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A Hybrid-Energy Harvesting System with Wastewater Treatment Using EBR, RED and CapMix

Abhinav Chandna[1], Aarna Malhotra[2], Aleya Chatterjee[3]
The Shriram Millennium School, India

Abstract: Salinity gradient power (SGP) or Salinity gradient energy (SGE) is a renewable energy source that has its origin from the mixing of waters of varying salinity. In this work, a novel hybrid system consisting of Capacitive Mixing (CapMix), Reverse Electrodialysis (RED), and Electroactive Biofilm Reactors (EBR) in a system that can generate energy from industrial effluent and treat wastewater simultaneously is explored. The hybrid system utilizes the synergistic advantages offered by CapMix and RED to enhance energy production and the application of EBR to prevent membrane fouling in RED to increase overall efficiency and ensure environmental responsibility. Another significant contribution of this work is the development of composite electrodes for the CapMix mechanism with 3D Porous Carbon, Chemically Activated Graphene Oxide, a chitosan–gelatin binder, and a Zwitterionic Polymer Coating to minimize fouling. Research on three-way hybrid systems and their applications in industrial effluent is limited despite the inherent potential of SGE technologies. This work addresses this gap by demonstrating the feasibility and advantages of the proposed system in clean energy generation and wastewater treatment, thus ensuring sustainable industrial operations and freshwater resource conservation.

I. INTRODUCTION

The global need for clean energy technologies and effective wastewater treatment technologies has been an incentive for more efforts to find new technologies that address both at once. Salinity gradient energy (SGE), founded on the Gibbs free energy released throughout the controlled mixing of two waters of different salinities, is a renewable energy technology with immense potential. Pressure Retarded Osmosis (PRO), Reverse Electrodialysis (RED), and Capacitive Mixing (CapMix) are technologies developed to capture this energy, exploitable from natural salinity gradients (e.g., river water and seawater) to man-made ones such as industrial effluents. But these technologies have major drawbacks: membrane fouling in RED and low power density in CapMix, which limit their use for large-scale applications and economic viability.

Hybrid systems combining different SGE technologies have been engineered as possible solutions to such limitations by leveraging the strengths inherent to each technology. RED, for instance, employs ion-exchange membranes to recover electricity from ionic gradients. At the same time, CapMix employs capacitive electrodes to recover energy from potential differences created by salinity. More recent studies have explored hybrid CapMix systems with enhanced electrodes to obtain maximum energy density; however, fouling is a major operating problem. Additionally, the use of bioelectrochemical systems, such as Electroactive Biofilm Reactors (EBR), could potentially be used for wastewater treatment and fouling mitigation through the action of electroactive microorganisms [8, 9].

Our proposed system introduces a new three-way hybrid system combining CapMix, RED, and EBR to harvest energy from industrial effluents while simultaneously treating wastewater. Industrial effluents, being generally high-salinity and high-organic content, are a useful resource for harnessing SGE despite their general tendency to contaminate freshwater bodies. The system we are proposing combines the RED's ionic energy harvesting, CapMix's capacitive energy harvesting, and EBR's anti-fouling and wastewater treatment features to produce a synergistic system. The innovation involves the design of new composite electrodes for the CapMix system made of, with a zwitterionic layer coating for improved anti-fouling performance [5, 14, 15, 16]. These are chosen for their high surface area, superior electrical conductivity, and zwitterionic coating compatibility, which build a hydration layer to minimize foulant adhesion [5, 16].

The integration of EBR utilizes electroactive biofilms to reduce organic pollutants and prevent membrane fouling in RED to increase system life and efficiency. In its use of the hybrid system in industrial effluents, the study seeks to show a multipurpose technology that generates clean energy while recycling wastewater, towards industrial sustainability.

Although SGE technologies are promising, a gap in research on three-way hybrid systems and their use in industrial effluents is apparent. This research bridges this gap by assessing the feasibility, efficiency, and environmental benefits of the proposed system, towards improving renewable energy and wastewater management.

II. BACKGROUND ON SALINITY GRADIENT ENERGY TECHNOLOGIES

Salinity gradient energy (SGE) takes advantage of the chemical potential difference between two differing-salinity solutions, like seawater and river water or industrial waste waters and fresh water. Gibbs free energy released upon mixing may be converted into electricity via engineered processes. The prevalent technologies for SGE are:

- Pressure Retarded Osmosis (PRO) uses a semipermeable membrane to permit water to pass from a low-salinity to a high-salinity solution, which drives a turbine to generate electricity. PRO has high power density (up to 10 W/m^2) but is constrained by membrane fouling and cost [1].
- Reverse Electrodialysis (RED) uses a stack of alternate anion and cation exchange membranes to create an electrochemical gradient, thus generating electricity through ionic transport. RED has a tendency to generate power density of about 1 W/m^2; however, it is susceptible to fouling, which reduces its ion exchange capacity [6].
- Capacitive Mixing (CapMix) employs capacitive electrodes to harvest energy from potential differences due to salinity. Although CapMix has a lower power density of approximately 0.2 W/m^2, it enjoys simpler configurations and the potential to function without membranes [7].

All technologies have their own strengths and weaknesses. Fouling in particular is a significant roadblock for membrane-based technologies like RED, where scaling and biofouling lead to losses in efficiency and increase maintenance costs.

A. Challenges in SGE Technologies

Scaling and biofouling as fouling are significant problems for SGE systems, especially in RED components, whose ion-exchange membranes are susceptible to organic and biological foulant accumulation [6]. This degrades ion exchange capacity, raises transmembrane pressure, and requires frequent cleaning or replacement of the membrane [6]. CapMix systems, while being membrane-independent to some extent, suffer from electrode fouling, which lowers energy extraction efficiency [7]. Furthermore, due to the low power density of CapMix, scalability is less compared to other renewable energy sources such as solar or wind [2].

