IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

Impact Factor 8.311 ⁜ Peer-reviewed & Refereed journal ⁜ Vol. 12, Issue 8, August 2025

DOI: 10.17148/IARJSET.2025.12848

Bioelectroactive Membranes for Heavy Metal Removal from Wastewater Remediation

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Abstract: Heavy metal contamination in wastewater is a serious environmental and public-health problem because metals such as chromium, lead, cadmium, nickel, copper, mercury, arsenic, and zinc are toxic, persistent, and difficult to degrade. Conventional technologies such as chemical precipitation, coagulation-flocculation, ion exchange, and adsorption are useful, but they can suffer from incomplete removal, sludge generation, high chemical demand, fouling, or high operational cost. Membrane-based processes, including ultrafiltration, nanofiltration, reverse osmosis, micellar-enhanced ultrafiltration, and polymer-enhanced ultrafiltration, provide compact and efficient methods for heavy metal removal. In parallel, microbial fuel cells (MFCs) and related bioelectrochemical systems provide a pathway for simultaneous wastewater treatment and electricity generation. The membrane or separator in an MFC regulates proton and ion transport, separates anodic and cathodic reactions, limits oxygen diffusion, and influences power density, current density, coulombic efficiency, and chemical oxygen demand removal. This review discusses bioelectroactive membrane systems for heavy metal removal by integrating membrane separation principles with MFC-based treatment. The paper reviews heavy metal contamination, conventional treatment methods, membrane processes, MFC fundamentals, separator materials, ceramic and earthen membranes, electrode reactions, fouling, surface modification, performance indicators, limitations, and future perspectives. New schematic figures are included to illustrate water contaminant classification, membrane separation processes, MFC configurations, oxygen reduction reactions, enhanced ultrafiltration mechanisms, membrane fouling, and surface modification strategies.

Keywords: Bioelectroactive membrane; microbial fuel cell; heavy metals; wastewater treatment; proton exchange membrane; ceramic membrane; earthen membrane; nanofiltration; reverse osmosis; surface modification; membrane fouling.

I. INTRODUCTION

Heavy metals in wastewater are among the most important inorganic pollutants because they are toxic even at low concentrations and can persist in the environment. Industrial activities such as electroplating, mining, battery production, tanneries, pesticide production, paint manufacturing, and metal finishing release metal-containing effluents into water bodies. Once released, these contaminants can damage aquatic ecosystems and create long-term risks for human health through water, food, air, or direct exposure [2].

Traditional water-treatment systems are often not sufficient for complex industrial effluents containing heavy metals and mixed organic-inorganic pollutants. Chemical precipitation, coagulation-flocculation, ion exchange, adsorption, and membrane filtration are widely studied for heavy metal treatment, but each method has specific advantages and limitations [2], [8], [9]. Membrane-based technologies are especially attractive because they can provide high separation efficiency, compact design, lower chemical dependence, and limited sludge generation [2], [10].

Microbial fuel cells (MFCs) are a complementary platform, as they treat wastewater and generate electricity by microbial oxidation of organic substrates. Anodic chamber of the MFCs organic matter is oxidized by the microorganisms, releasing electrons and protons. Electrons flow through an external circuit while protons travel through a membrane or separator to the cathode. The membrane is therefore of crucial importance for separation, ion transport and electrochemical efficiency [1], [3], [4].

This review addresses bioelectroactive membranes, membranes, separators, or membrane-electrode interfaces that operate in bioelectrochemical systems and impact ion transport, biofilm activity, oxygen diffusion, and removal of pollutants. These systems merge the membrane separation capacity with the redox activity of microorganisms and electrodes. The coupling of membrane filtration and bioelectrochemical treatment can facilitate heavy metal removal, wastewater purification, resource recovery and energy generation [1], [2], [4].

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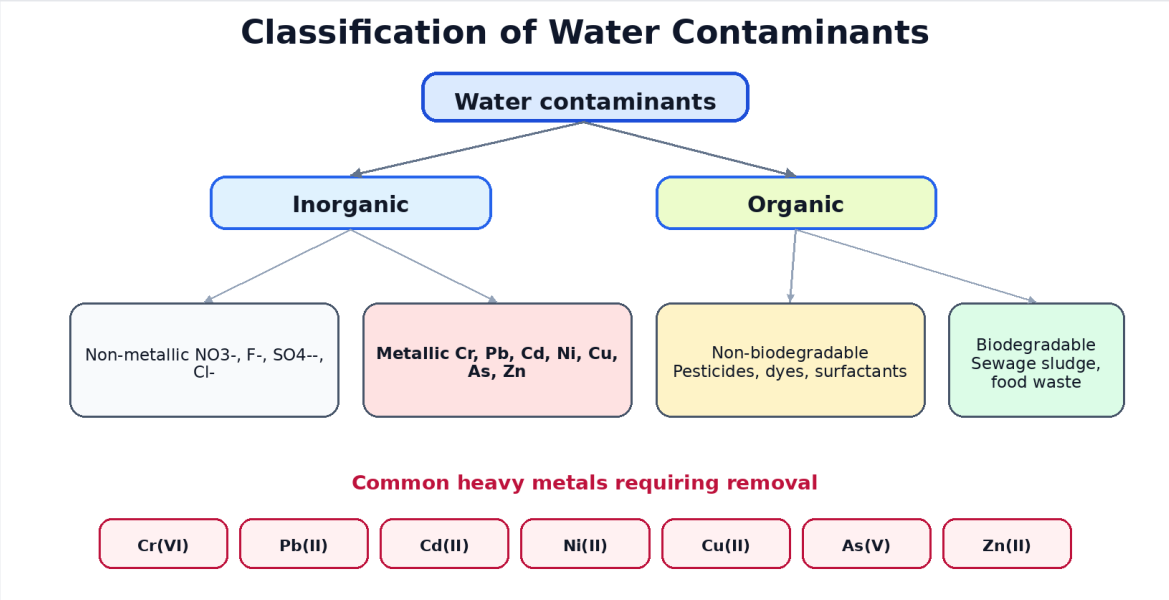

Figure 1. Classification of water contaminants, heavy metals are shown in bold as inorganic metallic pollutants. Redrawn for this paper based on Dawam et al. [2].

II. SCOPE AND REVIEW METHODOLOGY

This paper is prepared as a review article. The discussion is based mainly on two original review papers: a review on low-cost membranes for microbial fuel cells [1] and a review on membrane technologies for heavy metal removal from polluted water [2]. Additional supporting literature on MFC separators, ion-exchange membranes, proton exchange membranes, heavy metal removal, membrane materials, and polymeric membranes is used to support the discussion [3]-[20].

