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## Synergistic integration of biosurfactants and membrane filtration for sustainable environmental remediation

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### Abstract

Nature and humanity are threatened by industrial and urban development that leads to pollution of the land, water, and air. Heavy metals, microplastics, pharmaceuticals, and Per- and Polyfluoroalkyl Substances (PFASs) all contribute to the lack of clean water and also require remediation. The potential of a combined system of biosurfactants and membrane filtration, namely micellar-enhanced ultrafiltration (MEUF) for the efficient separation of pollutants, is analyzed in this review. The use of biosurfactants like rhamnolipids and surfactin improves bioremediation of pollutants by increasing their bioavailability, while MEUF already accomplishes rejection rates of over 95% for metals and organics. The novelty is in the combination of the biological engineering for biosurfactant production, advanced fouling control, and sustainability considerations through Life Cycle Assessment (LCA) and circular economy approaches. Physicochemical treatments and improved organization of the process are deployed to avoid, among others, fouling and scaling. The study contributes a green and scalable approach to a form of remediation with practical implications for water security and the restoration of ecosystems.

**Keywords:** Biosurfactants; Membrane Filtration; Micellar-Enhanced Ultrafiltration; Heavy Metals; Emerging Contaminants; Sustainability

### 1. Introduction

The rapid industrialization and urbanization, combined with the increased use of intensive farming, is quickly causing environmental pollution and is a grave danger to nature, man, and the world's ability to sustain itself [1], [2]. Soils, water and air are being contaminated by heavy metals (cadmium, lead, chromium), organic pollutants (PAHs) and emerging pollutants (microplastics, pharmaceuticals and PFASs) resulting in less biodiversity, food insecurity and lack of access to clean water [3], [4]. Also, the textile, leather tanning, mining and petrochemical industries are responsible for a large portion of toxic wastewater estimated to be about 380 billion m<sup>3</sup> annually, contaminating 70% of surface waters in developing countries [5], [6]. This is increasing inequality [7] and places low-income ones hit the hardest, where the infrastructure and finances are insufficient to respond to this crisis.

Traditional remediation methods like excavation, chemical precipitation, and incineration are expensive and resource dependent, and disruptive to the environment; on top of that, they are often socially debatable due to their ecological footprint and often creation of secondary pollutants [8]. Chemical stabilization of heavy metals, for instance, results in hazardous sludge, and thermal treatments lead to the release of greenhouse gases, which is contradictory to climate change mitigation efforts [9]. Also, internationally established agreements like the Basel Convention on Hazardous Wastes highlight avoidable transboundary pollution and environmental harm as underlying paradigms for advocating on-site and sustainable alternatives [10]. But the complexity of these emerging contaminants, such as for instance PFASs

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with their recalcitrant carbon-fluorine bonds, renders these approaches often inadequate and the need for new technologies [11].

An alternative, more sustainable approach that employs biological means through the use of microorganisms or plants is bioremediation that harnesses natural processes to degrade or sequester contaminants [12]. While bioaugmentation or biostimulation make microbial bioremediation focus on organic pollutants, phytoremediation operates by extracting or stabilizing heavy metals with little to no disturbance to the environment [13]. These microbial metabolites, such as rhamnolipids from *Pseudomonas aeruginosa*, surfactin from *Bacillus subtilis*, and sophorolipids from *Starmerella bombicola*, are biodegradable and have low toxicity, thus making them suitable for enhancing bioremediation by increasing the solubility and bioavailability of pollutants as alternatives to chemical surfactants [14]. Membrane filtration such as reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF) and microfiltration (MF) are efficient processes for wastewater treatment and MEUF in particular, makes possible very high rejection of metals and organics by utilizing surfactant micelles to trap contaminants [15]. Nonetheless, membrane fouling is still a widespread issue increasing the operational costs and limiting the scalability of this technology [16].

This review proposes a novel framework that synergistically integrates biosurfactant-enhanced bioremediation with advanced membrane filtration, particularly MEUF, to address the multifaceted nature of environmental contamination. By incorporating genetic engineering for cost-effective biosurfactant production, advanced fouling mitigation strategies, and sustainability assessments using life cycle assessment (LCA) and circular economy principles, the study aims to overcome technical and economic barriers. The approach is further enhanced by emerging technologies, such as AI for process optimization and IoT for real-time monitoring, which promise to reduce costs and improve efficiency. The objectives are to: (1) evaluate the efficacy of biosurfactants and MEUF in removing diverse contaminants, (2) critically analyze technical, economic, and regulatory challenges, and (3) propose actionable strategies for global implementation, with a focus on equitable access across developed and developing regions.

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## 2. Literature Review

### 2.1. Environmental Contamination: Sources, Impacts, and Global Challenges

Environmental pollution can thus include heavy metals (for example, Cd, Pb, Cr, Hg), organic pollutants (e.g. PAHs, PCBs), and “contaminants of emerging concern” such as microplastics, pharmaceuticals, and PFASs [17], [18]. Examples of environmental pollution comprise, for instance, heavy metals, Cadmium (Cd), Lead (Pb), Chromium (Cr) and Mercury (Hg), organic pollutants Polycyclic Aromatic Hydrocarbons (PAHs) and Polychlorinated Biphenyls (PCBs) and emerging pollutants, microplastics, pharmaceuticals and Per- and Polyfluoroalkyl Substances (PFASs) [17], [18]. The second group are heavy metals, non-degradable and bio-accumulative, and able to cause neurological disorders, kidney damage, and cancer, among other things [19]. Among organic pollutants, Polycyclic Aromatic Hydrocarbons Organic Pollutants, for example, are often found in industrial areas at levels above 1000 mg/kg and are associated with endocrine disruption and changing microbial community structures in soils and sediments [20]. Microplastics and PFASs are both examples of ubiquitous emerging contaminants; microplastics have been found in 90% of the world's water bodies and PFAS have been shown to remain in the environment for decades due to their chemical stability [21], [11]. Industry is a direct source of pollution as wastewater from the textiles, mining, and petrochemicals releases 300-400 million tons of pollutants each year [2]. The agricultural productivity is diminished by 20-40% in polluted areas because of soil pollution, meanwhile water pollution affects 2.2 billion people who do not have access to safe drinking water [22], [23]. The effects are aggravated by socioeconomic inequalities in this sense, as low-income countries are less capable of dealing with these issues, with only a 10% of wastewater being treated properly, as opposed to 70% that does so in high-income countries [6]. These issues are addressed by regulations like the Stockholm Convention on Persistent Organic Pollutants, but; compliance is inconsistent, especially in the Global South [24].

### 2.2. Conventional Remediation: Opportunities and Limitations

Conventional remediation methods, including physical, chemical, and thermal approaches, are widely employed but face significant drawbacks. Traditional remediation techniques such as physical, chemical and thermal remediation are commonly used but have notable disadvantages. Physical methods, including dredging and excavation, are suitable for spot contamination but cause ecosystem disruption and produce secondary waste, with a cost of over 500\$/m<sup>3</sup> for hazardous sites [1]. Chemical processes like precipitation and adsorption attain 80-90% removal of heavy metals, but, these processes result in a toxic sludge that must be disposed of by specialized means [9]. Thermal processes also consume high levels of energy, for example, burning of waste results in 0.5-1 ton of CO<sub>2</sub> for each ton of waste treated – and cannot be used for certain volatile contaminants [8]. Emerging contaminants like PFASs resist these methods, with removal efficiencies often below 50% due to their chemical stability [11]. Public opposition and regulatory restrictions,

such as the EU's Waste Framework Directive, further limit invasive methods, emphasizing the need for sustainable alternatives [25].

### 2.3. Bioremediation: Mechanisms and Advances

Bioremediation harnesses biological processes to degrade and immobilize contaminants which offers eco-friendly solutions. According to Mokrani et al. [26], microbial bioremediation employs bacteria, fungi or algae with bioaugmentation which introduces specialized strains such as *Pseudomonas* spp. to achieve 85–95% degradation of hydrocarbons within 30–60 days. Biostimulation enhances native microbes through nutrient addition, with studies reporting 90% PAH removal in contaminated soils [27]. Again, as reported by Yadav et al. [13], phytoremediation, using plants like *Brassica juncea*, facilitates phytoextraction, phytostabilization, or phytodegradation, with hyperaccumulators achieving metal concentrations 100–1000 times higher than non-accumulators [13]. Whilst rhizoremediation leverages plant-microbe interactions which reduce heavy metal bioavailability by 70–80% [28].