B. Hybrid Systems and Innovations

Hybrid systems integrating SGE technologies have been promising to overcome these challenges. For instance, a hybrid CapMix system using battery and capacitive electrodes realized an energy density of 130 J/m^2 and power output of 97 mW/m^2, much greater than conventional CapMix systems [3]. New progress in electrode materials, such as employing modified activated carbon and Prussian blue analogues, has made membrane-free CapMix possible, lowering costs and extending cycle life [4]. Nevertheless, three-way hybrid systems integrating CapMix, RED, and bioelectrochemical systems such as EBR remain untapped, especially for industrial effluent application.

C. The Applications of Electroactive Biofilm Reactors (EBR)

EBR systems employ electroactive microorganisms to break down organic contaminants and prevent fouling [8, 9]. The systems employ biofilms that pass electrons to electrodes, enabling pollutant breakdown and minimizing the deposition of high-molecular-weight substances [8]. In the present work, EBR is incorporated to break down RED membrane fouling by actively breaking down organic foulants and sustaining membrane performance [9]. This dual purpose—energy harvesting and wastewater treatment—increases the environmental and economic sustainability of the hybrid system [19].

D. Advanced Composite Electrodes

The hybrid energy system employed in this study consists of composite electrodes that involve a 3D Porous Carbon Foam or biochar and Chemically Activated Graphene Oxide layers. They also consist of Chitosan–Gelatin adhesion layers and Zwitterionic polymer surface layers [15, 16]. All the materials chosen were chosen due to their synergistic properties such as sufficient porous structure with high conductivity as well as mechanical stability and anti-fouling [5, 14, 15, 16]. These properties improve the system efficiency and lifetime in devices like electro-bioreactor (EBR), reverse electrodialysis (RED), and capacitive mixing (CapMix).

E. *Preferred Effluent*

Application in Industrial Wastewater Industrial effluents, which are typically saltier and organic pollutant-enriched, are best candidates for SGE as they possess salinity gradients when combined with freshwater or other low-salinity flows [19]. The suggested hybrid system not only derives energy from such gradients but also purifies the wastewater to minimize environmental pollution [19]. The two-in-one method encourages global sustainability goals by providing a means to purify contaminated freshwater reservoirs besides generating renewable energy.

III. RESEARCH OBJECTIVES AND SIGNIFICANCE

1) To develop and design an efficient, modular hybrid system integrating Reverse Electrodialysis (RED), Capacitive Mixing (CapMix), and Electroactive Biofilm Reactors (EBRs) for combined uses of wastewater treatment and energy production.
2) To incorporate and contrast anti-fouling technologies such as Vibration-Induced Flow Disturbance (VIFD) using piezoelectric actuators and zwitterionic fouling-resistant membrane coatings, make the system efficient and minimize any maintenance requirement.
3) To create a new electrode stack structure based on interdigitated designs, porous 3D carbon, and chitosan-based binders for enhanced conductivity, surface area, and mechanical strength.

To provide future scopes for further expansion of the proposed system.

By bridging the knowledge gap in three-way hybrid SGE system research and its application in industrial effluent, this study adds to the development of sustainable wastewater treatment and energy technologies. Integrating advanced materials and bioelectrochemical processes offers a solution for industries that want to reduce their impact on the environment but also generate renewable energy.