The review is organized into six major themes: heavy metal contamination, conventional treatment processes, membrane-based heavy metal removal, MFC fundamentals, separator and membrane materials for bioelectrochemical systems, and future development of bioelectroactive membranes. New schematic diagrams prepared for this paper are used to show the mechanisms and configurations discussed in the text.

III. CONTAMINATION OF WASTEWATER BY HEAVY METALS

Heavy metals are inorganic contaminants that are not readily biodegradable and can accumulate in wastewater, sediment, plants, animals and human tissues. Trace concentrations of metals such as arsenic, cadmium, lead, nickel, chromium, mercury, cobalt, selenium, zinc and copper may be toxic. Their toxicity is related to their ability to bind with biomolecules containing carboxylic, amino, sulfur-containing, and phosphate groups, thereby disrupting proteins, enzymes, and cellular processes [2].

The major sources of heavy metals include tanneries, electroplating, mining, batteries, paints, fertilizers, pesticides, metal processing, and chemical industries. The discharge of untreated or insufficiently treated industrial effluents into freshwater systems increases heavy metal exposure and makes removal a major objective in wastewater treatment [2], [8], [9].

TABLE I. COMMON HEAVY METALS AND TYPICAL WASTEWATER SOURCES [2], [8]

Heavy metal	Typical source	Treatment concern
Cr(VI)/Cr(III)	Electroplating, tanning, pigment and metal industries	Toxicity, redox transformation, regulatory control
Pb(II)	Battery, paint, metal processing and industrial discharge	Bioaccumulation and human-health risk
Cd(II)	Batteries, pigments, electroplating and mining	Toxicity even at low concentration
Ni(II)	Metal finishing, electroplating and alloy industries	Persistence and aquatic toxicity

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Cu(II)	Mining, plating, electronics and industrial wastewater	Toxicity at elevated concentration
As(III)/As(V)	Mining, geothermal discharge, pesticides and metallurgy	High toxicity and difficult removal
Zn(II)	Galvanizing, mining and metal industries	Discharge-limit compliance

IV. CONVENTIONAL METHODS FOR HEAVY METAL REMOVAL

Conventional methods for reducing heavy metal concentration include chemical precipitation, coagulation-flocculation, ion exchange, and adsorption. Chemical precipitation is the process of converting soluble metal ions into insoluble products by adding suitable precipitating agents. It is simple and inexpensive but it can generate large quantities of toxic sludge and may be less effective for low concentrations of metal ions [2].

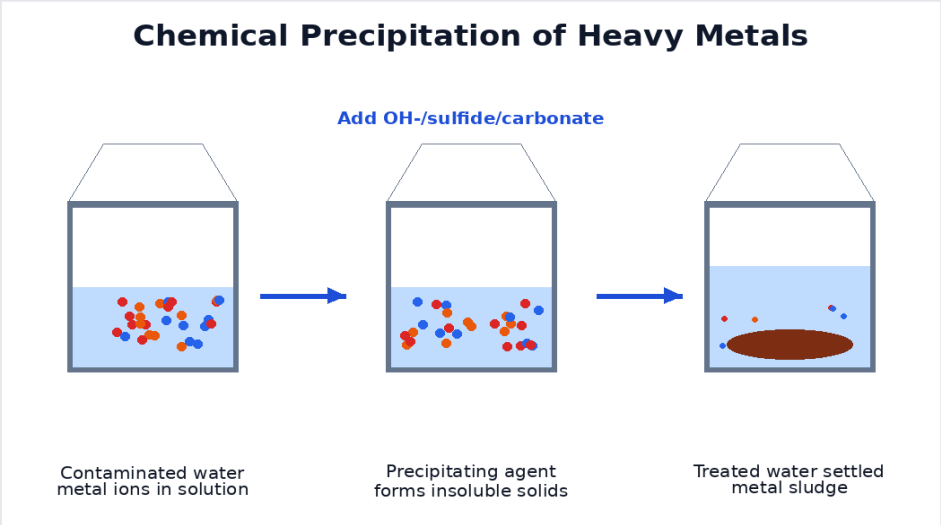

Fig. 2. Chemical precipitation mechanism for removing heavy metals. Redrawn for this paper based on Dawam et al. [2].

Coagulation and flocculation neutralize the charge on particles, allowing particles and dissolved metals to aggregate into larger flocs. These flocs may then be removed by sedimentation or by filtration. The method is useful for suspended solids and some dissolved metals, but it also produces sludge and may need to be combined with other methods to achieve complete heavy metal removal [2]. Ion exchange utilizes resins or solid exchange media that have functional groups that can exchange ions with the solution. It can be fast and selective but is sensitive to pH and can suffer from fouling of metal ions on the exchange media [2].

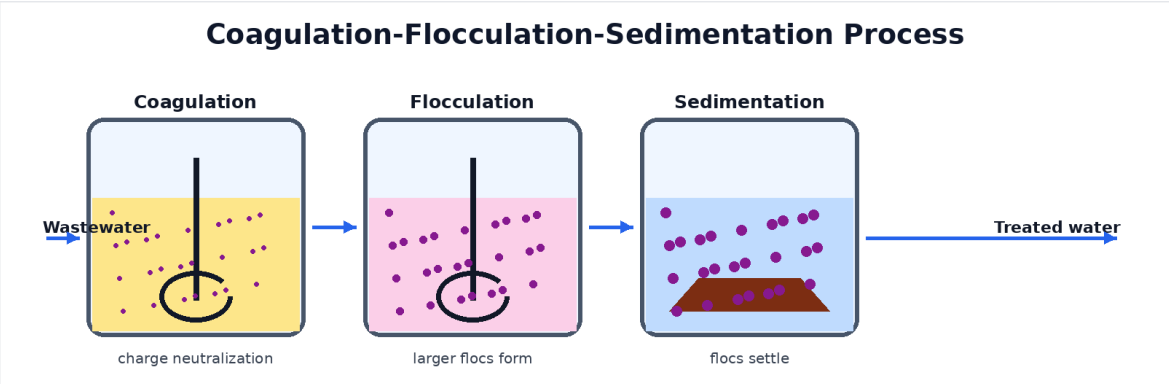

Fig. 3. Coagulation-flocculation treatment process. Redrawn for this paper based on Dawam et al. [2].