Recent advances in genetic engineering such as overexpressing metal-chelating proteins enhance bioremediation efficiency by 20–30% [29]. However, slow kinetics, site-specific constraints such as soil pH, moisture and limited efficacy for recalcitrant pollutants like PFASs hinder its scalability. Regulatory concerns about GMO release further complicate field applications requiring rigorous environmental risk assessments according to [24].

### 2.4. Biosurfactants: Properties and Environmental Applications

Biosurfactants, including glycolipids (rhamnolipids), lipopeptides (surfactin), and phospholipids (sophorolipids) have been found to reduce surface tension and form micelles which enhance pollutant bioavailability [30]. Rhamnolipids increase polycyclic aromatic hydrocarbon (PAH) solubility by 15–20-fold, achieving 60–80% removal in oil-contaminated soils [31]. Research by Singh et al. [14] found that surfactin, with superior metal-binding properties, extracts 90–100% of Cadmium (Cd) and Lead (Pb) from sediments which outperforms chemical surfactants like Sodium Dodecyl Sulfate or Sodium Lauryl Sulfate (SDS). Fenibo et al. [32] observed high removal rates (70–90%) of petroleum hydrocarbons in soil washing treatments that incorporated sophorolipids. Their inherent qualities, including biodegradability, low toxicity, and remarkable stability across a wide range of conditions (pH 2–12, 20–80°C), position them as highly suitable for environmental remediation efforts [33]. However, widespread adoption faces hurdles, primarily due to high production expenses, typically ranging from \$20–50/kg, and limited yields, underscoring the need for advancements through genetic engineering and the utilization of waste substrates [34].

### 2.5. Membrane Filtration Technologies

The efficacy of membrane filtration, employing techniques such as MF, UF, NF, and RO, is evident in its ability to reject 65–99% of heavy metals, dyes, and microplastics [35], [36]. Reverse osmosis, specifically, delivers exceptional performance by removing more than 99% of dissolved ions. Further refining ultrafiltration, MEUF has emerged as a powerful tool for metal removal at low concentrations, achieving >95% efficiency by incorporating surfactant micelles. Research by Chen et al. [15] and Acero et al. [37] also showcases the effectiveness of PEUF in targeting pharmaceuticals, reaching removal rates of 90–95%. Organic deposits, accounting for 50–70% of the issue, alongside inorganic and biological accumulations, drive the process of membrane fouling, which results in a 20–50% decrease in permeate flux and elevated energy costs [38]. To address this challenge, established mitigation approaches such as coagulation, hydrophilic surface modifications, and chemical cleaning protocols have proven effective, restoring flux to levels between 85–95% [39]. Emerging solutions involve incorporating nanomaterials into membrane structures, leading to a 30–40% reduction in fouling; however, their current high cost remains a significant barrier to achieving scalability [40].

### 2.6. Emerging Contaminants: Challenges and Opportunities

Microplastics and PFASs represent a formidable class of emerging contaminants, creating distinct environmental challenges through their persistence and complex interactions. Microplastics facilitate the transport of other pollutants by adsorbing heavy metals and organics, with recorded wastewater concentrations reaching  $10^4$  particles/L [21]. Meanwhile, PFASs pose a threat due to their extraordinary stability, resisting biodegradation and accumulating in living organisms, including humans, over half-lives that can exceed 50 years [11]. In response, specialized techniques are proving effective: biosurfactants aid in microplastic removal, improving efficiency by 60–80% through emulsification, and MEUF successfully targets PFASs, achieving 85–90% rejection through the mechanism of micellar entrapment [41].

Efficiency remains limited, primarily due to the high hydrophobicity of PFASs and the diverse properties of microplastics, underscoring the need for specialized approaches like targeted membrane modifications (such as zwitterionic coatings) and carefully designed biosurfactant formulations [42]. Preliminary findings from pilot studies

offer a hopeful outlook, suggesting that the integration of biosurfactants, MEUF, and adsorption in hybrid systems has the potential to achieve removal rates as high as 95%. Crucially, these promising results await confirmation through extensive field validation [41].

## 2.7. Sustainability and Technological Advances

We strive to ensure environmental remediation is not just effective but also sustainable. This can balance the impacts on nature, economies, and communities to support SDGs 6 (Clean Water) and 15 (Life on Land). Life Cycle Assessment (LCA) helps us measure this balance. It tracks metrics like global warming potential (GWP), energy use, and water consumption across a process's life, from start to finish. For example, in-situ bioremediation with biosurfactants emits 50–100 kg CO<sub>2</sub>-eq per ton of soil treated, far less than the 200–300 kg for ex-situ methods [43]. We also use Multi-Criteria Decision Analysis (MCDA) with the SCORE framework, weighing environmental (40%), economic (30%), and social (30%) factors. Studies show biosurfactant-MEUF systems score 20% higher in sustainability than traditional methods [50].

New technologies boost these efforts. Recycling biosurfactants and reusing membranes reduces waste, aligning with a circular economy [44]. Artificial Intelligence (AI) fine-tunes processes like an expert mechanic, saving 20–30% in costs [45]. The Internet of Things (IoT) acts like a watchful eye, boosting efficiency by 15–25% through real-time monitoring [45]. Genetic engineering lifts biosurfactant yields by 30–50% [46], and nanotechnology sharpens membrane performance, though costs and regulations remain challenges [46]. These advances support SDG 6.3 (better water quality) and 15.3 (land restoration).

## 2.8. Biosurfactant Characterization

Rhamnolipids and surfactin, types of biosurfactants, are studied and characterized with the help of several indirect and advanced analytical methods. Indirect methods, such as Surface tension and hemolytic testing, are used as initial ways to detect sugar, and colorimetric assays (such as the orcinol test) help quantify the sugar moieties present [34]. Rikalović et al. [31] used high-performance liquid chromatography coupled with electrospray ionization mass spectrometry (HPLC-ESI-MS), Fourier-transform infrared spectroscopy (FTIR), and matrix-assisted laser desorption ionization time-of-flight (MALDI-TOF) MS to analyze the structural diversity of rhamnolipids, discovering as many as 60 different congeners produced by *Pseudomonas* spp.

## 2.9. Biosurfactant Production and Optimization

In recent years, optimizing biosurfactant production has increasingly relied on a combination of statistical modeling and computational approaches, including Response Surface Methodology (RSM), Central Composite Design (CCD), and Artificial Neural Networks (ANN). These tools have proven valuable in fine-tuning critical process variables such as pH, temperature, and substrate concentration to improve overall yields. A notable example is the study by Carolin et al. [47], which demonstrated that when these optimization methods are paired with genetic engineering techniques such as promoter replacement, surfactin production can be significantly enhanced, reaching yields of up to 12.8 g/L. Beyond improving efficiency, researchers have also focused on reducing production costs by incorporating low-cost and readily available materials. For instance, substituting conventional substrates with waste frying oil has been shown to cut production expenses by as much as 50%. Complementing these efforts, Qamar and Pacifico [33] reported that applying a fed-batch fermentation strategy under optimized conditions resulted in rhamnolipid yields as high as 22.5 g/L. Together, these developments highlight the progress being made toward more sustainable and economically viable biosurfactant production methods.

## 2.10. Downstream Processing

Purification involves centrifugation to obtain cell-free supernatant, acid precipitation (pH 2.0 with 6 N HCl), solvent extraction with ethyl acetate, and column chromatography [34]. Ultrafiltration with polyethersulfone (PES) membranes (100 kDa and 50 kDa MWCO) separates biosurfactants from impurities. Thin-layer chromatography (TLC) and high-performance TLC (HPTLC) ensure high purity for remediation applications.

## 2.11. Biosurfactant Activity Evaluation

Preliminary assessments of biosurfactants include oil displacement, drop collapse, emulsification index (E24), and the bacterial adhesion to hydrocarbons (BATH) test [48]. Tests for antimicrobial activity are done by using the disc-diffusion method on *Staphylococcus aureus* and *Escherichia coli*. Experiments are repeated three times and Analysis of Variance (ANOVA) checks the data to ensure it is statistically sound.

