF, SPEEK, chitosan-based systems), as well as earthen/ceramic or clay-based separators that can be inexpensive and mechanically robust (Jenani et al., 2024; Tiwari et al., 2024). Porous separators (textiles, glass fiber, microfiltration/ultrafiltration media) can provide low-cost compartment separation with relatively low resistance, but they must be evaluated carefully for oxygen diffusion, substrate leakage, and fouling susceptibility (Mahendiravarman et al., 2025). Overall, contemporary membrane reviews converge on the idea that MFC commercialization is unlikely to rely on expensive "premium" membranes; instead, it will depend on stable, low-cost separators whose transport properties are tuned to specific wastewater matrices (Jenani et al., 2024; Tiwari et al., 2024).

Membrane-biofilm interfaces and impacts on performance and fouling

In real wastewater, the membrane surface is rapidly transformed into a reactive interface shaped by biofilm growth, organic deposition, and inorganic scaling. This membrane–biofilm interface can be both beneficial and detrimental. On one hand, cathode-associated biofilms can reduce oxygen crossover by acting as an additional diffusion barrier, which may improve coulombic efficiency under certain conditions (Yuan et al., 2013). On the other hand, biofouling on the membrane typically increases ionic resistance, disrupts ion selectivity, and intensifies pH splitting – ultimately reducing power density and long-term stability (Pasternak et al., 2022; Mahendiravarman et al., 2025).

Biofouling is not a single phenomenon but a set of coupled processes: microbial attachment, extracellular polymeric substance (EPS) accumulation, adsorption of colloids and macromolecules, and entrapment of fine suspended solids. Reviews focusing on MFC membrane fouling emphasize that it is influenced by wastewater composition (salinity, organics, colloids), operating conditions (hydraulic regime, external resistance), and membrane surface chemistry (hydrophilicity, charge, roughness) (Pasternak et al., 2022). Consequently, mitigation strategies increasingly combine: material modifications (surface functionalization, antifouling coatings, composite structures), operational controls (hydrodynamics, periodic cleaning, optimized loading), and architecture changes (membrane-less or alternative separator designs where feasible) (Pasternak et al., 2022; Mahendiravarman et al., 2025). This interface-centric view is crucial in a review comparing EC and MFC: while EC performance often hinges on electrode surface passivation and floc behavior, MFC performance often hinges on the long-term evolution of interfaces – biofilm on electrodes and fouling layers on membranes/separators.

Membranes in EC: When and why they are (or are not) necessary

Electrocoagulation can operate effectively without any membrane because its primary objective is to generate coagulant species that destabilize pollutants and form separable flocs. However, membranes may become relevant in EC under two common scenarios. First, membranes are used in hybrid EC–membrane filtration systems (e.g., EC followed by microfiltration/ultrafiltration/nanofiltration) to enhance clarification, reduce residual colloids, remove dissolved organics not captured by flocs, and produce high-quality water for reuse. In such trains, EC can act as a pretreatment that reduces membrane fouling propensity by removing suspended solids and emulsified organics upstream, while the membrane step provides final polishing and consistency in permeate quality (Aladily et al., 2025). Second, membrane elements may be used to support electrochemical separation configurations (e.g., electrocoagulation integrated with membrane modules, or electro-driven separation hybrids), primarily to improve operational robustness and reduce sludge carryover when effluent standards are strict (Aladily et al., 2025).

In this sense, membranes in EC are best described as process intensifiers rather than essential components. Their inclusion should therefore be justified by a clear benefit – reduced downstream fouling, improved reuse-grade quality, or improved control over solids separation – because membranes add capital cost, maintenance requirements, and their own fouling risks (Aladily et al., 2025). This is fundamentally different from many MFC configurations, where the membrane/separator is needed to control oxygen crossover and enable stable electrochemical operation (Sharma et al., 2024).

Selection criteria: Cost, durability, ionic conductivity, fouling, toxicity

Selecting membranes/separators for EC and MFC requires a multi-criteria perspective, but the weighting of criteria differs by technology. For MFCs, ionic conductivity and low area-specific resistance are often first-order requirements because internal resistance directly limits power production; simultaneously, crossover control (oxygen and substrate) and long-term stability under wastewater conditions are decisive for coulombic efficiency and durability (Sharma et al., 2024; Mahendiravarman et al., 2025). For EC–membrane hybrids, the membrane is primarily evaluated by permeate quality, flux sustainability, fouling behavior, and total cost of ownership across cleaning cycles and membrane lifetime (Aladily et al., 2025).