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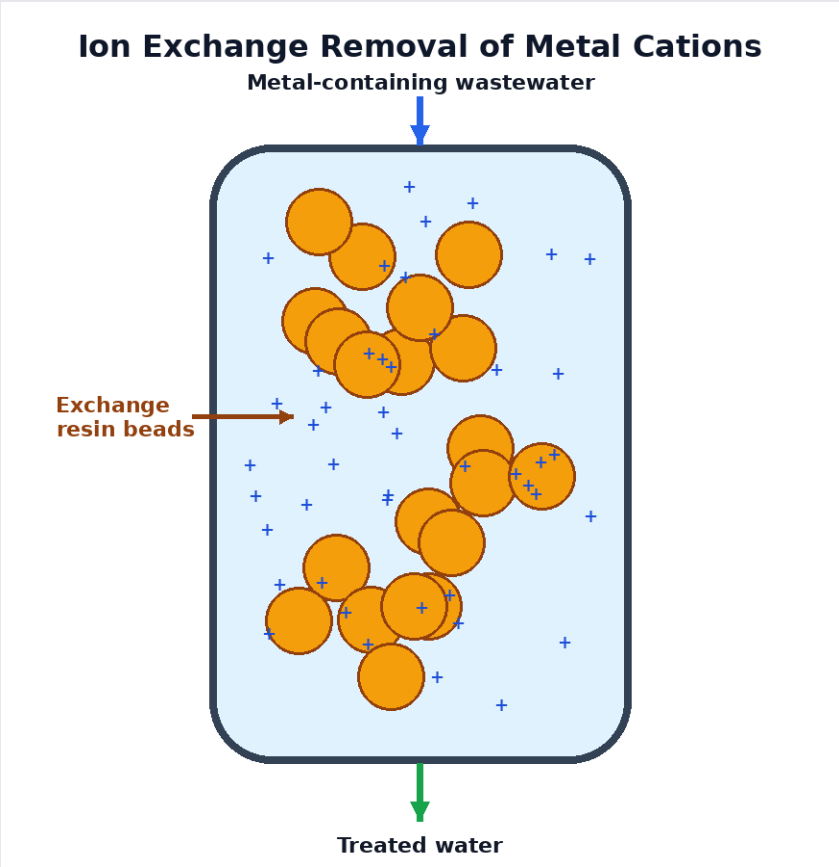

Fig. 4. Ion exchange process for removal of heavy metals. Redrawn for this paper based on Dawam et al. [2].

TABLE II. COMPARISON OF COMMON HEAVY METAL REMOVAL METHODS [2], [8], [9]

Method	Principle	Advantages	Limitations
Chemical precipitation	Conversion of dissolved metals into insoluble precipitates	Simple equipment and low reagent cost	Sludge production and lower efficiency at low metal concentration
Coagulation-flocculation	Charge neutralization and aggregation of contaminants into flocs	Simple operation and useful for suspended pollutants	Incomplete metal removal and sludge generation
Ion exchange	Exchange of ions between resin functional groups and dissolved metal ions	Fast kinetics and regenerable media	pH sensitivity, fouling and reduced suitability for high metal loads
Adsorption	Binding of metal ions to adsorbent surfaces	Wide adsorbent options and low-cost materials possible	Regeneration and commercial-scale limitations
Membrane filtration	Selective separation through membrane pores or dense barriers	High removal efficiency and little sludge generation	Fouling, cost and pressure/energy requirements

V. MEMBRANE-BASED HEAVY METAL REMOVAL

Membrane processes are considered clean separation technologies because they can separate contaminants without large chemical addition and without producing large sludge volumes. The main pressure-driven membrane processes used for heavy metal treatment are microfiltration, ultrafiltration, nanofiltration and reverse osmosis. Selectivity is a function of pore size, membrane charge, molecular size, hydrated ion size, diffusion and operating pressure [2, 10].

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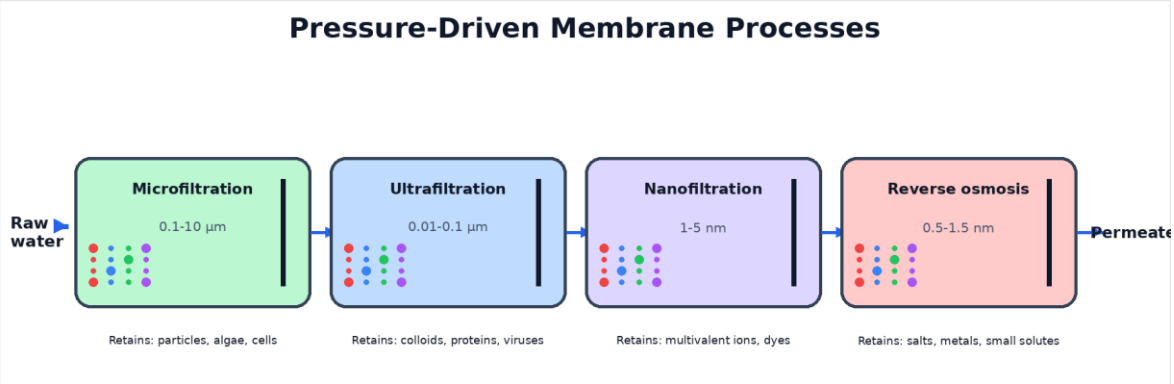

Fig. 5. Membrane process characteristics for microfiltration, ultrafiltration, nanofiltration, and reverse osmosis. Redrawn for this paper based on Dawam et al. [2].

Ultrafiltration membranes are typically larger than most metal ions dissolved in the water. Hence, in micellar-enhanced ultrafiltration (MEUF) and polymer-enhanced ultrafiltration (PEUF) processes, additives such as surfactants or water-soluble polymers are employed to complex or increase the size of metal-containing species prior to separation. MEUF relies on the formation of surfactant micelles while PEUF is based on the use of polymers which complex metal ions and are retained by the membrane [2].

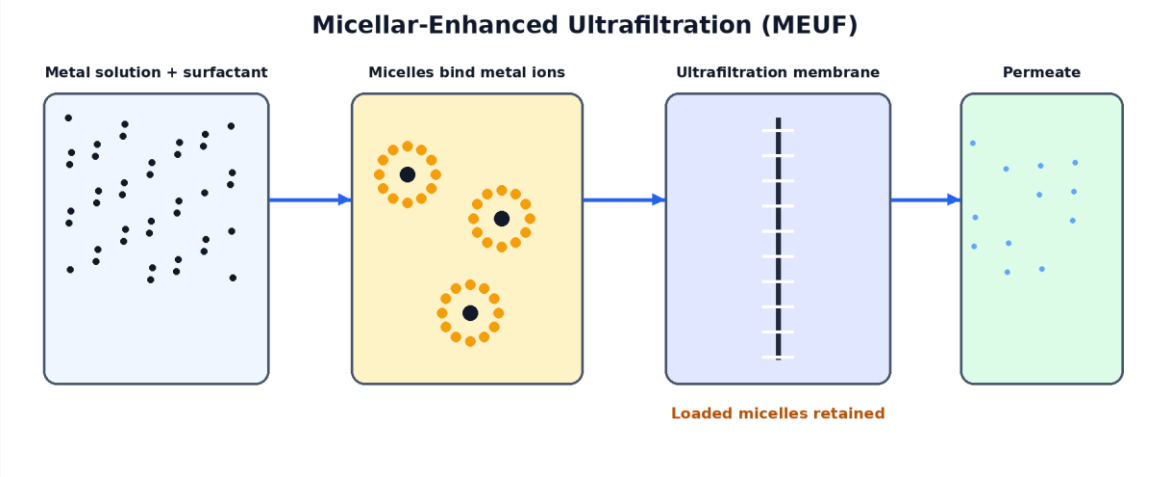

Fig. 6. Micellar-enhanced ultrafiltration process schematic. Redrawn for this paper based on Dawam et al. [2].