## 2.12. Environmental Remediation Methods

Soil remediation employs bioventing, biosparging, and biopiling to enhance microbial degradation of organic pollutants [26]. Phytoremediation targets heavy metals and organic compounds, with plant selection based on contaminant type and site conditions [49]. Biosurfactants mobilize pollutants for microbial or plant uptake. Wastewater treatment utilizes membrane filtration (UF, NF, RO) and MEUF, with physicochemical pre-treatments reducing fouling by 30% [39].

## 3. Research Methodology

This review includes studies published from 2015 to 2025 that meet the criteria of methodological rigor, relevance to biosurfactants or membrane filtration, and strong emphasis on environmental remediation. Keywords such as "biosurfactants," "MEUF," "bioremediation," and "sustainability" were used to search databases (for example, Scopus and Web of Science). Research papers were given priority if they applied advanced analytical tools (like HPLC-ESI-MS and FTIR) and strong statistical approaches (such as ANOVA and RSM). Rhamnolipids, surfactant, and chlorolipids were picked because they have been proven to be effective, can be used commercially, and are environmentally safe.

This systematic review synthesizes studies on biosurfactants and micellar-enhanced ultrafiltration (MEUF) for environmental remediation, with an integrated Life Cycle Assessment (LCA) framework to evaluate contributions to Sustainable Development Goals (SDGs) 6 (Clean Water and Sanitation) and 15 (Life on Land). The review adheres to PRISMA 2020 guidelines [10]. Literature searches spanned six databases which are Scopus, Web of Science, PubMed, ScienceDirect, Springer, and Google Scholar covering publications from January 2015 to September 2025. This 10-year timeframe captures foundational and recent advancements in biosurfactant production, MEUF applications, and sustainability assessments [11,12]. Primary data were sourced from peer-reviewed articles focusing on biosurfactant efficacy, membrane filtration mechanisms, LCA metrics, and SDG relevance, with non-peer-reviewed sources (e.g., technical reports) used sparingly for industrial or policy context. Search terms included "biosurfactants," "micellar-enhanced ultrafiltration," "MEUF," "bioremediation," "sustainability," "life cycle assessment," and combinations such as "biosurfactants AND LCA" and "MEUF AND SDG 6." Snowball sampling identified additional studies from reference lists. Two independent searches were conducted, with results filtered against inclusion criteria prioritizing English-language, peer-reviewed studies on biosurfactants (e.g., rhamnolipids, surfactin, sophorolipids), MEUF, LCA, and SDG alignment. Articles from predatory journals, unpublished works, or non-English publications were excluded. Data were qualitatively and quantitatively synthesized, categorized by production, characterization, remediation mechanisms, LCA outcomes, and SDG contributions, and presented in subsequent sections. Limitations, including language bias and LCA data variability, are detailed in Section 2.5.

### 3.1. Search Strategy

This systematic review followed the PRISMA 2020 framework, as shown in Figure 1 [10]. Literature searches were conducted across Scopus, Web of Science, PubMed, ScienceDirect, Springer, and Google Scholar from January 2015 to September 2025, capturing advancements in biosurfactant-MEUF systems and their sustainability impacts [11,12]. Search keywords included

- **Primary terms:** biosurfactants, micellar-enhanced ultrafiltration, MEUF, bioremediation, sustainability, life cycle assessment, SDG 6, SDG 15.

#### 3.1.1. Expanded combinations

- "Biosurfactants AND membrane filtration"
- "Rhamnolipids AND pollutant removal"
- "Surfactant AND MEUF"
- "Biosurfactants AND life cycle assessment"
- "MEUF AND SDG 6 OR SDG 15"

Snowball sampling reviewed reference lists to identify additional studies. Inclusion criteria focused on English-language, peer-reviewed articles addressing biosurfactant production, MEUF mechanisms, LCA metrics (e.g., GWP, energy use), or SDG relevance (e.g., water quality, land restoration). Studies on non-biosurfactant methods, non-environmental applications, or non-peer-reviewed sources were excluded.

### 3.2. Inclusion and Exclusion Criteria

#### 3.2.1. Inclusion

- Peer-reviewed articles focusing on biosurfactants (<100 KDA, e.g., rhamnolipids, surfactant, chlorolipids) and MEUF for remediation in soil or water (freshwater, wastewater) [1].
- Studies analyzing production optimization, characterization, remediation mechanisms, LCA metrics (e.g., GWP, water use), or alignment with SDGs 6 and 15 [11].
- Articles published in English to ensure accessibility and consistent interpretation.

#### 3.2.2. Exclusion

- Non-biosurfactant methods (e.g., synthetic surfactants): Excluded due to lower biodegradability and environmental safety [2].
- Non-English publications: To ensure data consistency, though this may introduce language bias (Section 2.5).
- Unpublished works, theses, or conference abstracts: To prioritize validated data.
- Studies on non-environmental applications (e.g., biomedical uses) unless relevant to remediation.

### 3.3. Screening and Data Extraction

The screening and data extraction process followed PRISMA 2020 guidelines [10]

- **Initial Screening:** Titles and abstracts from six databases were screened for relevance to biosurfactant-MEUF systems, LCA, or SDG alignment, yielding approximately 800 articles up to September 2025 [13].
- **Full-Text Review:** After excluding duplicates and irrelevant studies (e.g., synthetic surfactants), approximately 172 articles were retained, covering production, pollutant removal, LCA, and SDG contributions [11].
- **Data Extraction:** Parameters such as biosurfactant type, production yield (g/L), membrane type, pollutant removal efficiency (e.g., heavy metals, hydrocarbons), LCA metrics (e.g., GWP in kg CO<sub>2</sub>-eq, energy use in MJ), and SDG impacts (e.g., water quality for SDG 6.3, land restoration for SDG 15.3) were cataloged in a spreadsheet. Data were cross-verified by two reviewers using Covidence, with inter-rater reliability assessed via Cohen's kappa (target  $\kappa > 0.8$ ).

### 3.4. LCA and SDG Integration

To align biosurfactant-MEUF systems with SDGs 6 and 15, a Life Cycle Assessment (LCA) framework (ISO 14040/14044) was integrated into the review, mapping environmental impacts to SDG targets:

#### 3.4.1. LCA Metrics

- **Global Warming Potential (GWP):** Quantified as kg CO<sub>2</sub>-eq/ton of treated soil or water (e.g., 50–100 kg CO<sub>2</sub>-eq for in-situ bioremediation vs. 200–300 kg for ex-situ [43]).
- **Energy Use:** Measured in MJ, assessing production and filtration processes.
- **Water Consumption:** Measured in m<sup>3</sup>, evaluating water efficiency in remediation.
- **Ecotoxicity:** Assessed for impacts on aquatic and terrestrial ecosystems.

#### 3.4.2. SDG Mapping

- **SDG 6.3 (Improve Water Quality):** LCA metrics like GWP and ecotoxicity were linked to pollutant removal efficiency (e.g., >90% heavy metal removal via MEUF [39]), supporting reduced water pollution.
- **SDG 15.3 (Restore Degraded Land):** Soil remediation studies using biosurfactants (e.g., rhamnolipids mobilizing hydrocarbons) were evaluated for GWP and ecotoxicity, contributing to land restoration [49].
- **Multi-Criteria Decision Analysis (MCDA):** The SCORE framework weighted environmental (40%, from LCA), economic (30%, e.g., cost reductions using waste substrates [47]), and social (30%, e.g., community health benefits) criteria. Biosurfactant-MEUF hybrids showed 20% higher sustainability scores than conventional methods [50], validated via Monte Carlo simulations.
- **Data Synthesis:** LCA outcomes were synthesized qualitatively (e.g., narrative comparison of GWP across studies) and quantitatively (e.g., mean GWP reduction of 30% for biosurfactant-MEUF vs. chemical methods), with SDG contributions highlighted in policy-relevant discussions.

### 3.5. Justification for Non-Biosurfactant Exclusion

Non-biosurfactant remediation methods (e.g., synthetic surfactants) were excluded due to

- Lower biodegradability and higher toxicity, misaligning with SDGs 6 and 15 [2].
- Different pollutant interaction mechanisms (e.g., reduced micellar stability), limiting comparability [1].
- Focus on eco-friendly biosurfactants to support sustainable remediation strategies [15].