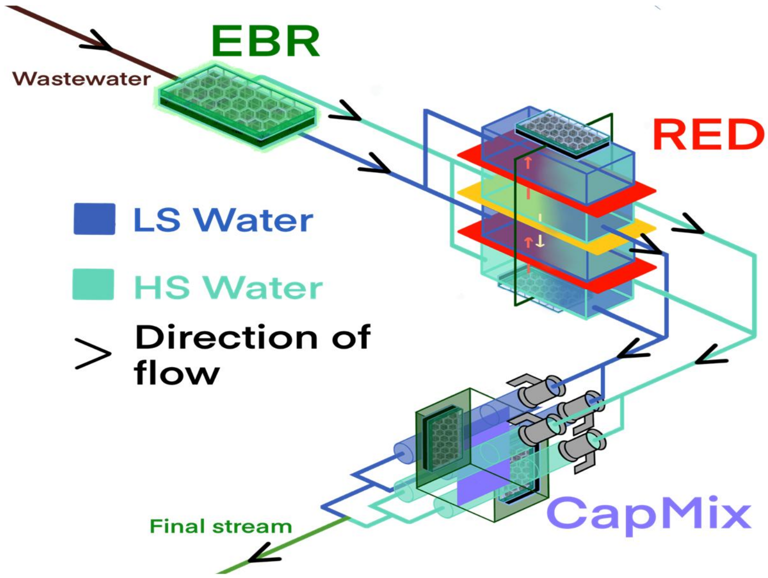
IV. LITERATURE REVIEW

1) In the recent past, Bioelectrochemical systems (BES) like Microbial Fuel Cells (MFCs) and Electroactive Biofilm Reactors (EBRs) have attracted significant attention as they possess the ability to recover electricity while breaking down organic compounds, thereby performing a dual role. Logan et al. initially experimentally substantiated this direct extracellular electron transfer (EET) process by demonstrating that microbial biofilms could be effectively employed in electric circuits for energy retrieval [8]. This is being extended a step further by EBRs than traditional MFCs by placing special focus on stable long-term biofilm development, enhanced electrode surface area, and modular geometries compatible with real wastewater treatment processes [9].
2) Reverse electrodialysis (RED), originally envisaged in 1954, is a state-of-the-art membrane-based technology that exploits the intrinsic energy potential of mixing salt and freshwater—e.g., river water and seawater—under controlled conditions to generate energy in the form of electricity. Alternating anion and cation exchange membranes in the RED stack create compartments for high- and low-salinity streams. Voltage and electricity generation take place through ion flow. Research is currently aimed at the development of low-resistance, fouling-resistant membranes and stack design optimization to enhance power generation and stability in operation [6]. Hybrid RED systems, integrating RED with other processes like bioelectrochemical systems, have been shown to be compatible and exhibit improved energy recovery, which outlines the future horizon of this technology [3].
3) Capacitive mixing (CapMix) is a comparatively new and latest technology that takes advantage of the differential electrode potential for high- to low-salinity electrode switching. The simplicity of operation, low cost, flexibility and low maintenance of CapMix make it one of the best options for decentralized applications [7]. As opposed to RED, no ion-exchange membranes are required for CapMix and cyclic charging and discharging of electrodes rather, eliminating any room for fouling, a major problem with other membrane-based technologies. Brogioli demonstrated that CapMix can generate comparable energy yields to RED in low-resource environments [10].
4) Integrated hybrid systems and Electrode Utilization: Over the past decade, our definition of wastewater has slowly but surely changed. No longer viewed as just the grime of urban life, wastewater is increasingly being imagined as a hotbed of untapped potential—teeming with nutrients, ions, and even energy [19]. As the requirement for water conservation and energy harvesting is on the rise, researchers have shifted towards hybrid systems that can be applied to combine biological treatment and energy harvesting in a single system [19]. These hybrid systems offer the best of both worlds with enhanced operational efficiency, and enhanced outputs. Among the technologies that enable such integration is the application of high-grade electrode stacks, which find multiple roles across systems. The combination of advanced electrodes of the same type—3D porous carbon, graphene oxide, and antifouling zwitterionic coatings—performs the role of [11, 12, 13, 14, 15, 16].:

- A microbial substrate for EBRs,
- A RED electron collector
- A capacitor surface in cycles of CapMix.

V. PROPOSED SYSTEM DESIGN

A. System Architecture

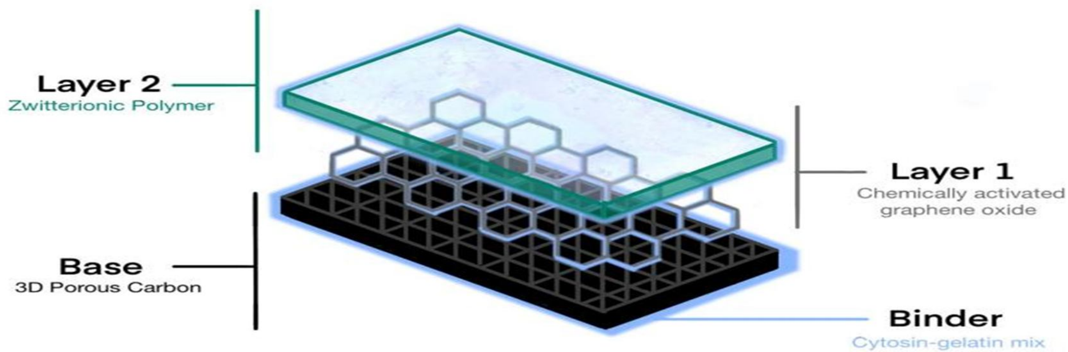


B. Subsystems Explained

1) Electrode Subsystem

The advanced electrode subsystem is utilized across EBR, RED, and CapMix modules. It enables efficient charge transfer, supports microbial activity (in EBR), and resists fouling and degradation in all operational environments.

Material Stack of the Electrode:



a) Base Layer: 3D Porous Carbon (Biochar or Carbon Foam)

The structural material of the electrode is a three-dimensional porous carbon network, e.g., carbon foam or biochar, that serves as the structural skeleton and current collector. Its sponge pore structure and high surface area provide a highly conducting environment for microbial growth in the electro-bioreactor (EBR) and for efficient ion exchange in reverse electrodialysis (RED) and capacitive mixing (CapMix). In the EBR, the carbon network serves as a substrate for the growth of electroactive bacteria, e.g., Geobacter spp., that break down organic pollutants and produce electrons [12]. In RED and CapMix, the open pore structure provides ion accessibility for efficient electron transfer and charge storage [13].

This layer has two extremely vital roles:

- It transfers electrons from microbial reactions to outside circuits in the EBR.
- It facilitates rapid ion migration in RED and CapMix, thus enhancing energy generation.

Biochar, derived from sustainable biomass, is light, economical, and long-lasting, and hence is ideal for widespread uses [13]. Its long lifespan under fluctuating flow conditions, especially when applied with Vibration-Induced Flow Disturbance (VIFD) technology, provides reliable performance without compromising the structure.

b) Chemically Activated Graphene Oxide (Layer 1)

A chemically activated graphene oxide (GO) with high conductivity and oxygen-rich functional groups sits atop the base layer. It is a high-speed road for the electrons and ions in the system, with a high enhancement of charge transfer in all parts of the system. Research highlights that in EBR, GO increases electron harvesting from microbial biofilms and thereby bioelectrochemical efficiency [14]. Likewise in CapMix, it facilitates rapid adsorption and desorption cycles, necessary for voltage generation in salinity gradients. In RED, GO conductivity facilitates ions' permeation through the membranes with minimal loss of energy [14]. Oxygen groups in GO also enhance hydrophilicity (surface attraction to water), which in turn prepares the surface for the outer zwitterionic layer. This is a transition layer to facilitate sensitivity and reactivity at high levels, avoiding sudden voltage drop and improving the system's overall energy efficiency.

c) Chitosan-Gelatin Binder (Between Layers)

A gelatin-chitosan binder is employed to bind the layers of the electrode together as a flexible adhesive that stabilizes the system under stress. The biocompatible binder is mechanically stable even when the system undergoes the micro-vibrations of VIFD or RED and the electrochemical demands of CapMix. In EBR, it stabilizes the biofilm by hydrating the layers, which enhances antimicrobial activity [15]. The binder possesses a built-in flexibility that does not permit delamination (separation of the consistent layers due to stress), enabling intimate contact between the carbon base and GO layer without the reduction of conductivity [15]. The natural antimicrobial activity of the binder, with chitosan as the source, prevents any biofouling on the system, hence augmenting the anti-fouling strategies.

d) Zwitterionic Polymer Coating (Layer 2 – Outer Layer)

The zwitterionic polymer film, e.g., poly(sulfobetaine methacrylate) (polySBMA) or carboxybetaine methacrylate (CBMA), forms a protective film at the topmost surface of the electrode. The film forms a hydration shell that repels bacteria, proteins, and organic substances and reduces fouling on RED membranes and electrodes to a large extent. In the hybrid configuration, the zwitterionic film works synergistically with VIFD, which dislodges loosely bound foulants by micro-vibrations [21, 23, 24, 25, 26, 27].