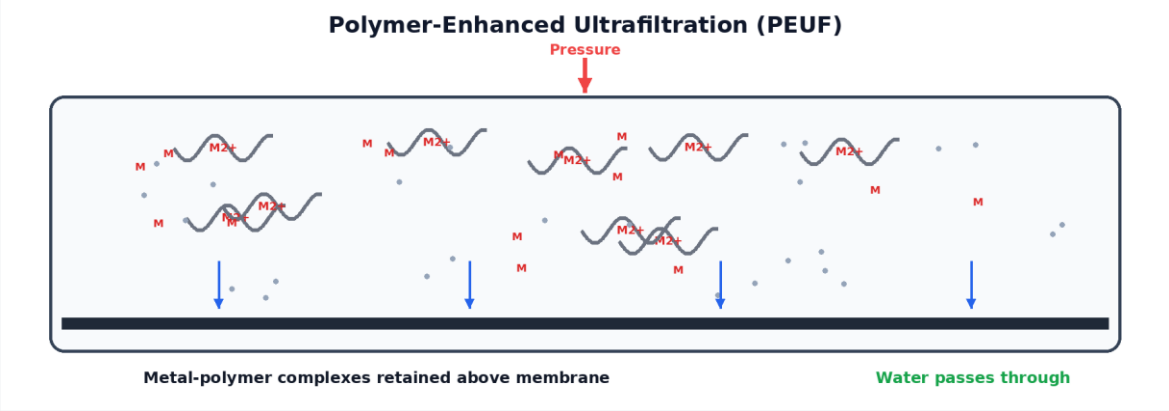

Fig. 7. Polymer-enhanced ultrafiltration process schematic. Redrawn for this paper based on Dawam et al. [2].

Nanofiltration is positioned between ultrafiltration and reverse osmosis. It is particularly suitable for many metallic ions because it uses a combination of size exclusion, charge effects, hydration effects, and diffusion. Reported extraction efficiencies for NF membranes commonly fall within the range of 94% to 99.9%, depending on metal ion, membrane charge, feed chemistry, and operating conditions [2], [13], [14].

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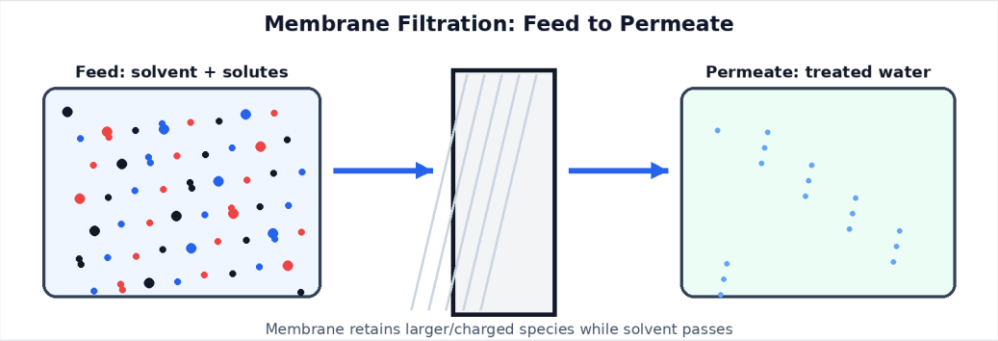

Fig. 8. Schematic representation of membrane filtration used in nanofiltration. Redrawn for this paper based on Dawam et al. [2].

Reverse osmosis uses a dense semi-permeable membrane and applies hydraulic pressure to move water against the concentration gradient. RO provides very high heavy metal and salt rejection, but it also requires higher pressure and energy and is affected by fouling and concentrate-disposal challenges [2], [10].

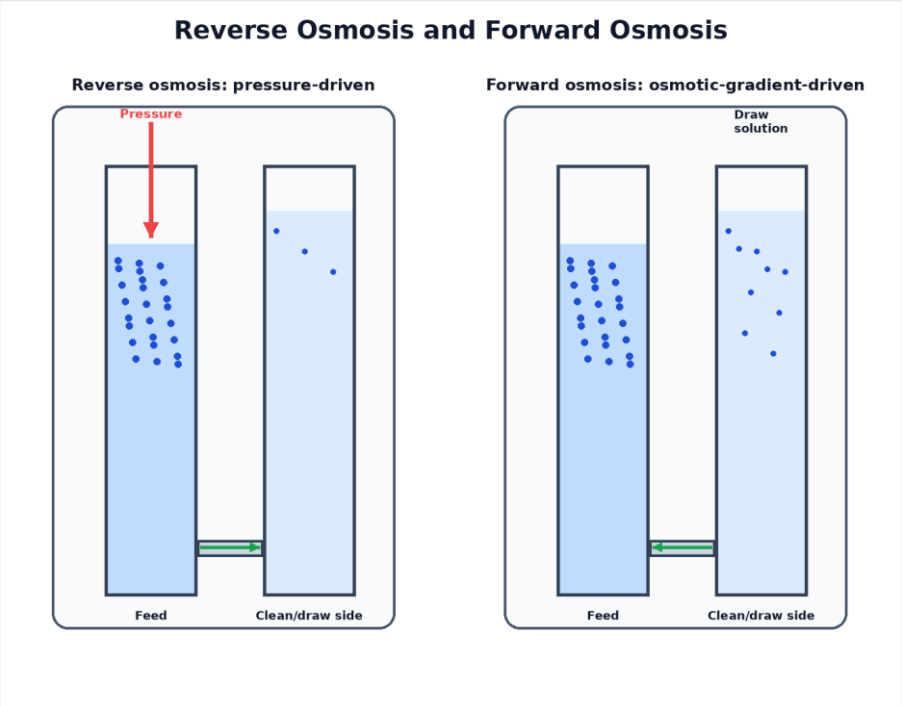

Fig. 9. Reverse osmosis and forward osmosis separation methodologies. Redrawn for this paper based on Dawam et al. [2].