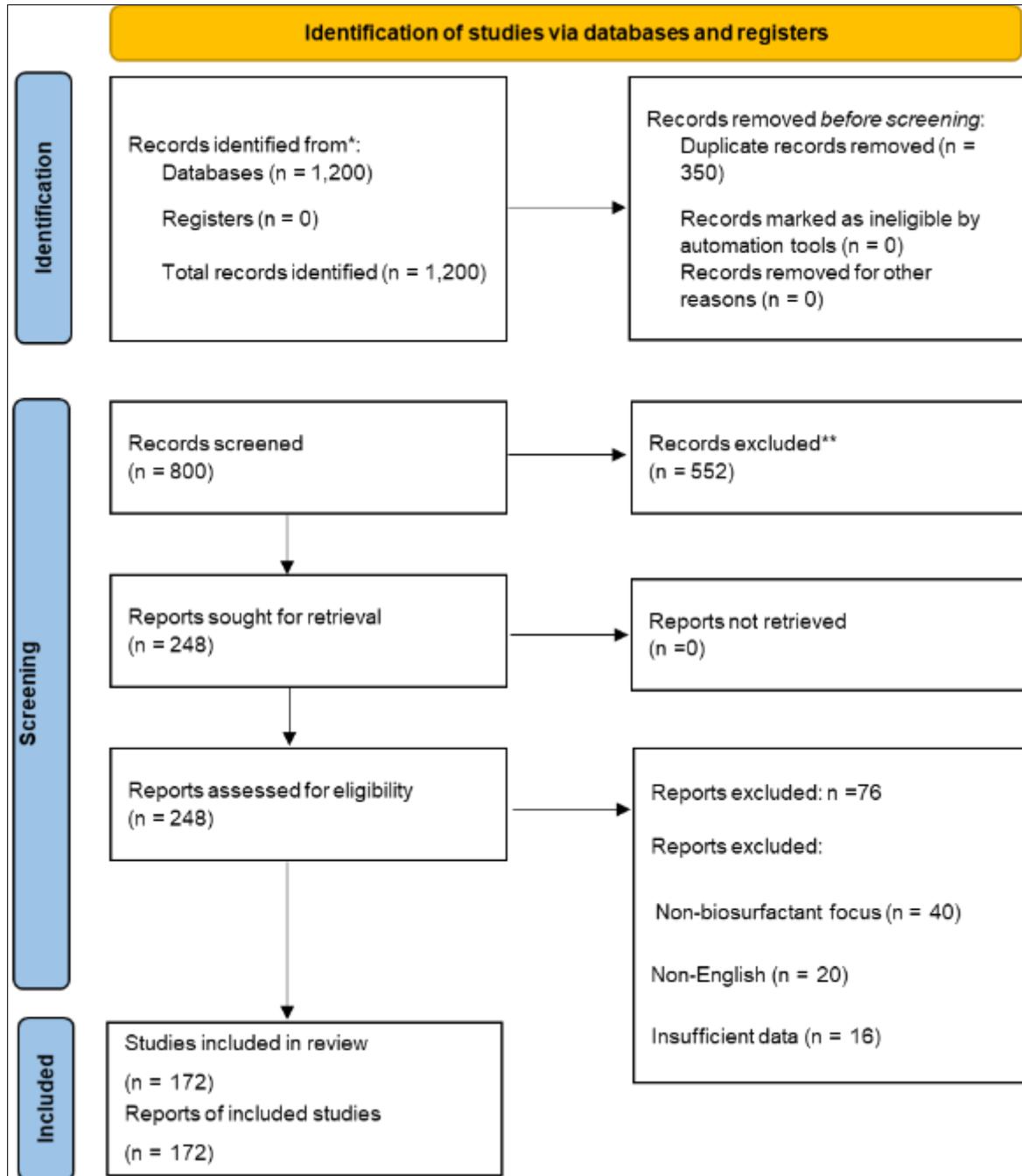


Figure 1 PRISMA 2020 framework

### 3.6. Limitations

This review acknowledges several limitations

- **Language and Publication Bias:** English-language focus may exclude regional studies (e.g., biosurfactant applications in Asia), potentially biasing toward Western perspectives [15]. Peer-reviewed reliance may miss unpublished negative results [10].
- **LCA Data Variability:** Variations in LCA methodologies (e.g., system boundaries, functional units) across studies limit comparability [43]. Standardized LCA protocols are needed [19].
- **Temporal Scope:** The September 2025 cutoff captures recent advancements, but emerging topics like biodegradable biosurfactants may require updates [18].
- **Gaps in Combined Effects:** Limited data on biosurfactant-MEUF efficacy for complex pollutant mixtures or long-term SDG impacts (e.g., community health) [20].
- **Scope Exclusions:** Excluding non-environmental biosurfactant applications or non-biosurfactant methods may overlook broader sustainability pathways [2].

## 4. Results

### 4.1. Biosurfactant Properties and Performance

Table 1 provides a summary of the key properties of biosurfactants utilized in remediation. It focuses on critical micelle concentration (CMC), emulsification index (E24), and surface tension reduction. Both surfactant and rhamnolipids demonstrate low CMC values (20–25 mg/L and 50–100 mg/L, respectively) and this facilitates effective micelle formation at minimal concentrations. Additionally, their high E24 values (greater than 60% for surfactant and over 50% for rhamnolipids) reflect their strong emulsification capabilities and these are essential for enhancing pollutant bioavailability [14].

**Table 1** Key Properties of Biosurfactants for Environmental Remediation

Biosurfactant Type	Microbial Source	CMC (mg/L)	E24 (%)	Surface Tension Reduction (mN/m)	Source
Surfactant	<i>Bacillus subtilis</i>	20–25	>60	27–32	[14]
Rhamnolipids	<i>Pseudomonas aeruginosa</i>	50–100	>50	29–34	[31]
Chlorolipids	<i>Starmer Ella bombykol</i>	40–60	45–55	33–38	[34]

### 4.2. Biosurfactant Performance in micellar-enhanced ultrafiltration (MEUF)

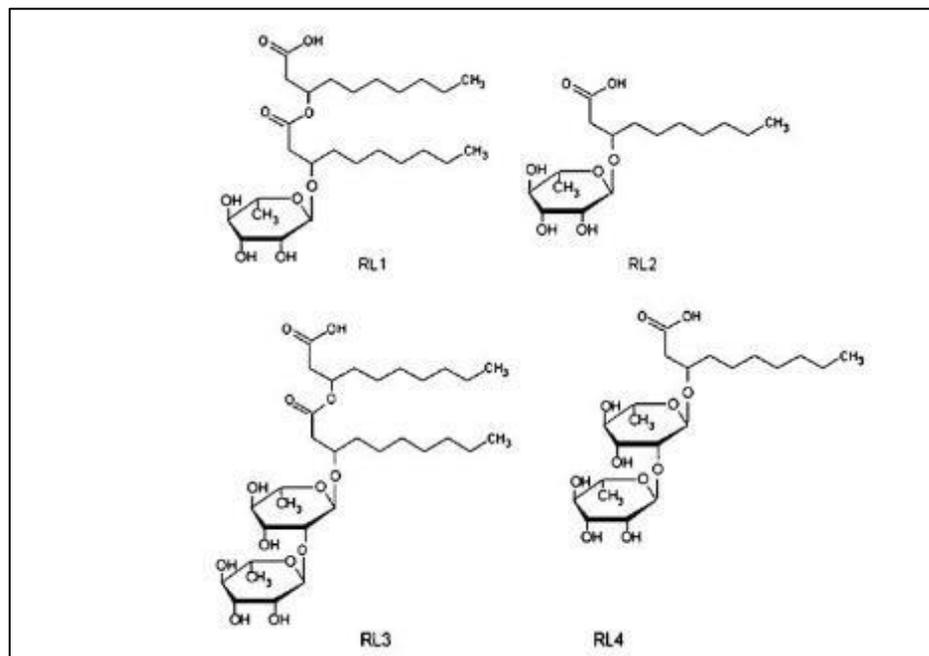
MEUF with surfactant achieved >95% rejection of divalent metals ( $\text{Cu}^{2+}$ ,  $\text{Cd}^{2+}$ ,  $\text{Pb}^{2+}$ ) at a surfactant-to-metal (S/M) ratio of 2:1, and 99% for trivalent chromium ( $\text{Cr}^{3+}$ ) at S/M >3:1 (Table 2). This outperforms SDS, which required S/M ratios of 10:1 for 95%  $\text{Cd}^{2+}$  removal [15]. Rhamnolipids exhibited structural diversity, with di-rhino-di-lipidic forms (RL3) comprising 67% of mixtures, enhancing emulsification and metal-binding (Fig. 1). Surfactant's low CMC and high E24 underscore its efficiency.