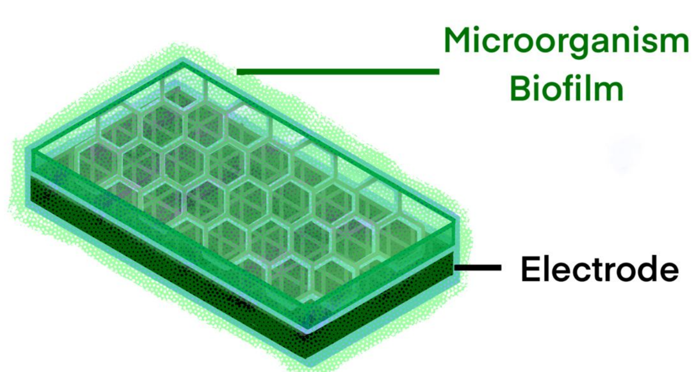
2) Electroactive Biofilm Reactor (EBR) Subsystem

EBR is the first subsystem and is primarily responsible for biological treatment of wastewater and the generation of a salinity gradient. It utilizes electroactive microorganisms, i.e., Geobacter Sulfurreducens and Shewanella Oneidensis, which are immobilized on the surface of conductive electrodes and form a stable biofilm.

Key functions:

- Pollutant degradation: In order to treat the wastewater, it metabolizes pollutants (through microbial metabolism) causing a reduction in Chemical Oxygen Demand (COD) and Ammonium-Nitrogen [17].
- Ion enrichment: The electrons released generate the high-ionic-strength effluent that creates a salinity gradient in the system.
- Electron generation: It provides an initial current output via microbial electrochemical activity.

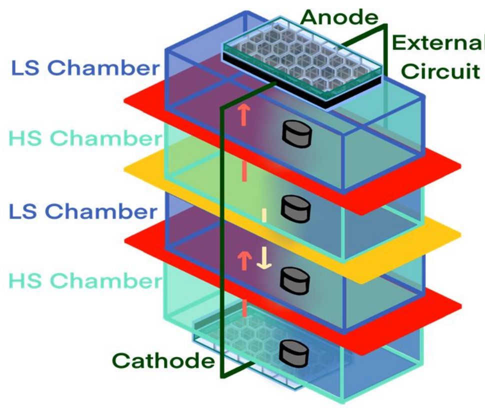
It initiates the energy recovery process and supports integrated waste treatment, serving a dual purpose.



3) Reverse Electrodialysis (RED) Subsystem

The RED stack functions as the primary energy recovery unit. It exploits the salinity gradient between the EBR's high-salinity (HS) effluent and a diluted low-salinity (LS) stream to generate electricity via controlled ion migration].

The RED stack is built as a sandwich of repeating units (cell pairs) consisting of multiple alternating Cation Exchange Membranes (CEMs) and Anion Exchange Membranes (AEMs) placed between HS and LS flow chambers. This sequence is repeated many times between two electrodes at the ends.



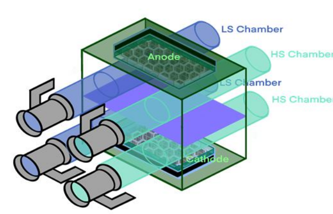
a) Key Functions

- Ion transport: Cations move through CEMs towards the cathode, and anions through AEMs towards the anode, creating a one-way ionic flow.
- Electric potential generation: Movement of ions across membranes creates an electric potential between the terminal electrodes.
- Energy Generation- Harvesting the salinity gradient is the main function of this subsystem.
- Scalability: Modular RED stacks extended to improve power density (~0.57 W/m² reported in hybrid systems) [6].

b) To mitigate biofouling and scaling

- Zwitterion membrane coatings create hydrophilic, anti-adhesive surfaces [5, 16].
- Vibration-Induced Flow Disturbance (VIFD) using piezoelectric actuators introduces turbulence to dislodge accumulated particulates preventing residue collection or fouling.

4) Capacitive Mixing (CapMix) Subsystem:



The CapMix module consists of a membraneless supporting energy-harvesting sub-system. It alternately brings capacitive electrodes into contact with HS and LS flows, generating a voltage due to differential ion adsorption and desorption.

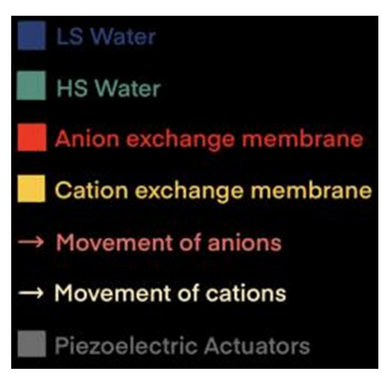
Electrodes:

The CapMix cell consists of two electrodes and a chamber in between.