Cost is a dominant selection axis in both systems: MFC reviews consistently argue that expensive commercial PEMs are a major barrier to scale-up, motivating the shift toward low-cost polymers and earthen/ceramic separators (Jenani et al., 2024; Tiwari et al., 2024). Durability must be assessed in realistic matrices, because long-term exposure to variable salinity, organics, and microbial communities can cause swelling, mechanical weakening, and functional degradation (Pasternak et al., 2022; Jenani et al., 2024). Fouling is a universal constraint but expressed differently: in MFCs, fouling increases internal resistance and exacerbates pH splitting; in EC–membrane systems, fouling determines permeate flux decline and cleaning frequency (Pasternak et al., 2022; Aladily et al., 2025). Finally, toxicity and environmental safety become particularly important when new functional materials are introduced (e.g., advanced polymers, ionic-liquid phases, antimicrobial additives). Even if performance is improved, a separator cannot be considered sustainable if it introduces leaching risks or end-of-life hazards; thus, recent MFC membrane reviews increasingly call for stability and environmental safety assessments to be integrated into performance reporting (Jenani et al., 2024; Mahendiravarman et al., 2025).

Overall, the membrane/separator question is a central differentiator between EC and MFC: in EC it is an optional intensification tool, while in MFC it is often an enabling technology that shapes the fundamental electrochemical balance between treatment, energy recovery, and long-term stability.

IONIC LIQUIDS AND IL-BASED MEMBRANES: CONCEPTS AND MATERIALS

Definition of ILs and useful properties (conductivity, stability, hydrophobicity)

Ionic liquids (ILs) are commonly defined as organic salts with melting points below ~100 °C, composed of an organic cation (e.g., imidazolium, pyridinium, ammonium, phosphonium) and an inorganic or organic anion (e.g., Cl^-, BF_4^-, PF_6^-, Tf_2N^-). This “designer salt” chemistry is the reason ILs cover a broad spectrum of physicochemical behaviors – ranging from strongly hydrophilic to strongly hydrophobic systems—simply by modifying ion pairs (Welton, 1999; Bonhôte et al., 1996). In the specific context of electrochemical/bioelectrochemical wastewater treatment, three IL properties are particularly valuable.

First, many ILs show high ionic conductivity (or can be formulated to enhance charge transport), which is central when the IL is used as the “active phase” within a separator: charge balance between anode and cathode can be accelerated without relying on expensive perfluorosulfonic membranes (Hernández-Fernández et al., 2016). Second, ILs are often highlighted for thermal and chemical stability and very low vapor pressure, which supports safer processing and reduced evaporative losses compared with volatile organic solvents (Welton, 1999). Third, IL hydrophobicity/hydrophilicity can be tuned and this controls water uptake, ion partitioning, and leaching tendency – parameters that strongly influence long-term stability of IL-based membranes in aqueous environments (Hernández-Fernández et al., 2012; Friess et al., 2021).

Your own experimental corpus also uses this standard definition and frames ILs as organic salts with long-term stability and high conductivity, while emphasizing that properties can be tailored by changing the cation/anion pair.

Types of IL membranes

SILM (supported ionic liquid membranes)

Supported ionic liquid membranes (SILMs) are typically constructed by impregnating a porous support (polymeric or inorganic) with an IL so that the IL fills the pore network and forms the transport phase. SILMs have been widely developed in separation science (gas separations, solvent-resistant separations, reactive/facilitated transport), and the most recurring challenge is retaining the IL inside the pores under real operating gradients (Malik et al., 2011; Friess et al., 2021).

From a mechanistic standpoint, the IL is “held” mainly by capillary forces and IL–support affinity; therefore, SILM stability is sensitive to transmembrane pressure, wetting changes, and the presence of surfactants/organics that can change interfacial tension (Friess et al., 2021; López-Porfiri et al., 2025). These stability issues are not abstract: in aqueous matrices, even a small IL loss can alter conductivity, selectivity, and (in MFCs) internal resistance. This is why SILM-based designs in water treatment tend to evolve toward additional immobilization strategies (multilayers, polymerized ILs, gels) rather than relying purely on capillary retention (Friess et al., 2021).