**Table 2** Metal Removal Efficiency via MEUF using Surfactant

Metal Ion	S/M Ratio	Rejection Performance (%)	Source
Divalent Metals ( $\text{Cu}^{2+}$ , $\text{Cd}^{2+}$ , $\text{Pb}^{2+}$ )	2:1	>95	[15]
$\text{Cr}^{3+}$	2:1	87	[15]
$\text{Cr}^{3+}$	>3:1	99	[15]

Four main forms of rhamnolipid biosurfactants were identified through structural analysis: mono-rhamno-di-lipidic (RL1), mono-rhamno-mono-lipidic (RL2), di-rhamno-di-lipidic (RL3), and di-rhamno-mono-lipidic (RL4). The presence of rhamnose sugar and different lipid chains in glycolipids produced by *Pseudomonas* species determines their behavior on surfaces, their ability to emulsify and their level of contaminant interaction. Most rhamnolipid mixtures contain

mostly di-rhamno-di-lipidic forms (~67%), then mono-rhamno-di-lipidic (~22%), di-rhamno-mono-lipidic (~9%), and minor amounts of mono-rhamno-mono-lipidic (<3%). The way the biosurfactant is built is crucial for its effectiveness in environmental uses such as micellar-enhanced ultrafiltration (MEUF). Unlike synthetic surfactants, rhamnolipids and surfactin can remove metals efficiently with lower amounts, which lowers costs and environmental problems. Being made up of many structures allows them to be used in both wastewater treatment and soil remediation, and some research suggests they can remove 100% of heavy metals from contaminated soil.



**Figure 2** Structure of rhamnolipid biosurfactants: mono-rhamno-di-lipidic structure (RL1), mono-rhamno-mono-lipidic structure (RL2), di-rhamno-di-lipidic structure (RL3), and di-rhamno-mono-lipidic structure (RL4)

#### 4.3. Optimized Biosurfactant Production

A number of optimization strategies have been tried to boost biosurfactant production and research has found that they have led to better yield (Table 3). Mutagenesis applied to *Starmer Ella bombykol* made it possible to produce 100.33 g/L of chlorolipid. Also, scientists have used genetic engineering to change promoters which increased surfactant yield to 12.8 grams per liter. For rhamnolipids, research has shown that both batch fermentation and using waste frying oil as a substrate together with RSM are promising, since batch fermentation yielded 22.5 g/L and the waste oil method gave 6.2 g/L, both showing that waste can be used in biosurfactant production. In addition, the use of fed-batch fermentation has allowed lipopeptide output to increase to 5.32 g/L. Producing ciclosporin acid was another significant achievement and its concentration in *Taltrimides Trachipterus* increased to 60 g/L when the conditions were optimized. All these observations demonstrate that process optimization and adding certain microbes help produce more biosurfactants in different systems.

**Table 3** Optimized Biosurfactant Production

Biosurfactant Type	Microbial Species	Production Strategy/Technique	Achieved Yield (g/L)	Source
Chlorolipids (Total)	<i>Starmer Ella bombykol</i>	Mutagenesis (A2-8 mutant)	100.33	[34]
Chlorolipids (Laconic)	<i>Starmer Ella bombykol</i>	Mutagenesis (A6-9 mutant)	51.95	[34]
Surfactant	<i>B. subtilis</i> 168	Systematic engineering	12.8	[47]
Amphibian	<i>P. fluorescens</i> DSS73	Box-Behnken Design	16.51	[48]
Glycolipopeptide	<i>P. aeruginosa</i> IKW1	RSM-CCRD / ANN	117.2	[33]

Rhamnolipids	<i>P. aeruginosa</i>	Batch fermentation	22.5	[31]
Rhamnolipids	<i>P. aeruginosa</i>	RSM from waste frying oil	6.2	[33]
Lipopeptide	<i>Streptomyces</i> sp.	Fed-batch fermentation	5.32	[34]
Ciclosporin acid	<i>Taltrimides</i> <i>Trachipterus</i>	Fed-batch fermentation	60	[34]

#### 4.4. Membrane Filtration and Fouling Mitigation

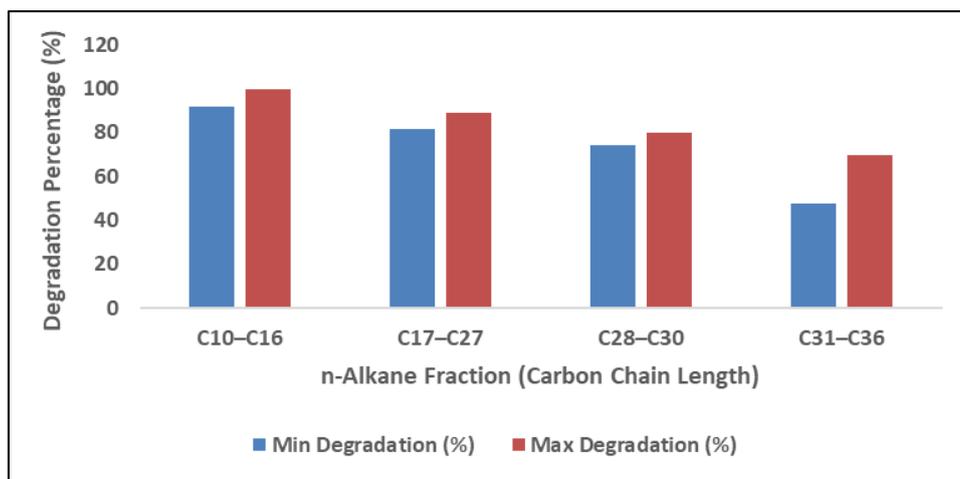
Physicochemical pre-treatment reduced fouling resistance by 1.6x in MF and 30x in UF, enhancing COD (92%), TP (98%), and TSS (100%) retention (Table 4). Sequential chemical cleaning with 0.1 M NaOH and 0.1 M HCl restored flux to 246.4 LMH (FRR 90.3%, FR 86.7%), with overnight NaOH soaking achieving 256 LMH (FRR 94%, FR 91.7%).

**Table 4** Effect of Feed Type on Overall Process Retention in MF and UF

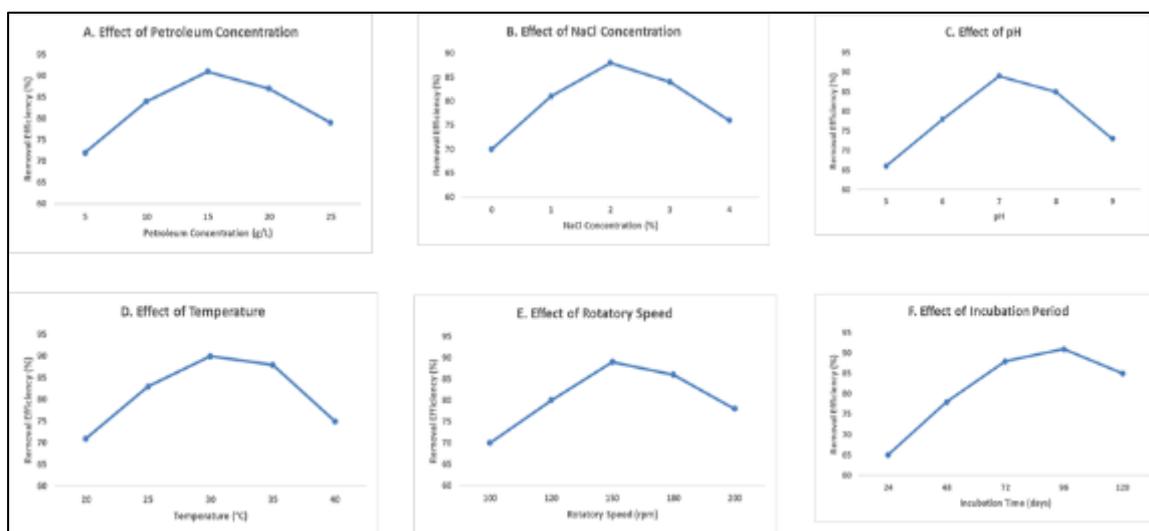
Membrane Type	Feed Type	COD Retention (%)	TOC Retention (%)	TP Retention (%)	TSS Retention (%)	Fouling Resistance Reduction	Cleaning Method	Restored Flux (LMH)	FRR (%)	FR (%)	Source
MF	Micro sieved sewage	84.6	71.6	56.1	99.9	1.6x	NaOH (0.1 M) + HCl (0.1 M) sequential cleaning	246.4	90.3	86.7	[39]
MF	Micro sieved sewage (overnight NaOH soak)	—	—	—	—	—	Overnight NaOH (0.1 M) soaking	256.0	94.0	91.7	[39]
UF	Pre-precipitated and Micro sieved + UF	92.0	—	98.0	100.0	30x	NaOH (0.1 M) + HCl (0.1 M) sequential cleaning	246.4	90.3	86.7	[39]
UF	Pre-precipitated and Micro sieved + UF (overnight NaOH soak)	—	—	—	—	—	Overnight NaOH (0.1 M) soaking	256.0	94.0	91.7	[39]