Key functions:

- Charge-Discharge cycle[7]

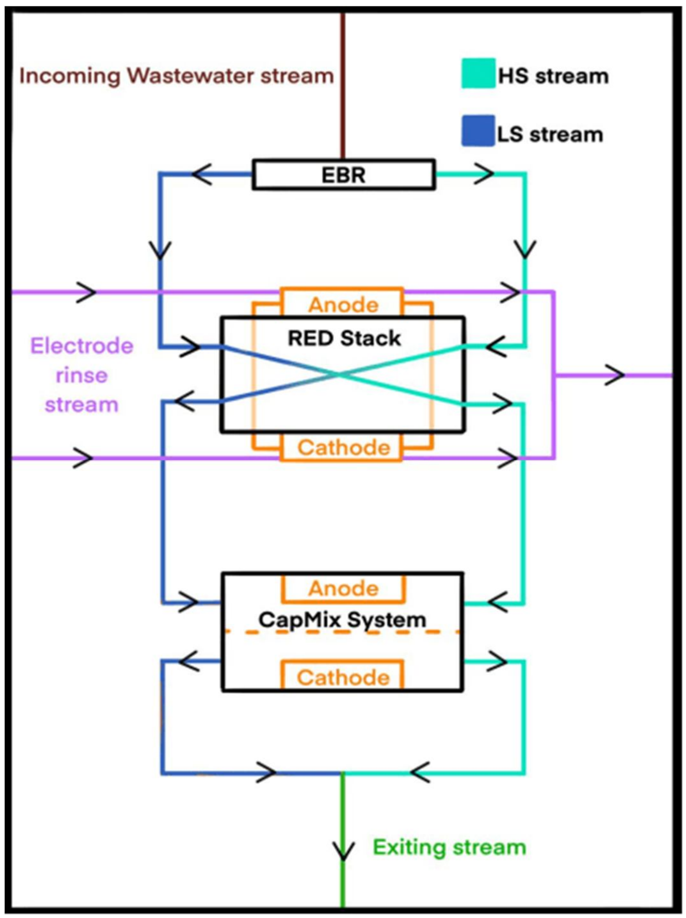
  The cell alternately exposes the electrodes to high-salinity (HS) and low-salinity (LS) solutions in a four-step cycle:
  - Charging in HS: Electrodes are immersed in the high-salinity solution, where ions adsorb, charging the double layer.
  - Solution Exchange: The HS solution is flushed out and replaced with LS solution.
  - Discharging in LS: In the LS environment, the double layer expands, increasing the cell voltage, and the stored charge is released through the external circuit, generating power.



- Solution Exchange: The LS solution is replaced with HS again, and the cycle repeats.
- Supplementary energy yield: Adds to the total system energy output, particularly under variable salinity conditions.
- Simplicity and reliability: Absence of membranes reduces cost and maintenance demands.

C. Mechanism and Working of the Hybrid Energy-Wastewater Treatment System

The hybrid device comprises an Electroactive Biofilm Reactor (EBR), Reverse Electrodialysis (RED), and Capacitive Mixing (CapMix) for wastewater treatment and renewable energy generation. The device utilizes microbial metabolism, salinity gradient energy harvesting, as well as high-performance materials to capture pollutants and generate renewable power. We explain below the system operation, backed by recent evidence, to show the potential of the system in satisfying water and energy demands.



Flowchart depicting the working of the system

1) STEP 1: Pre-Treatment of Wastewater in the Electroactive Biofilm Reactor(EBR):

First, the wastewater is pumped into the Electroactive Biofilm Reactor (EBR) where naturally occurring electroactive microbes, including Geobacter sulfurreducens and Shewanella oneidensis, create a biofilm on a conductive multi-layered electrode made up of porous 3D biochar, graphene oxide, chitosan–gelatin composite, and a zwitterionic polymer coating. The biofilm topography aids microbial adhesion, electrical conductivity, and antifouling [12, 15, 16]. The microbes degrade organic pollutants—imagine them as little cleanup crews dismantling sugars, proteins, and other substances—and the bioelectrochemical reactions facilitate oxidation of organic matter, minimizing oxygen demand and ammonium-hydrogen, and releasing electrons and ions into the solution in parallel. The conductive, saline sludge is the basis for energy harvesting through the formation of ion-rich EBR effluent.

2) STEP 2: Salinity Gradient Generation and Effluent Splitting:

The EBR ion-rich effluent consists of two components:

- Portion A is maintained dense and focused as the High-Salinity (HS) stream.
- Portion B is combined with freshwater or fully treated effluent to create the Low-Salinity (LS) stream.

In the process, an electrochemical potential gradient like that of a natural battery is established. The electrochemical potential gradient (~512.8 mol/m³ HS vs. ~17.4 mol/m³ LS) enables ion transport and plays an important part in the establishment of an electrochemical potential difference needed for energy production in potential RED and CapMix strategies [19]. The disparity between the two streams is necessary for the best power harvesting.

3) STEP 3: Generating Power using Reverse Electrodialysis (RED) Stack:

The HS and LS flows are supplied to alternate chambers of the RED stack via exclusive inlets. The salinity gradient improves energy generation by facilitating a pathway for the movement of cations and anions from HS to LS chambers via alternate cation-exchange membrane (CEM) and anion-exchange membrane (AEM) pathways, respectively. The ion selective transport creates an electric potential between electrodes at the stack terminal ends, generating an electric current (electron flow) between anode and cathode via an external circuit. The process effectively converts the chemical energy immanent in the salinity gradient to electrical energy. The RED stack is the system's main energy converter, converting the flow of ions to useful power.

4) STEP 4. Boosting Energy with Capacitive Mixing (CapMix) Unit

To generate the maximum possible energy output, the system utilizes Capacitive Mixing (CapMix), a technology that seeks a membrane-less operation and also utilizes the salinity gradient by means of a cyclical process.

During the process, the electrode stack acts as a capacitor. Reverse Electrodialysis high salinity (HS) effluent is fed into the CapMix cell and fills the chamber, coming into contact with the electrodes. When immersed in HS, ions of the HS solution are adsorbed on the electrode surfaces, raising the potential.

The HS solution is displaced and refilled with low salinity (LS) solution, wherein ions are desorbed on LS immersion, thus completing a charge-discharge cycle [7]. The water streams, now more equilibrated (less saline-different), are discharged as the final effluent.

5) STEP 5. Output Collection and Utilization

The final outputs consist of:

- Clean water: which is appropriate for reuse or discharge, adhering to regulatory standards.
- Harvested energy: which can be stored in supercapacitors or batteries for future use or can be immediately utilized for low-voltage applications.