PIM/PILIM (polymer inclusion membranes / polymer–ionic liquid membranes)

Polymer inclusion membranes (PIMs) incorporate an IL inside a continuous polymer matrix (e.g., PVC, CTA), usually prepared by casting from a volatile solvent. Compared with SILMs, PIMs often provide improved mechanical integrity and better resistance to pressure fluctuations, because the IL is immobilized within the polymer network rather than only trapped in pores (Vázquez et al., 2014; Friess et al., 2021).

In MFC research, PIMs (and closely related “polymer ionic liquid inclusion membranes”, PILIMs) are especially interesting because they can act as low-cost separators/proton exchange media. A landmark example is the use of IL-based PIMs as proton exchange membranes in MFCs, showing that such membranes can reach COD removal and power outputs comparable to conventional membranes in selected conditions (Hernández-Fernández et al., 2016). Your own IL separator is exactly in this category: a PVC-based membrane containing a high loading of the ammonium IL methyl trioctyl ammonium chloride ([$MTOA^+$] [Cl^-]). This formulation choice is not trivial: high IL content tends to increase ionic conductivity but can increase risks of exudation/leaching and mechanical softening if not well stabilized (Vázquez et al., 2014; Ebrahimi et al., 2023).

Composite membranes (PVA–IL, PVC–IL, PVDF–IL)

Composite IL membranes generalize the PIM concept: ILs are blended, immobilized, or structured within polymeric hosts such as PVA, PVC, PVDF and other matrices. The polymer acts as the mechanical scaffold, while the IL contributes ionic transport and interfacial properties. Recent studies continue to show the viability of this approach for MFC separators. For example, an IL-infused PVA-based membrane (doped system) has been used as an MFC separator and reported as a low-cost alternative strategy to expensive commercial membranes (Tomar et al., 2025).

From a design perspective, composite membranes offer a larger “tuning space”: polymer crystallinity, crosslink density, plasticizer effects, IL content, and fillers (e.g., oxides, carbon materials) can be adjusted to balance conductivity, selectivity, and mechanical stability (Bernardo et al., 2025; Ebrahimi et al., 2023).

Ionic transport mechanisms in IL-based membranes

Transport in IL-based membranes is commonly described through coupled mechanisms: solution-diffusion, ion-exchange/ion-pairing, and in some cases facilitated transport if reactive carriers exist. In SILMs, species dissolve into the IL phase and diffuse according to their partitioning and diffusivity in the IL; the effective flux is then controlled by IL viscosity, water uptake, and interfacial resistances (Malik et al., 2011; Friess et al., 2021). In polymer-hosted systems (PIM/PILIM/composites), an additional layer of complexity arises: transport occurs through an IL-rich microphase dispersed within a polymer matrix, and therefore depends on percolation/connectivity of the IL domains and polymer free volume (Vázquez et al., 2014; Bernardo et al., 2025).

For MFC separators specifically, the dominant objective is fast migration of charge carriers (H^+ and/or other cations/anions depending on configuration) to maintain electroneutrality while minimizing oxygen/substrate crossover. Your slaughterhouse-wastewater study explicitly interprets proton transport in the IL-based separator via a solution–diffusion type picture, emphasizing the interaction between protons and the negative charge in the ionic liquid phase. In practice, however, MFCs rarely operate with pure proton conduction; mixed-ion transport (Na^+, K^+, NH_4^+, Cl^-, HCO_3^-, etc.) often dominates charge balance in real wastewaters. This can be beneficial for lowering ohmic losses but may intensify pH gradients and influence nutrient migration, meaning that reporting only “proton exchange” can underrepresent the true transport picture in complex substrates (Friess et al., 2021; Mahendiravarman et al., 2025).

Risks and limitations: leaching, potential toxicity, aging

Leaching (IL loss) is one of the most critical limitations for IL-based membranes in aqueous systems, because it directly threatens membrane lifetime, stable conductivity, and environmental acceptability. In your own studies, SEM–EDX results before/after operation show a reduction in chlorine signal attributable to IL release. In the slaughterhouse MFC work, the authors conclude that “some ionic liquid have been released” based on the decrease in Cl content after use, while still noting that the IL is not completely removed and some signal changes may be influenced by surface deposits (Air breathing cathode-microbial…). In the mineral oil refinery wastewater study, the EDX analysis similarly observes a reduction in Cl content and concludes that a certain amount of ionic liquid has been released from the membrane into the medium.