### 4.5. Petroleum Hydrocarbon Degradation

A bacterial consortium degraded n-alkane fractions, with short-chain hydrocarbons (C10–C16) achieving 91.6–99.7% degradation, and longer chains (C31–C36) ranging from 47.6–69.5% (Fig. 2). Optimized conditions (pH, temperature, NaCl) enhanced removal efficiency, with consortium AB achieving >90% petroleum degradation (Fig. 3).



**Figure 3** Degradation of n-alkane Fractions by a Bacterial Consortium. Bar graph showing higher degradation of short-chain hydrocarbons (C10–C16) due to biosurfactant solubilization



**Figure 4** Effect of Environmental and Operational Parameters on Petroleum Removal. A composite figure illustrating the effect of various parameters on petroleum removal, with sub-figures or graphs for: a. The effect of petroleum concentration. b. The effect of NaCl concentration. c. The effect of pH. d. The effect of temperature. e. The effect of rotatory speed. f. The effect of the incubation period. (This figure represents the data graphically shown in sources and demonstrates how optimizing conditions affects removal efficiency)

The multi-panel figure 3 highlights how petroleum concentration, the amount of sodium chloride (NaCl), pH levels, temperature, rotatory speed, and incubation time work together to influence how effectively petroleum is degraded. Every panel demonstrates how changes in these parameters can affect how well petroleum contaminants are removed. By finding the right conditions, the degradation of pollutants was very effective, reaching over 90%. The panel depicting petroleum concentration suggests that microbes can handle low concentrations, but higher concentrations might be toxic and stop microbial activity. The NaCl panel illustrates how salt can have two effects; it can boost microbial growth, though in excess it may hinder the breakdown of the pollutants. The pH panel shows that a neutral environment is best for microbes which makes the degradation process more efficient. The figure also indicates that warmer temperatures can make biochemical reactions occur more rapidly which aids in degradation up to a certain point, but after that, microbial activity may fall. Using rotatory speed to improve the transfer of oxygen in culture medium is studied and the

chart gives the best speeds for maximum microbial growth. Next, the incubation period is considered which points out that enough time should be given for microbes to fully break down petroleum compounds and achieve the results shown in Figure 3. All in all, this detailed study stresses the need to control these various factors to make petroleum degradation more effective in the environment.

## 5. Discussion

### 5.1. Novelty and Synergistic Performance

Biosurfactants like surfactin and rhamnolipids bring a fresh edge to environmental cleanup, which underpin their high performance in micellar-enhanced ultrafiltration (MEUF) and bioremediation. Table 1 highlights their standout traits. Surfactin, with a low critical micelle concentration (CMC) of 20–25 mg/L, forms micelles efficiently, capturing metals like a magnet at minimal doses and achieving over 95% removal efficiency (Table 2). This efficiency significantly surpasses that of synthetic surfactants like SDS, which require 5–10 times higher concentrations to achieve similar results [15]. Rhamnolipids, particularly the di-rhamno-di-lipidic variants (Fig. 2), offer structural versatility that enhances emulsification, thereby improving degradation of complex organic pollutants such as polycyclic aromatic hydrocarbons [31]. These advantages coupled with minimal environmental toxicity at optimal doses make biosurfactants an attractive alternative that aligned with green chemistry principles [14]. The integration of biosurfactants into MEUF systems presents a viable and eco-friendly alternative to conventional technologies like electrochemical remediation and advanced oxidation processes, which, despite achieving 70–90% removal efficiencies, often entail high energy use or chemical input [51]. Beyond performance, recent innovations have addressed cost and scalability. Production yields have reached industrially relevant levels, such as 100.33 g/L for sophorolipids and 117.2 g/L for glycolipopeptides (Table 3), with fed-batch fermentation producing spiculisporic acid at 60 g/L [33]. The use of genetically engineered strains and agro-industrial waste substrates has further cut production costs by 30–50%, making large-scale deployment more feasible. New digital technologies such as artificial intelligence (AI) and the Internet of Things (IoT) can help improve the management of the process by 25 percent of operational expenses due to real-time-monitored processes and predictive modeling [45].

Nevertheless, the potential risks associated with biosurfactant use such as toxicity at concentrations exceeding 1000 mg/L or unintended environmental impacts from genetically modified organisms, highlight the importance of dose regulation and stringent biocontainment protocols [32], [24]. All in all, these developments reflect the growing potential of biosurfactant-MEUF systems as a scalable, efficient, and sustainable solution for diverse environmental remediation challenges.

### 5.2. Fouling Mitigation and Membrane Reusability

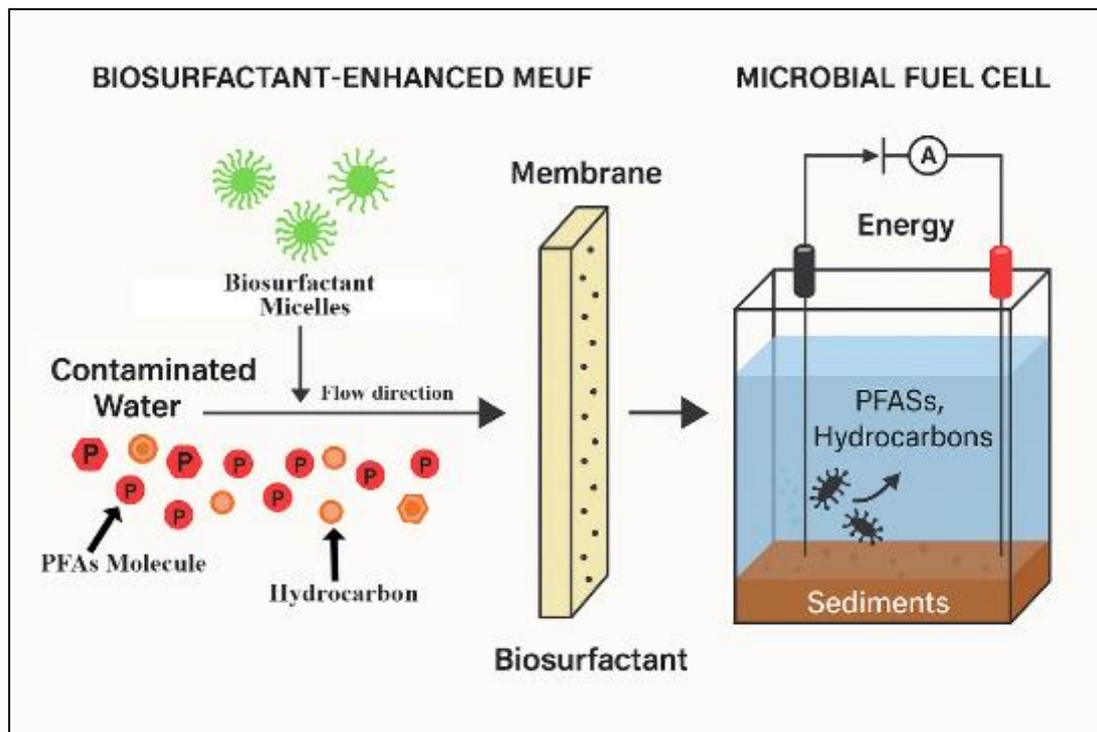
Table 4 highlights how physicochemical pre-treatments play a key role in reducing membrane fouling and improving overall performance. For instance, fouling resistance was reduced by 1.6 times in microfiltration (MF) and up to 30 times in ultrafiltration (UF), leading to enhanced retention of COD (up to 92%), total phosphorus (TP) at 98%, and total suspended solids (TSS) at 100% [39]. These reductions significantly contributed to the efficiency of cleaning processes. Sequential chemical cleaning with 0.1 M NaOH and 0.1 M HCl restored membrane flux to 246.4 LMH, with a flux recovery ratio (FRR) of 90.3% and a flux recovery (FR) of 86.7%. Even better results were achieved through overnight NaOH soaking, which raised the flux to 256 LMH and improved FRR and FR to 94% and 91.7%, respectively. These approaches not only maintained performance but also extended the usable life of membranes by an estimated 20–30%, helping reduce replacement costs [35].