This double output of clean water and green power emphasizes the system's sustainability and adherence to the principles of a circular economy.

D. Innovations in the System

1) Use of EBR systems instead of MFCs

1. Superior Anti-Fouling Performance of EBR

EBR integrates a variety

- Proactive Electrochemical Cleaning:

EBR systems utilize controlled electrochemical cleaning mechanisms to proactively remove biofilms from electrode surfaces, ensuring sustained operational capacity and long-term energy efficiency.

- Rapid and Complete Biofilm Removal:

By applying potentials negative of -1.5 V vs. Ag/AgCl, EBR enables vigorous hydrogen gas evolution, which mechanically detaches bacteria and extracellular polymeric substances from electrodes within seconds [20]. This process achieves high removal efficiencies throughout repeated fouling-cleaning cycles.

- Consistent Long-Term Performance:

The electrochemical cleaning process in EBR maintains consistent performance by preventing irreversible fouling, unlike MFCs, which experience progressive performance degradation due to membrane and electrode fouling.

2. Integration of Electroactive Microorganisms in EBR

- Self-Maintaining System:

EBR technology enables the integration of electroactive microorganisms that promote polysaccharide degradation and reduce high-molecular-weight compound deposition [8, 17].

- Proactive Fouling Prevention:

This creates a self-maintaining system that prevents fouling rather than merely responding to it, ensuring stable power generation over extended periods.

3. Suitability of EBR for Long-Term Salinity Gradient Energy Applications

- Consistent Performance:

The proactive anti-fouling approach of EBR makes it more suitable for long-term salinity gradient energy applications, where consistent performance is critical for economic viability.

- Reduced Downtime and Costs:

By minimizing downtime and maintenance, EBR systems offer a more reliable and cost-effective solution compared to MFCs.

4. Limitations of MFCs

- Immediate Power Generation but Progressive Degradation:

MFCs can generate immediate electrical power through bacterial metabolism but suffer from significant performance loss—up to 90% reduction in power output after just 3 months of operation—due to biofilm accumulation on cathodes and proton exchange membranes [20].

- Irreversible Fouling-Related Decline:

Membrane biofouling in MFCs reduces ion exchange capacity, conductivity, and proton transfer rates, ultimately leading to cation transfer limitations and electrical generation deterioration.

- Maintenance and Operational Costs:

MFCs require external cleaning interventions or membrane replacements, which interrupt energy generation and increase operational costs [8,20].

- Energy Balance and System Optimization

Minimal Energy Consumption for Cleaning:

The energy consumption for electrochemical cleaning in EBR is minimal compared to the sustained energy output achieved through effective fouling prevention.

- Enhanced Energy Balance:

EBR systems optimize energy balance by minimizing maintenance-related energy losses and maximizing continuous power generation.

2) Anti-Fouling Strategies

a) Vibration-Induced Flow Disturbance (VIFD)

Technology Overview

Vibration-Induced Flow Disturbance (VIFD) using piezoelectric actuators represents an innovative anti-fouling technology for hybrid RED-CapMix systems . This approach leverages controlled vibrations to prevent membrane fouling through multiple synergistic mechanisms while maintaining system integrity.

Anti-Fouling Mechanisms

VIFD operates through three primary mechanisms: mechanical vibration effects that create flow disturbances preventing foulant deposition, reactive oxygen species (ROS) generation at high frequencies (>100 kHz) producing hydroxyl radicals and hydrogen peroxide with redox potentials of 1.9-2.7 V, and hydrodynamic enhancement through vortex creation improving mass transfer . These combined effects address both organic and inorganic fouling simultaneously [23].

Performance Benefits

Quantitative studies demonstrate significant improvements: up to 59% reduction in flux decline when operated at optimal conditions (100 kHz frequency, 100 Vpp voltage) [24] and 63.4% flux improvement for oil wastewater treatment applications [25]. The technology shows frequency-dependent performance with integrated "soft" PZT materials outperforming "hard" PZT at vibration amplitudes above 10 kHz [26]. VIFD effectively mitigates multiple foulant types including high-concentration oil (2500 ppm), bacteria, and charged colloidal particles [25].

Integration Strategy

For hybrid RED-CapMix-EBR systems, VIFD should be integrated at three key locations: directly into ion exchange membranes (AEM and CEM) within RED stacks for continuous fouling prevention, on CapMix electrode surfaces to maintain capacitive performance, and in pre-treatment sections to reduce downstream fouling load . Optimal placement requires membrane surface integration rather than external mounting to maximize vibrational energy transmission [21].

System Optimization

Different membrane types require specific frequency optimization: ceramic membranes perform optimally at 265 kHz with 20V amplitude [27], while polymeric membranes show best performance around 100 kHz [24]. Lead-free piezoelectric materials such as Mn/$BaTiO_3$ are preferred for water treatment applications due to non-toxic properties and environmental compatibility [28]. The system can be powered using generated energy from the RED-CapMix system itself, creating self-sustaining anti-fouling operation [21].

Implementation Advantages

VIFD integration provides 40-63% anti-fouling performance improvements through combined mechanical and chemical mechanisms, significantly extending operational life while maintaining energy harvesting efficiency [24, 25]. Real-time monitoring capabilities using electrochemical impedance spectroscopy enable adaptive fouling control responding to changing conditions [23]. This technology addresses critical membrane fouling challenges limiting practical salinity gradient power system implementation.

b) Zwitterion Coatings

Molecular Basis and Mechanism

Zwitterion coatings are composed of molecules containing both positive and negative charges, resulting in a neutral, superhydrophilic surface. This unique structure allows them to tightly bind water molecules, forming a dense hydration layer that acts as a robust barrier against organic, biological, and colloidal foulants such as extracellular polymeric substances (EPS), soluble microbial polymers (SMP), and proteins [5,16].