Beyond leaching, toxicity is context-dependent and varies strongly with cation chain length, anion type, and functional groups. A growing ecotoxicology literature shows that many ILs can affect microorganisms and aquatic primary producers, which matters for wastewater bioprocesses and receiving waters if leaching occurs (Chu et al., 2022). This does not mean all ILs are inherently "unsafe"; rather, it motivates a design-for-environment approach: choose less toxic ion pairs, demonstrate leaching bounds under realistic operation, and include fate/toxicity screening when proposing IL membranes for water treatment.

Finally, aging occurs via multiple pathways: polymer plasticization or embrittlement, IL redistribution within the matrix, chemical attack by organics/surfactants, and progressive fouling/scaling that changes interfacial wetting and accelerates IL loss. Reviews of IL membranes repeatedly emphasize that long-term stability—not just initial permeability or conductivity—is the real bottleneck to translation from lab demonstrations to robust processes (Friess et al., 2021; López-Porfiri et al., 2025).

Immobilization and enhancement strategies (crosslinking, multilayers, gels, fillers)

Stabilizing ILs inside membranes is essentially an exercise in increasing retention forces and reducing IL mobility while preserving ionic transport. Several strategies are particularly relevant to MFC separators:

- Crosslinking / network tightening: Crosslinking polymer chains can reduce IL exudation and swelling, especially in hydrophilic hosts like PVA. The general composite-membrane literature highlights IL leakage as a main drawback of simple impregnation and notes that enhanced mechanical stability does not automatically solve leakage unless immobilization is addressed directly (Ebrahimi et al., 2023).
- Multilayer or "skin" layers: Adding a thin selective top layer (or asymmetric structures) can reduce direct IL–water contact and limit washout, while the bulk layer retains ion-conducting pathways. This is frequently discussed for SILMs where capillary retention alone is vulnerable to operational perturbations (Friess et al., 2021; López-Porfiri et al., 2025).
- Gels/ionogels: Transforming the IL phase into a gel-like domain (physically or chemically) can markedly improve retention. "Ionogel" concepts – where IL is immobilized in a polymer/gel network – are widely explored in electrochemical materials, and the same concept is transferable to aqueous separators: the IL remains the conductive medium, but the gel network suppresses convection and reduces loss under gradients (Chae et al., 2024; Zhang et al., 2024).
- Fillers and hybrid composites: Adding inorganic or carbonaceous fillers (e.g., silica, oxides, layered materials) can increase tortuosity,

Table 1. Comparative treatment performances: EC vs. MFC with IL-based membranes

Criterion	Electrocoagulation (EC)	MFC with IL-based membrane/ separator	Reporting / normalization essentials
Primary removal domain	TSS/turbidity, color/ dyes, emulsified oils, metals, phosphate (fast physicochemical capture)	Biodegradable COD with potential energy recovery; nutrients/metals possible (configuration-dependent)	Report influent/effluent + rates (e.g., $\mathrm{kg\ COD \cdot m^{-3} \cdot d^{-1}}$). For MFC include CE
Energy profile	Electricity consumption + electrode consumption	Electricity generation (often modest)	Compare on net $\mathrm{kWh \cdot m^{-3}}$ when possible; state MFC normalization ($\mathrm{W \cdot m^{-3}}$ vs $\mathrm{W \cdot m^{-2}}$)
Main residuals	EC sludge (metal hydroxides + captured pollutants)	Biofilm/biomass; cathode/separator fouling	Include sludge yield/composition (EC) and cleaning frequency/ performance decay (MFC)
Typical timescale	Minutes to <1–2 h (often)	Hours to days (often)	Specify batch/continuous + HRT; compare via space–time yield
Robustness drivers	Conductivity + current density; passivation	Microbial inhibition, pH/salinity, internal resistance, cathode durability	Include step-load tests (COD/ salinity/pH) + recovery time
Key constraints	Passivation, electrode replacement, sludge handling, energy cost	Low CE, internal resistance, crossover, cathode aging, membrane fouling/leaching	Report IR (polarization/EIS) and long-run stability