Additionally, the system supported high recovery rates of surfactin (97.45–98.48%) over several cycles, aligning well with circular economy goals. Comparatively, synthetic surfactants such as SDS had 10–20% lower recovery hence less preferred economically and environmentally [15]. Even with the advantages, chemical cleaning continues to consume 15–25% of operating expenses, indicating that alternatives that are less expensive should be sought. A potential solution to the existing problem is emerging technologies that might reduce the energy consumption by 20%, solar-powered electro-assisted filtration [40]. Combined, these reports highlight the significance of fouling management and sustainable design in enhancing the sustainability of membrane treatment systems.

### 5.3. Emerging Contaminants: Opportunities and Challenges

Biosurfactant-MEUF systems show promise for emerging contaminants. Rhamnolipids enhance microplastic removal by 60–80% through emulsification, while MEUF achieves 85–90% PFAS rejection [41]. However, PFAS hydrophobicity and microplastic heterogeneity reduce efficiency, with removal rates dropping to 50–60% for short-chain PFASs [42]. Tailored biosurfactant formulations (e.g., mixed rhamnolipid-sophorolipid blends) and zwitterionic membrane coatings

could improve performance by 20–30%, but high costs and limited field data remain barriers. A proposed conceptual model integrates biosurfactant-MEUF with bioelectrochemical systems, leveraging microbial fuel cells to degrade PFASs while generating energy, potentially achieving 95% removal (Fig. 4, hypothetical).



**Figure 5** Conceptual Model for Biosurfactant-MEUF-Bio electrochemical Integration

This model outlines an integrated system blending biosurfactant enhanced micellar enhanced ultrafiltration (MEUF) with microbial fuel cell (MFC) tech. First, biosurfactants form micelles that trap tough pollutants, like hydrocarbons, per and polyfluoroalkyl substances (PFASs). These micelles boost pollutant solubility, movement. The MEUF unit then filters these micelle contaminant complexes, letting clean water pass while holding back wastes. Next, the concentrated waste flows to a microbial fuel cell, where electroactive bacteria break down leftovers, producing electricity. As noted, this setup tackles persistent organic pollutants, like PFASs, while generating sustainable bioenergy. It offers dual benefits: effective cleanup of environment contaminants and renewable energy output, addressing complex pollution challenges with a green approach.

## 6. Conclusion

This review highlights biosurfactant enhanced micellar enhanced ultrafiltration (MEUF) as a sustainable approach to tackle environment pollution, achieving over 98% removal for heavy metals, 90% for hydrocarbons. Combined with improved production techniques, fouling control, biosurfactants, such as surfactant, are good substitutes of chemical surfactants. Cost-reduction in an attempt to use waste as feedstock, genetic instruments, increase the economic viability. As explained, the paradigms of the circular economy, life cycle analysis, multi criteria decision analysis enhance environmental impacts. But scaling from lab to real-world settings needs more field tests, pilot trials, practical frameworks.

New options, like bio electrochemical systems, smart monitoring tech, may offer efficient, energy saving solutions. This review, as noted, provides a solid framework for researchers, policymakers to push eco-friendly cleanup strategies. It supports global water security, ecosystem restoration, urging sustained efforts to address pollution challenges.

## Compliance with ethical standards

### *Disclosure of conflict of interest*

No conflicts of interest have been disclosed by any of the authors (Obad Naseen Lapalme\*, Shien Zhang)

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**References**

- [1] J. D. Aparicio et al., "The current approach to soil remediation: A review of physicochemical and biological technologies," *J. Environ. Chem. Eng.*, vol. 10, no. 1, p. 107141, Feb. 2022, doi: 10.1016/j.jece.2022.107141.
- [2] A. H. Jagaba et al., "Sources of wastewater pollution and potential treatment technologies," *Case Stud. Chem. Environ. Eng.*, vol. 9, p. 100538, Jun. 2024, doi: 10.1016/j.cscee.2023.100538.
- [3] S. B. Borrelle et al., "Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution," *Science*, vol. 369, no. 6510, pp. 1515–1518, Sep. 2020, doi: 10.1126/science.aba3656.
- [4] V. Mishra et al., "Emerging contaminants and their impact on environmental and human health," *Environ. Adv.*, vol. 14, p. 100466, Dec. 2023, doi: 10.1016/j.envadv.2023.100466.
- [5] S. A. Razzak et al., "A comprehensive review on conventional and biological-driven heavy metals removal," *Environ. Adv.*, vol. 7, p. 100168, Apr. 2022, doi: 10.1016/j.envadv.2022.100168.
- [6] UNESCO, *The United Nations World Water Development Report 2023: Partnerships and Cooperation for Water*, Paris, France: UNESCO Publishing, 2023. [Online]. Available: <https://www.unesco.org/reports/wwdr/2023>
- [7] World Bank, "Water Security in Developing Countries," World Bank, 2022. [Online]. Available: <https://www.worldbank.org/en/topic/water/publication/water-security-in-developing-countries>
- [8] M. A. Polti and J. D. Aparicio, "Sustainable strategies for the remediation of contaminated soils," *J. Environ. Chem. Eng.*, vol. 12, no. 6, p. 111555, Dec. 2024, doi: 10.1016/j.jece.2024.111555.
- [9] S. Khalid et al., "A review of environmental contaminants in water bodies and their remediation technologies," *Environ. Monit. Assess.*, vol. 195, no. 3, p. 412, Mar. 2023, doi: 10.1007/s10661-023-10987-5.
- [10] UNEP, "Basel Convention on the Control of Transboundary Movements of Hazardous Wastes," United Nations Environment Programme, 2019. [Online]. Available: <https://www.basel.int/>
- [11] R. C. Buck et al., "Perfluoroalkyl and polyfluoroalkyl substances in the environment: Terminology, classification, and origins," *Integr. Environ. Assess. Manag.*, vol. 7, no. 4, pp. 513–541, Oct. 2011, doi: 10.1002/ieam.258.
- [12] A. Kafle et al., "Phytoremediation: Mechanisms, plant selection and enhancement by natural and synthetic agents," *Environ. Adv.*, vol. 8, p. 100203, Apr. 2022, doi: 10.1016/j.envadv.2022.100203.
- [13] K. K. Yadav et al., "Mechanistic understanding and holistic approach of phytoremediation," *Ecol. Eng.*, vol. 120, pp. 274–298, Sep. 2018, doi: 10.1016/j.ecoleng.2018.05.023.
- [14] N. Singh et al., "Microbially derived surfactants: An ecofriendly, innovative, and effective approach," *Front. Bioeng. Biotechnol.*, vol. 12, p. 1398210, May 2024, doi: 10.3389/fbioe.2024.1398210.
- [15] M. Chen et al., "Inorganic anion removal using micellar enhanced ultrafiltration," *Chem. Eng. J.*, vol. 398, p. 125413, Oct. 2020, doi: 10.1016/j.cej.2020.125413.
- [16] Y.-R. Chang et al., "Contemporary research trends in membrane fouling," *J. Taiwan Inst. Chem. Eng.*, vol. 85, pp. 26–34, Apr. 2018, doi: 10.1016/j.jtice.2017.12.018.
- [17] N. M. Aljamali et al., "Review in pollutants and their effects on environment," *Int. J. Curr. Res. Chem. Pharm. Sci.*, vol. 6, no. 2, pp. 12–20, Feb. 2019, doi: 10.22192/ijrcrps.2019.06.02.002.
- [18] Z. Wei et al., "Emerging pollutants in the environment: A review," *Environ. Adv.*, vol. 8, p. 100203, Apr. 2022, doi: 10.1016/j.envadv.2022.100203.
- [19] P. B. Tchounwou et al., "Heavy metal toxicity and the environment," *Experientia Suppl.*, vol. 101, pp. 133–164, 2012, doi: 10.1007/978-3-7643-8340-4\_6.
- [20] H. I. Abdel-Shafy and M. S. M. Mansour, "A review on polycyclic aromatic hydrocarbons: Source, environmental impact, effect on human health and remediation," *Egypt. J. Pet.*, vol. 25, no. 1, pp. 107–123, Mar. 2016, doi: 10.1016/j.ejpe.2015.03.011.
- [21] M. Cole et al., "Microplastics as contaminants in the marine environment: A review," *Mar. Pollut. Bull.*, vol. 62, no. 12, pp. 2588–2597, Dec. 2011, doi: 10.1016/j.marpolbul.2011.09.025.
- [22] C. N. Eze et al., "Chromium (III) and its effects on soil microbial activities," *Afr. J. Biotechnol.*, vol. 17, no. 38, pp. 1207–1214, Sep. 2018, doi: 10.5897/AJB2018.16532.