TABLE III. MEMBRANE METHODS USED FOR HEAVY METAL REMOVAL [2], [13], [14]

Process	Approximate structure/pore scale	Mechanism	Advantages	Limitations
UF	Porous asymmetric; about 5-20 nm	Sieving and preferential adsorption; improved by MEUF/PEUF	High separation efficacy and relatively low pressure	May require surfactants or polymers and post-treatment
NF	Finely porous asymmetric/composite; about 1-5 nm	Sieving, electrostatic effects, hydration and diffusion	High heavy metal rejection at intermediate pressure	Lower flux than UF and higher energy use

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RO	Dense/nonporous asymmetric or composite; about 0.5-1.5 nm	Diffusion through dense membrane	Excellent rejection of metals and salts	High pressure, energy requirement and fouling
MEUF	UF plus surfactant micelles	Metal ions bind with micelles retained by UF membrane	Useful for low-concentration contamination	Surfactant recovery and secondary contamination issues
PEUF	UF plus soluble metal-binding polymers	Metal-polymer complexes are retained by UF membrane	High extraction efficiency and low energy demand	Polymer recovery and process optimization required

VI. BIOELECTROACTIVE MEMBRANES AND MICROBIAL FUEL CELL PRINCIPLES

Microbial fuel cells convert chemical energy stored in biodegradable substrates into electrical energy through microbial metabolism. In the anode chamber, exoelectrogenic microorganisms oxidize organic matter and produce electrons, protons and carbon dioxide. The electrons flow through the external circuit, and the protons move through the membrane or separator to the cathode. At the cathode, an electron acceptor such as oxygen is reduced, completing the electrochemical circuit [1], [3], [15].

The membrane in an MFC is not only a passive separator. It regulates proton transfer, ion selectivity, oxygen crossover, internal resistance, substrate losses, biofouling, and long-term stability. For this reason, membranes are central to MFC efficiency and to the feasibility of bioelectrochemical treatment systems [1], [4]-[6].

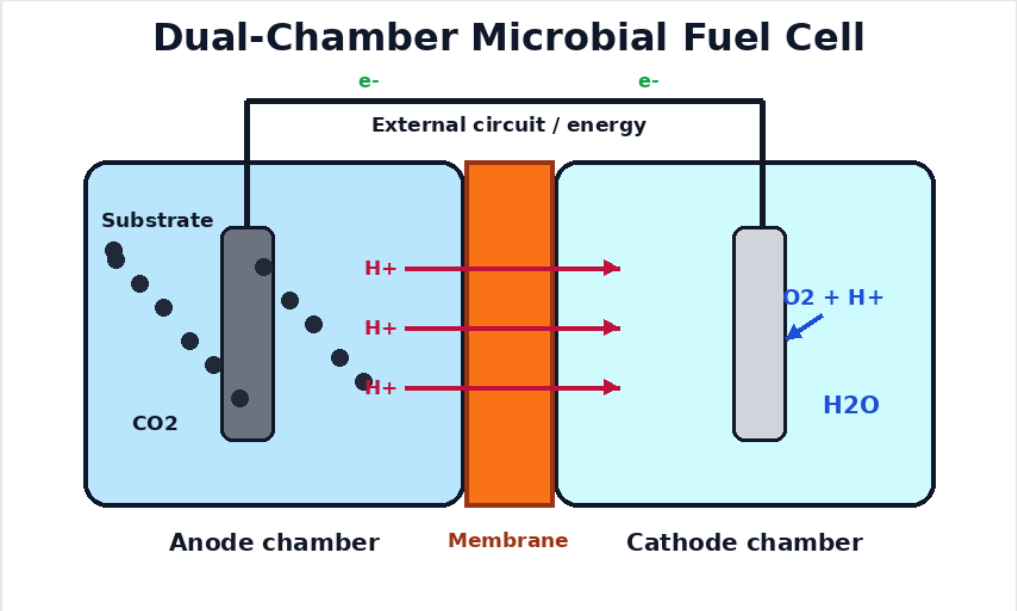

Fig. 10. Dual-chamber microbial fuel cell showing anode, membrane, cathode, proton transfer and electron flow. Redrawn for this paper based on Tiwari et al. [1].

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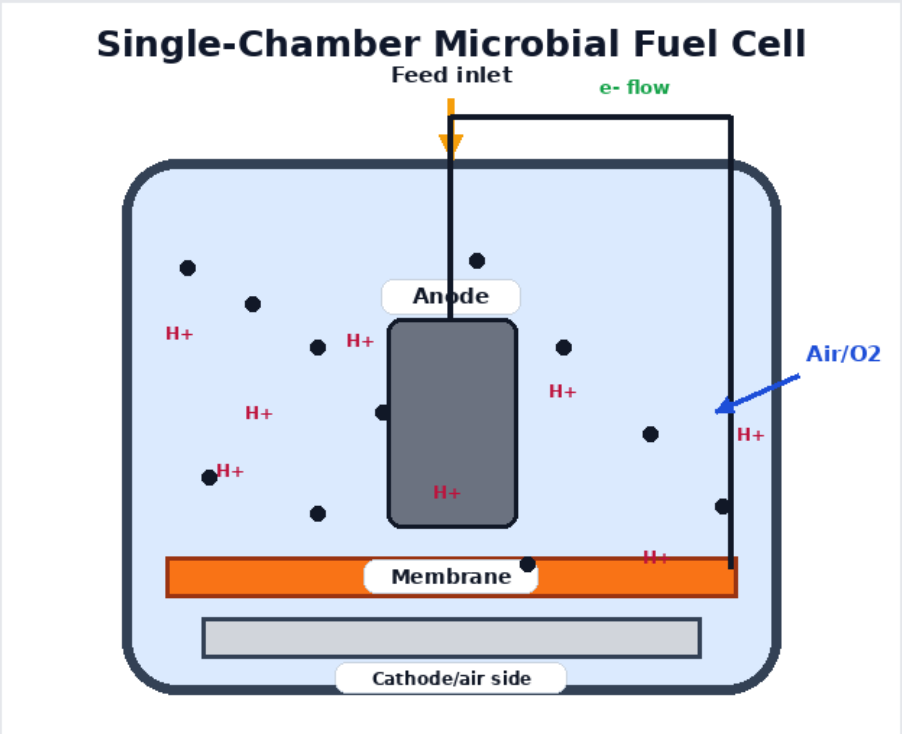

Fig. 11. Single-chamber microbial fuel cell configuration. Redrawn for this paper based on Tiwari et al. [1].