Anti-Fouling Performance

The hydration layer created by zwitterion coatings significantly reduces attractive forces between the membrane and foulants, minimizing nonspecific adsorption and making foulants easier to remove. Studies show that zwitterion-coated membranes can double operational cycles before cleaning is needed (e.g., from 32 to 66 days), maintain higher critical flux, and experience lower transmembrane pressure buildup compared to unmodified membranes [5].

Integration in Hybrid Systems

In hybrid RED-CapMix-EBR systems, applying zwitterion coatings to ion exchange membranes and electrode surfaces helps preserve long-term performance by minimizing irreversible foulant accumulation. These coatings are compatible with various membrane materials and can be applied using several methods, such as surface grafting or chemical vapor deposition [5,16].

Synergy with Other Strategies

Zwitterion coatings complement other anti-fouling approaches, such as Vibration-Induced Flow Disturbance, to ensure stable energy output and reliable operation. Their ability to maintain membrane integrity makes them essential for advancing practical, low-fouling salinity gradient energy systems.

VI. FUTURE SCOPE

In this study, we have focused on the theoretical integration of new anti-fouling technologies i.e., Zwitterion coatings, Vibration-Induced Flow Disturbance, and EBR systems into a new RED-CapMix hybrid model. While the results are very promising for enhanced membrane performance and energy production, it should be emphasized that the results are in an early and conceptual phase. Future research must be done with large-scale field experiments to ascertain the practicality of the proposed model, especially as this concept has high theoretical potential.

To increase the system's relevance to practical applications, more changes would be required to maximize energy efficiency and cost-effectiveness. One of them would be incorporating the system into a dam facility. There, available hydroelectric power generation could be utilized to greatly enhance overall energy output, while minimizing environmental impact. Such integration, however, must be maximized with care so as not to interfere with the dynamic water pressure and flow conditions characteristic of dam environments, while maximizing each standalone subsystem—such as RED, CapMix, and anti-fouling technologies to effectively perform.

A successful realization of such an optimization would not take energy production to an entirely new level but also minimize the use of rivers in energy production. This would, in turn, conserve natural ecosystems, keep wildlife intact, and create more room for human settlements near water sources- removing the usual problem where local communities are usually forced out to make way for huge energy projects. Such developments could ultimately establish a new benchmark for sustainable and environmentally friendly salinity gradient energy systems.

VII. CONCLUSION

In this paper, we have mentioned some different innovations applied in utilizing salinity gradient energy. To begin with, the whole system performs two purposes-wastewater treatment and power generation. The system incorporates biological elements (i.e, the biofilm of microorganisms of the EBR) and electrochemical systems in an attempt to miniaturize and make the process efficient. EBR, for example, is an innovation that reduces fouling to a much greater degree than the conventional MFCs.

The electrodes used throughout all 3 components of the system are also built with a particular set of materials. Specifically, the use of biochar, graphene, and zwitterionic coating, as a whole, is key to system efficiency enhancement. In the RED stack, the use of zwitterionic coating and piezoelectric actuators significantly prevents membrane fouling. Therefore, anti-fouling measures in RED membranes significantly reduce pollutants.

Our device uses RED and CapMix in order to harness the maximum energy that is available. Anti-fouling technology is used in RED, but CapMix does not suffer from this issue because it harvests energy without the need for membranes. It is thus able to harness the remaining salinity gradient to create energy without creating more issues.

At present, this model has been developed for producing clean energy from a comparatively smaller channel of wastewater. After being showcased in real-world conditions, the system can then be scaled up to dams- which contain much higher water flow. Consequently, it would be capable of producing more energy from fewer acres of land.

Overall, this integrated design provides us with a vision of a future that is full of hope where energy is being harnessed efficiently and in a sustainable manner.

REFERENCES

[1] Y. Mei and C. Y. Tang, "Salinity gradient energy: desalination and beyond," Environ. Sci. Technol., vol. 52, no. 7, pp. 3859–3875, Apr. 2018, doi: 10.1021/acs.est.7b06477.

[2] B. E. Logan and M. Elimelech, "Membrane-based processes for sustainable power generation using water," Nature, vol. 488, no. 7411, pp. 313–319, Aug. 2012, doi: 10.1038/nature11477.

[3] R. A. Rica et al., "Energy harvesting from salinity differences by reverse electrodialysis and capacitive mixing," J. Phys.: Condens. Matter, vol. 25, no. 12, p. 125901, Mar. 2013, doi: 10.1088/0953-8984/25/12/125901.

[4] D. Brogioli, "Extracting renewable energy from a salinity difference using a capacitor," Phys. Rev. Lett., vol. 103, no. 5, p. 058501, Jul. 2009, doi: 10.1103/PhysRevLett.103.058501.

[5] Y. He et al., "Zwitterionic polymers for anti-fouling membranes," J. Membr. Sci., vol. 510, pp. 30–39, Jul. 2016, doi: 10.1016/j.memsci.2016.03.028.

[6] M. Tedesco, H. V. M. Hamelers, and C. J. N. Buisman, "Reverse electrodialysis: Performance of a stack with 50 cells on the mixing of sea and river water," J. Membr. Sci., vol. 405–406, pp. 391–398, Jul. 2012, doi: 10.1016/j.memsci.2012.03.008.

[7] S. Porada, R. Zhao, A. van der Wal, V. Presser, and P. M. Biesheuvel, "Review on the science and technology of water desalination by capacitive deionisation," Prog. Mater. Sci., vol. 58, no. 8, pp. 1388–1442, Oct. 2013, doi: 10.1016/j.pmatsci.2013.03.005.

[8] B. E. Logan and J. M. Regan, "Electricity-producing bacterial communities in microbial fuel cells," Trends Microbiol., vol. 14, no. 12, pp. 512–518, Dec. 2006, doi: 10.1016/j.tim.2006.10.003.