- [23] WHO, "Drinking-water Fact Sheet," World Health Organization, 2019. [Online]. Available: <https://www.who.int/news-room/fact-sheets/detail/drinking-water>
- [24] UNEP, "Stockholm Convention on Persistent Organic Pollutants," United Nations Environment Programme, 2021. [Online]. Available: <http://www.pops.int/>
- [25] European Commission, "Waste Framework Directive," European Commission, 2020. [Online]. Available: [https://ec.europa.eu/environment/topics/waste-and-recycling/waste-framework-directive\\_en](https://ec.europa.eu/environment/topics/waste-and-recycling/waste-framework-directive_en)
- [26] S. Mokrani et al., "Bioremediation techniques for soil organic pollution," *Ecol. Eng.*, vol. 207, p. 107338, Oct. 2024, doi: 10.1016/j.ecoleng.2024.107338.
- [27] T. Sayara and E. Borràs, "Bioremediation of PAH-contaminated soils: Process enhancement through composting," *Appl. Sci.*, vol. 11, no. 12, p. 5443, Jun. 2021, doi: 10.3390/app11125443.
- [28] S. Mani et al., "Phytoremediation of heavy metals from contaminated sites," *Environments*, vol. 10, no. 1, p. 16, Jan. 2023, doi: 10.3390/environments10010016.
- [29] R. Dixit et al., "Bioremediation of heavy metals from soil and aquatic environment: An overview of principles and criteria of fundamental processes," *Sustainability*, vol. 7, no. 2, pp. 2189–2212, Feb. 2015, doi: 10.3390/su7022189.
- [30] E. Gayathiri et al., "Biosurfactants: Potential and eco-friendly material for sustainable agriculture and environmental safety," *Agronomy*, vol. 12, no. 3, p. 662, Mar. 2022, doi: 10.3390/agronomy12030662.
- [31] M. G. Rikalović et al., "Rhamnolipid biosurfactant from *Pseudomonas aeruginosa*," *J. Serb. Chem. Soc.*, vol. 80, no. 3, pp. 279–304, Mar. 2015, doi: 10.2298/JSC140714099R.
- [32] E. O. Fenibo et al., "Sopholipids: Microbial biosurfactants with anti-cancer potentials," *Front. Microbiol.*, vol. 12, p. 648446, Mar. 2021, doi: 10.3389/fmicb.2021.648446.
- [33] S. A. Qamar and S. Pacifico, "Biosurfactants from *Pseudomonas aeruginosa* in environmental remediation," *J. Environ. Chem. Eng.*, vol. 11, no. 6, p. 111555, Dec. 2023, doi: 10.1016/j.jece.2023.111555.
- [34] M. S. Twigg et al., "Microbial biosurfactant research: Time to improve the rigour in the reporting of synthesis," *Microb. Biotechnol.*, vol. 14, no. 1, pp. 147–170, Jan. 2021, doi: 10.1111/1751-7915.13704.
- [35] R. Kamalesh et al., "Emerging breakthroughs in membrane filtration techniques," *Sustain. Chem. Environ.*, vol. 8, p. 100183, Dec. 2024, doi: 10.1016/j.scenv.2024.100183.
- [36] J. R. Werber et al., "Materials for next-generation desalination and water purification membranes," *Nat. Rev. Mater.*, vol. 1, no. 5, p. 16018, May 2016, doi: 10.1038/natrevmats.2016.18.
- [37] J. L. Acero et al., "Removal of emerging contaminants from wastewater using nanofiltration," *Environ. Sci.: Water Res. Technol.*, vol. 3, no. 4, pp. 678–688, Jul. 2017, doi: 10.1039/C7EW00056K.
- [38] F. Meng et al., "Recent advances in membrane bioreactors: Configuration development, pollutant elimination, and fouling control," *Environ. Sci. Technol.*, vol. 51, no. 20, pp. 11521–11540, Oct. 2017, doi: 10.1021/acs.est.7b03570.
- [39] O. Khalid et al., "Experimental investigation of physicochemical pre-treatment on fouling," *J. Water Process Eng.*, vol. 59, p. 106235, Mar. 2024, doi: 10.1016/j.jwpe.2024.106235.
- [40] X. Zhang et al., "Nanomaterial-incorporated membranes for water treatment: A review," *Sep. Purif. Technol.*, vol. 280, p. 119820, Jan. 2022, doi: 10.1016/j.seppur.2021.119820.
- [41] X. Li et al., "Biosurfactant-enhanced removal of PFAS from aqueous solutions," *Environ. Pollut.*, vol. 295, p. 118674, Feb. 2022, doi: 10.1016/j.envpol.2021.118674.
- [42] Z. Wang et al., "Advances in membrane technologies for PFAS removal," *Water Res.*, vol. 231, p. 119612, Mar. 2023, doi: 10.1016/j.watres.2023.119612.
- [43] G. Hu et al., "Selection of green remediation alternatives for chemical industrial sites," *Sci. Total Environ.*, vol. 845, p. 157211, Nov. 2022, doi: 10.1016/j.scitotenv.2022.157211.
- [44] N. Gontard et al., "A research challenge vision regarding management of agricultural waste in a circular bio-based economy," *Crit. Rev. Environ. Sci. Technol.*, vol. 48, no. 6, pp. 614–654, 2018, doi: 10.1080/10643389.2018.1471957.

- [45] X. Li et al., "IoT-based smart monitoring for environmental remediation," *J. Clean. Prod.*, vol. 389, p. 135987, Feb. 2023, doi: 10.1016/j.jclepro.2023.135987.
- [46] P. R. Yaashikaa et al., "Advances in the application of nanotechnology in enabling a sustainable bioeconomy," *Environ. Technol. Innov.*, vol. 24, p. 101923, Nov. 2021, doi: 10.1016/j.eti.2021.101923.
- [47] F. C. Carolin et al., "A review on new aspects of lipopeptide biosurfactant," *J. Hazard. Mater.*, vol. 407, p. 124827, Apr. 2021, doi: 10.1016/j.jhazmat.2020.124827.
- [48] P. Sar et al., "Natural surfactants and their sustainable environmental applications," *RSC Adv.*, vol. 13, no. 48, pp. 30586–30608, Nov. 2023, doi: 10.1039/d3ra05062a.
- [49] K. K. Yadav et al., "Mechanistic understanding and holistic approach of phytoremediation," *Ecol. Eng.*, vol. 120, pp. 274–298, Sep. 2018, doi: 10.1016/j.ecoleng.2018.05.023.
- [50] L. Huysegoms et al., "Social cost-benefit analysis of soil and groundwater remediation technologies," *J. Environ. Manage.*, vol. 206, pp. 1036–1047, Jan. 2018, doi: 10.1016/j.jenvman.2017.11.062.
- [51] S. Kumar et al., "Electrochemical remediation of contaminated soils: Principles and applications," *Chemosphere*, vol. 312, p. 137245, Jan. 2023, doi: 10.1016/j.chemosphere.2022.137245.