In a bioelectroactive membrane system, the membrane may participate indirectly by maintaining ion transport and directly by influencing biofilm growth, ion migration, metal speciation, and electrochemical reduction. Heavy metal removal in these systems can be achieved through precipitation, adsorption, membrane rejection, cathodic reduction, microbial transformation or through combined mechanisms. The exact pathway depends on the metal species, pH, electrode potential, membrane material, reactor configuration and composition of wastewater [1], [2], [3].

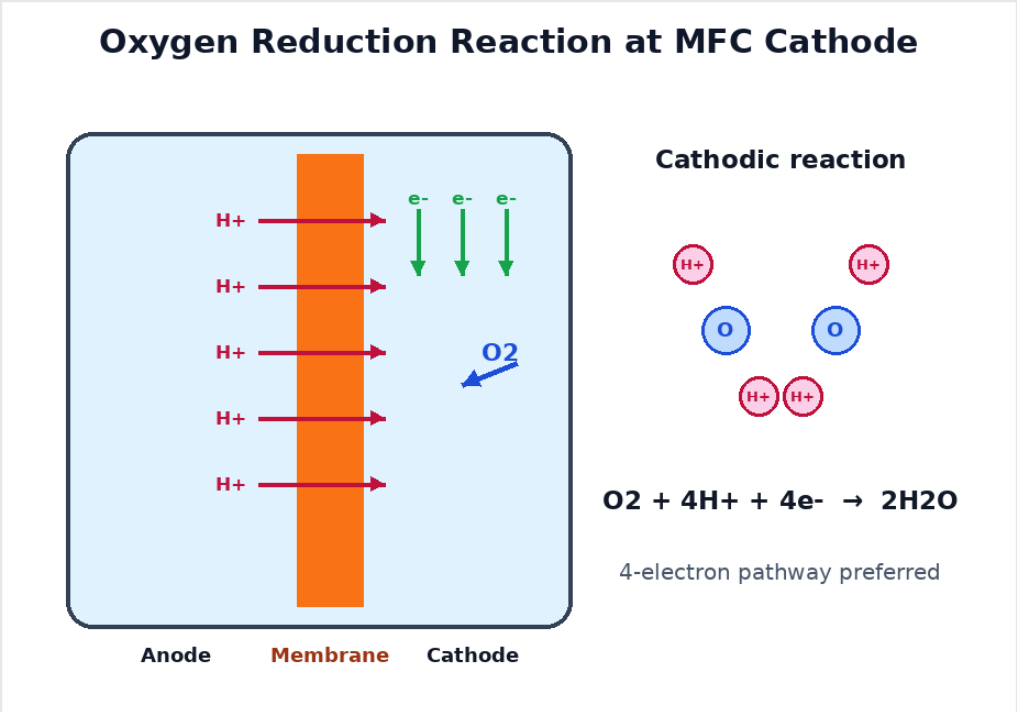

Fig. 12. Oxygen reduction reaction mechanism at the cathode side of an MFC. Redrawn for this paper based on Tiwari et al. [1].

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VII. MEMBRANE AND SEPARATOR MATERIALS IN BIOELECTROCHEMICAL SYSTEMS

Conventional MFCs have often used Nafion or other proton exchange membranes because of their proton conductivity. However, Nafion is expensive and can suffer from oxygen leakage, substrate loss, biofouling, and practical cost limitations. Membrane cost can represent a major share of MFC capital cost, making low-cost alternatives necessary for scale-up [1], [5], [6].

Low cost separators are earthen membranes, clayware membranes, ceramic membranes, natural clay membranes, composite ceramic membranes. Materials from the earth such as clay, soil, red soil, bentonite and Kalporgan soil are attractive because they are cheap, locally available and environmentally accessible. Ceramic membranes are mechanically stronger, more resistant to chemicals, thermally more stable, have a controllable pore size and a long lifetime, but are more expensive than earthen or clayware ones [1], [17]-[20].

TABLE IV. COMPARISON OF LOW-COST MFC MEMBRANE MATERIALS [1]

Property	Earthen membrane	Clayware membrane	Ceramic membrane
Composition	Natural materials such as soil, sand and clay	Fired clay	Inorganic ceramic materials
Mechanical strength	Moderate	Improved	Excellent
Chemical resistance	Limited	Moderate	Excellent
Cost	Low	Moderate	High
Availability	Abundant	Widely available	Widely available
Ion conductivity	Moderate	Good	Excellent
Stability	Limited	Moderate	Excellent
Pore-size control	Limited	Limited	Excellent
Overall performance	Variable	Good	Excellent

The membrane material must support ion transfer while restricting oxygen diffusion into the anaerobic anode chamber. High proton conductivity, low internal resistance, durability, mass-transfer control, stability, and compatibility with wastewater conditions are important properties. Ceramic and earthen membranes are therefore promising for field-scale MFCs where cost reduction is essential [1], [4], [18]-[20].

VIII. PERFORMANCE INDICATORS AND REPORTED FINDINGS

Performance of MFC-based membrane systems is evaluated using both treatment and electrochemical indicators. The most important parameters include chemical oxygen demand (COD) removal, power density, current density, coulombic efficiency, oxygen mass transfer, proton mass transfer, internal resistance, water uptake, ion-exchange capacity, and operating stability [1], [3], [4].

The reviewed literature on MFC membranes indicates that ceramic and modified clay-based membranes can achieve strong treatment and energy results. Several studies have demonstrated the high power density and the high current density of the ceramic membrane systems. Earthen materials such as red soil, bentonite clay and Kalporgan soil have shown promise for cost effective applications. The results show that membrane composition and reactor configuration significantly affect the performance of MFCs [1].