Table 2. Most appropriate treatment option (EC, MFC–IL, or a hybrid configuration) for common wastewater types

Effluent type	Recommended option	Why (dominant reasons)	Minimum metrics to report
Agro-food (slaughterhouse, dairy)	Hybrid (EC → MFC–IL) (often best)	EC rapidly removes FOG/TSS and stabilizes feed; MFC targets remaining biodegradable COD with potential energy recovery	COD (total/soluble), TSS/FOG, pH, conductivity; EC: kWh·m^{-3} + sludge; MFC: CE + power density + IR
Petroleum/refinery (oily, complex)	EC (stand-alone or EC → polishing)	Strong for emulsified oil/color/metals; MFC often shows low CE due to toxicity/complexity unless carefully acclimated	Oil & grease, COD fractionation, metals, salinity; EC energy + electrode use + sludge; (if MFC used) CE + inhibition indicators
Textile/dye effluents	EC (benchmark)	Fast and reliable decolorization; MFC dye removal is often slow/variable unless dyes are biodegradable	Color (ADMI/Pt–Co), COD, TSS; EC energy + sludge and color removal kinetics
Urban/mixed wastewater	MFC–IL (niche) or Hybrid	MFC can treat biodegradable COD with reduced aeration demand; EC is best as polishing for turbidity/phosphate	COD/BOD, nutrients, conductivity; MFC: CE + power density + IR + stability; EC (if polishing): P removal + sludge
Acidic/high-strength (e.g., citrus processing)	EC or Hybrid (conditioning + MFC–IL)	Strong acidity inhibits exoelectrogens; EC robust if conductivity adequate; MFC needs buffering/conditioning	pH evolution, alkalinity, COD, inhibition/toxicity; MFC: CE + IR drift; EC: energy + sludge
Metal-rich wastewater (electroplating/mining, etc.)	EC (primary)	Direct precipitation/coprécipitation; fast compliance	Metals speciation, pH, conductivity; sludge characterization/leachability
Reuse-driven polishing (strict turbidity/P limits)	EC as polishing (after biological/MFC)	Efficient phosphate/turbidity removal to meet reuse specifications	TP/PO_4–P, turbidity, relevant reuse indicators; sludge

create stronger IL–matrix interactions, and stabilize microphase morphology. The broader polymer/IL blend literature provides practical design rules: fillers can improve mechanical strength and sometimes increase effective ionic conductivity if they promote continuous ion pathways or water management (Bernardo et al., 2025).

- Comparative treatment performances: EC vs. MFC with il-based membranes is shown in Table 1 and 2.

CONCLUSIONS

This review demonstrates that EC and MFCs equipped with IL-based membranes should be understood as mechanistically distinct and strategically complementary approaches to wastewater treatment rather than direct substitutes. Their divergence originates from fundamental process architecture: EC operates as a current-driven electrochemical dosing system in which pollutant removal is inherently coupled to electrode consumption and sludge generation, whereas MFCs rely on microbially mediated electron transfer, with performance constrained by bioelectrochemical kinetics and internal resistance.

The comparative analysis shows that EC is particularly advantageous for rapid treatment of highly turbid, oily, colored, or metal-rich effluents, offering operational robustness and broad contaminant removal. However, its effectiveness is intrinsically linked to electricity demand and material consumption. In contrast, MFCs are more suitable for biodegradable wastewaters where partial energy recovery is desirable, yet their scalability remains critically dependent on improving coulombic efficiency, minimizing resistive losses, and ensuring long-term stability of cathodes and separators.

A central finding of this review is that IL-based membranes represent both an opportunity and a bottleneck for MFC advancement. While their tunable physicochemical properties and potential cost advantages position them as promising alternatives to conventional membranes, practical deployment hinges on controlling IL leaching, fouling, oxygen crossover, and resistance drift under real wastewater conditions. Membrane stability and net energy balance therefore emerge as decisive parameters governing the comparative sustainability of IL-enabled MFC systems.

From an engineering and system-integration perspective, hybrid configurations (e.g., EC as pretreatment followed by MFC polishing, or MFC coupled with EC for residual contaminant removal) appear particularly promising. Such integration can align rapid physicochemical removal with bioelectrochemical energy recovery, mitigating the individual limitations of each process.

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