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TABLE V. SELECTED PERFORMANCE EXAMPLES FROM MFC MEMBRANE SYSTEMS [1]

Membrane/separator	Wastewater type	Configuration	Key result	COD removal	Source
Ceramic membrane with CHI/MMT	Domestic wastewater	Dual chamber	Power density 119.58 ± 19.16 mW/m2; current density 869.44 ± 27.49 mW/m2	95.67%	[1]
Ceramic membrane with CHI/MMT and stainless-steel cathode	Domestic wastewater	Dual chamber	Current density 1422.22 ± 41.2 mW/m2; power density 229.12 ± 18.5 mW/m2	87%	[1]
Ceramic membrane with mixed materials	Domestic wastewater	Dual chamber	Current density 1535.0 ± 29 mW/m2	96.6%	[1]
Earthen membrane using Kalporgan soil and SiO2	Domestic wastewater	Dual chamber	Current density 769.23 mW/m2	85.8%	[1]
Earthen red soil membrane with bentonite	Kitchen waste slurry/leachate	Dual chamber	Current density 52 mW/m2; oxygen transfer 9.33 × 10^-4	98.41%	[1]
Clayware membrane with bentonite clay	Sewage	Dual chamber	Power density 15.38 mW/m3; current density 38.46 mW/m2	Not reported	[1]

For heavy metal removal, membrane-based systems such as NF and RO show high metal rejection. NF can remove Cu(II), Cd(II), Cr(VI), Pb(II), Ni(II), and As(V), with many reported values above 90%. RO often reaches very high removal efficiencies for Cu(II), Pb(II), Ni(II), Cd(II), Cr(VI), Mn, and Zn(II), although it has higher pressure and energy demands [2], [13], [14].

TABLE VI. SELECTED HEAVY METAL REMOVAL PERFORMANCE BY MEMBRANE PROCESSES [2], [13], [14]

Process	Metal examples	Reported removal range/examples	Main concern
NF	Cu(II), Cd(II), Cr(VI), Pb(II), Ni(II), As(V)	Commonly high; many examples 88-99.7%	Fouling and membrane-charge dependence
RO	Cu(II), As(III), As(V), Pb(II), Ni(II), Cd(II), Cr(VI), Mn, Zn(II)	Often about 94-99.9% depending on metal and membrane	High pressure and energy demand
MEUF	Pb(II), Ni(II), Cd(II), Cr species	High removal reported for several metals, especially with suitable surfactants	Surfactant recovery and secondary pollution
PEUF	Cu(II), Ni(II), Cd(II), Cr(VI), Cr(III)	Several reported removals near or above 99%	Polymer recovery and complexation control

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IX. INTEGRATION OF BIOELECTROACTIVE MEMBRANES WITH HEAVY METAL REMOVAL

The integration of MFCs with membrane-based heavy metal removal can occur in several ways. First, the membrane separator inside the MFC controls proton and ion migration, thereby influencing electrochemical performance. Secondly, the biofilm-electrode system can promote the redox transformation of pollutants. Third, membrane filtration can be added before or after MFC treatment for removing metals, colloids, organic matter and other contaminants. Fourth, membrane materials can be modified for improved selectivity, antifouling behavior, and stability under real wastewater conditions [1], [2], [4].

Bioelectroactive membrane systems are particularly attractive as they can combine heavy metal removal and organic wastewater treatment with energy recovery. In the anode chamber, organic contaminants function as electron donors, whereas in the cathode, metal ions or oxygen related reactions can be involved depending on the configuration. Such integration can reduce treatment cost and improve sustainability, but practical implementation requires optimization of pH, conductivity, membrane material, electrode material, metal concentration, and microbial community [1], [2], [3].

TABLE VII. ROLE OF MEMBRANE COMPONENTS IN BIOELECTROACTIVE HEAVY METAL TREATMENT [1], [2], [4], [11]

Component	Function	Importance for heavy metal removal
Anode biofilm	Microbial oxidation of organic matter and electron release	Provides electrons and supports wastewater treatment
External circuit	Transfers electrons from anode to cathode	Enables electrochemical reduction pathways
Membrane/separator	Allows ion/proton transport and separates chambers	Controls internal resistance, crossover and selectivity
Cathode	Supports reduction reactions such as ORR or pollutant reduction	May support metal reduction or precipitation depending on conditions
Membrane modification	Changes surface charge, hydrophilicity and fouling resistance	Improves stability and separation efficiency
Post-treatment membrane	NF/RO/UF polishing after bioelectrochemical treatment	Improves final heavy metal removal and water quality

X. FOULING AND SURFACE MODIFICATION

Fouling is one of the major barriers to membrane application in heavy metal removal and MFC operation. It occurs when dissolved or suspended solids, organic compounds, precipitates, microorganisms, or salts accumulate on the membrane surface or inside the membrane pores. Fouling causes decrease in water flux, increase in internal resistance, decrease in separation efficiency, increase in operating cost and decrease in membrane lifetime [2], [11].

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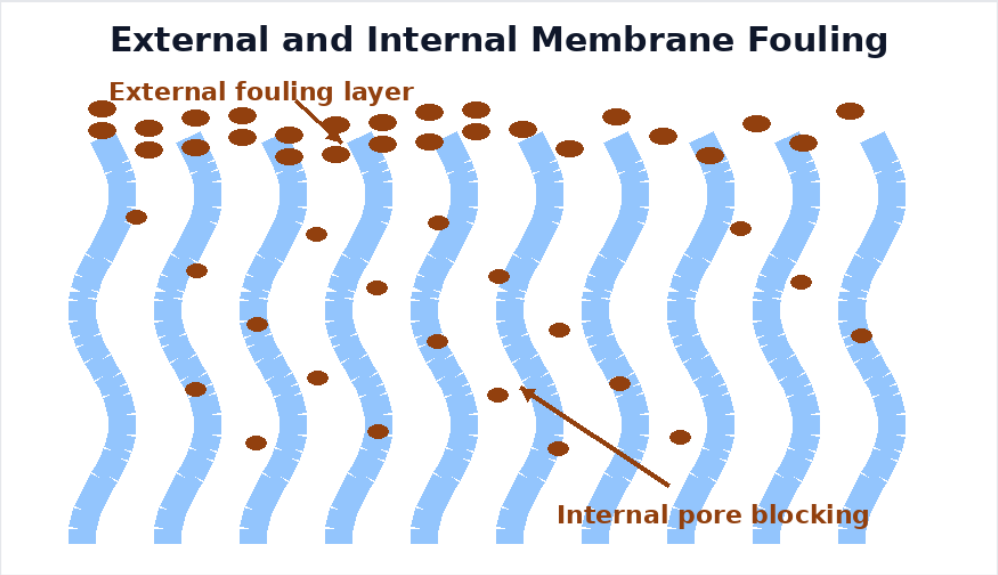

Fig. 13. Schematic showing external and internal fouling of membranes. Redrawn for this paper based on Dawam et al. [2].

Surface modification is applied for antifouling resistance, selectivity and durability enhancement. Two general strategies are often mentioned: coating the membrane surface with a thin film and grafting polymer chains on the membrane surface . Nanomaterials, hydrophilic coatings, charged polymers and composite layers can also be employed to enhance membrane performance [2], [11], [12].

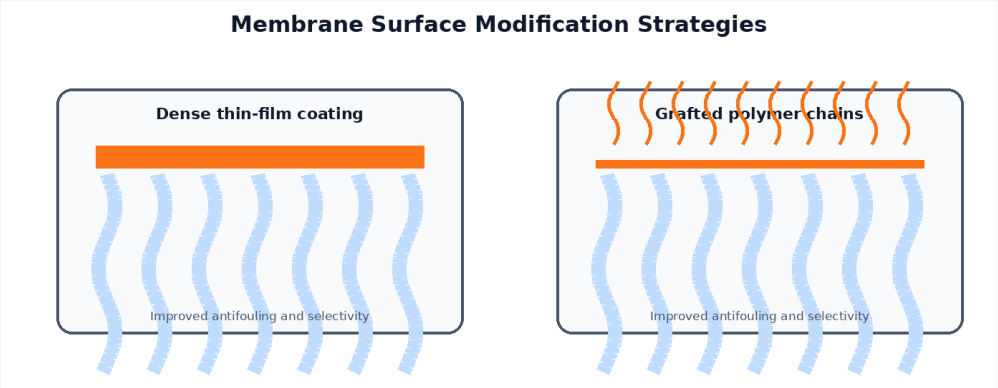

Fig. 14. Membrane surface modification by dense film coating and grafted polymer chains. Redrawn for this paper based on Dawam et al. [2].

TABLE VIII FOULING CHALLENGES AND CONTROL STRATEGIES [1], [2], [11], [12]

Problem	Systemic effect	Control strategy
2. Organic fouling	Drop in flux and higher resistance	Pretreatment and cleaning hydrophilic modification
Biofouling	Growth of biofilm and reduced ion transport	Surface modification and controlled operation and periodic cleaning
Inorganic fouling/scaling	Blocking of pores and build-up of pressure	pH control, antiscalants and pre-treatment
Metal membrane precipitation	Lower selectivity and permeability.	Speciation control and choosing the right membrane

IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

Impact Factor 8.311 ⁜ Peer-reviewed & Refereed journal ⁜ Vol. 12, Issue 8, August 2025

DOI: 10.17148/IARJSET.2025.12848

Oxygen cross-over in MFCs	Loss of anaerobic conditions at anode	Optimized separator material and chamber design
High internal resistance	Lower power density	Thinner membranes and greater proton conductivity

XI. RESEARCH GAPS AND CHALLENGES

Despite strong potential, bioelectroactive membrane systems face several research and scale-up challenges. The first challenge is cost. Commercial proton exchange membranes are effective but expensive, and membrane expenses can form a large portion of MFC capital cost. Low-cost ceramic, clayware, and earthen membranes are promising, but their reproducibility, pore-size control, mechanical stability, and long-term chemical durability need improvement [1], [4]-[6].

The second challenge is treating real wastewater. Many studies on membrane and bioelectrochemical processes use synthetic or controlled wastewater, whereas real industrial effluents contain mixed metals, salts, organics, suspended solids, oils, pH variation and competing ions. These factors influence metal speciation, membrane fouling, microbial activity and removal efficiency [2].

The third challenge is the joint optimization of treatment and electricity production. Conditions that improve metal removal may not always maximize power density, and conditions that improve microbial activity may not be ideal for metal precipitation or membrane selectivity. Therefore, design must balance removal efficiency, current density, power density, internal resistance, fouling, cost, and operational stability [1], [2].

TABLE IX. RESEARCH GAPS AND FUTURE NEEDS [1], [2], [4], [11]

Research gap	Future need
High cost of commercial PEMs	Develop low-cost ceramic, clayware, earthen and composite membranes
Membrane fouling	Use antifouling coatings, grafting and pretreatment
Limited real-wastewater validation	Test mixed industrial effluents containing metals and organics
Material variability in earthen membranes	Improve processing, pore control and durability
Scale-up of MFC systems	Develop modular reactors with low internal resistance
Metal recovery	Design systems that recover rather than only remove metals
Energy-treatment balance	Optimize both power output and pollutant removal
Long-term operation	Study ageing, clogging, biofilm development and maintenance

XII. FUTURE PERSPECTIVES

Future research should focus on membranes that are low-cost, durable, easy to fabricate, resistant to fouling, and capable of stable ion transfer. Ceramic and earthen membranes are promising because they can reduce cost and use locally available materials, but their mechanical strength and chemical resistance must be improved for long-term use [1], [17]-[20].

Bioelectroactive composite membranes can be made from polymers, ceramics, carbon-based materials and natural substances. Such membranes can offer controlled pore size, increased proton conductivity, low oxygen crossover, selective heavy metal capture and improved biofilm compatibility. Surface modification and nanomaterial addition could enhance fouling resistance and heavy metal selectivity [2], [11], [12].

Another future direction is the coupling of MFCs with membrane filtration steps such as NF, RO, MEUF or PEUF. In these hybrid systems, MFCs can reduce organic load and generate electricity, and membrane polishing can remove

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DOI: 10.17148/IARJSET.2025.12848

dissolved metals and remaining contaminants. This integrated treatment train could be of special interest in the treatment of industrial wastewaters containing both organic pollutants and heavy metals [1], [2].

XIII. CONCLUSION

Heavy metal contamination in wastewater is a critical problem because metals are toxic, persistent, and difficult to degrade. Conventional treatment methods can reduce metal concentration, but they often involve limitations such as sludge generation, incomplete removal, sensitivity to pH, high chemical demand, or regeneration problems. Membrane based methods are more selective and compact in operation. NF, RO, MEUF and PEUF are found to have high potential for heavy metal removal.

Microbial fuel cells (MFCs) provide an alternative aspect to wastewater treatment by enabling simultaneous degradation of pollutants and bioelectricity generation . The membrane or separator in an MFC is essential to the proton transfer, chamber separation, oxygen control and internal resistance reduction. Bioelectroactive membrane systems can achieve heavy metal removal, organic wastewater treatment, energy recovery and resource recovery when microbial electrochemical activity is coupled with membrane separation.

According to literature review, ceramic, clayware, earthen and composite membranes could be low cost alternative to conventional proton exchange membranes. The ceramic membranes show good performance in terms of power density, current density and COD removal. Earthy materials such as red soil, bentonite and Kalporgan soil offer sustainable and economical options toward the development of MFC separators. But fouling, oxygen crossover, mechanical weakness, material variability and scale up cost still remain important barriers.

In general, bioelectroactive membranes are a promising approach for sustainable treatment of heavy metal wastewater. Future work should focus on real industrial wastewater, membrane durability, antifouling design, selective metal recovery, low-cost fabrication, hybrid MFC-membrane treatment trains, and long-term field operation.

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Figure use note: Figures are newly redrawn schematic illustrations for this review and are based on the concepts discussed in source papers [1] and [2].