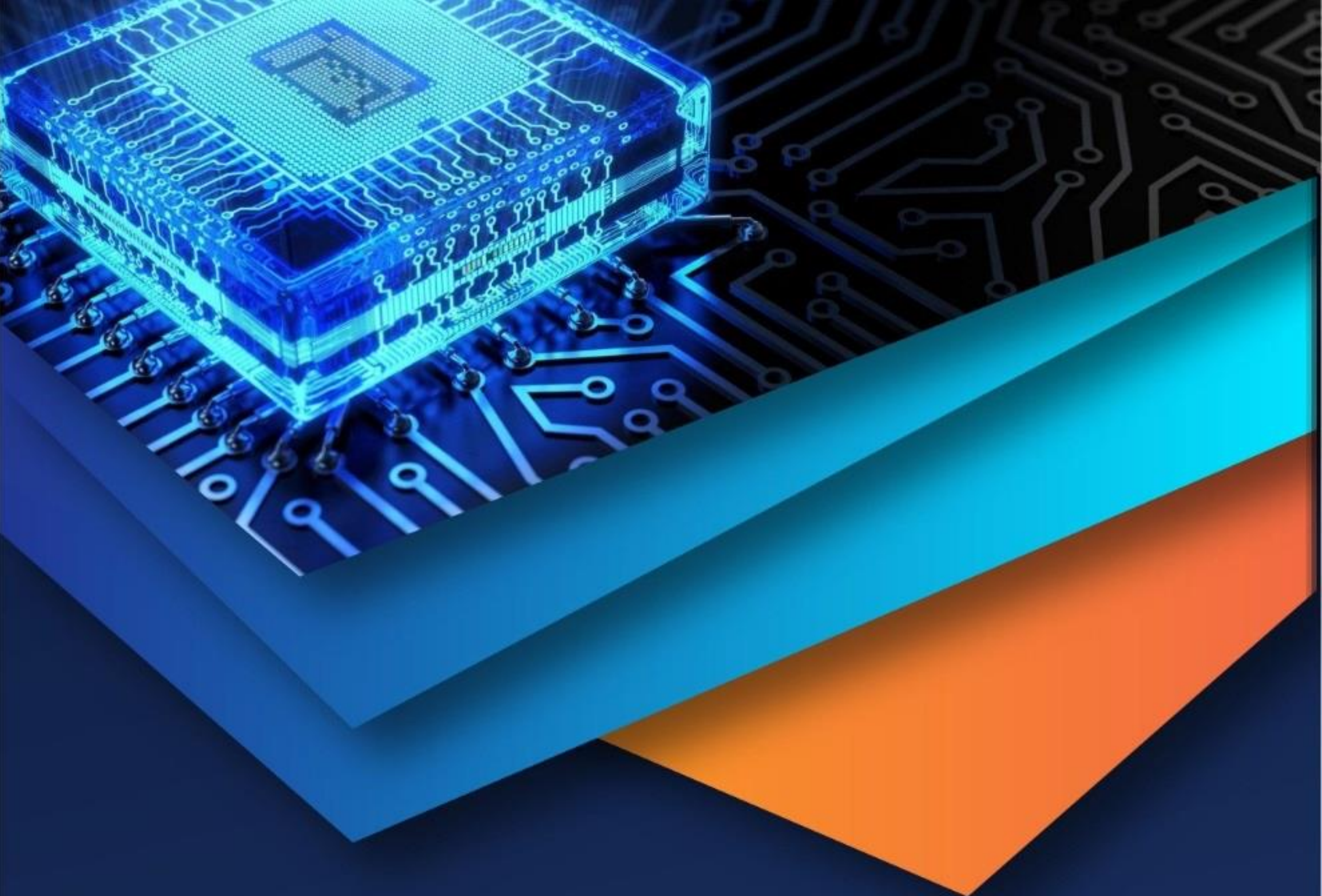
[9] C. Santoro et al., "Modular electrodes for scalable microbial fuel cells," Electrochim. Acta, vol. 247, pp. 423–432, Sep. 2017, doi: 10.1016/j.electacta.2017.07.013.

[10] D. Brogioli, "Extracting renewable energy from a salinity difference using a capacitor," Phys. Rev. Lett., vol. 103, no. 5, p. 058501, Jul. 2009, doi: 10.1103/PhysRevLett.103.058501

[11] Y. Liu et al., "Interdigitated electrode architecture for enhanced ion transport," Electrochim. Acta, vol. 174, pp. 394–401, Aug. 2015, doi: 10.1016/j.electacta.2015.05.165.

[12] E. Marsili, J. Sun, and D. R. Bond, "Voltammetry and growth physiology of Geobacter sulfurreducens biofilms," Electroanalysis, vol. 20, no. 5, pp. 619–626, Mar. 2008, doi: 10.1002/elan.200704159.

[13] T. M. Huggins et al., "Biochar as a sustainable electrode material for bioelectrochemical systems," Bioresour. Technol., vol. 157, pp. 114–119, Apr. 2014, doi: 10.1016/j.biortech.2014.01.058.
[14] T. Kim, J. Yoon, and J. Choi, "Capacitive mixing power generation using graphene electrodes," Energy Environ. Sci., vol. 9, no. 1, pp. 194–199, Jan. 2016, doi: 10.1039/C5EE02950B.
[15] I. Aranaz et al., "Functional characterization of chitin and chitosan," Curr. Chem. Biol., vol. 3, no. 2, pp. 203–230, May 2009, doi: 10.2174/187231309788166397.
[16] H. Yang, L. Liu, and H. Xie, "Zwitterionic polymers for antifouling membrane surface modification," J. Membr. Sci., vol. 627, p. 119199, Jun. 2021, doi: 10.1016/j.memsci.2021.119199.
[17] D. R. Lovley, "Microbial Energisers: Fuel Cells That Keep on Going," Microbe Magazine, vol. 1, no. 7, pp. 323–329, 2006.
[18] H. Li, J. Liu, Z. Fan, W. Tang, and C. Sun, "Chitosan–gelatin hydrogel as a flexible electrode matrix," Electrochim. Acta, vol. 220, pp. 596–604, Dec. 2016, doi: 10.1016/j.electacta.2016.10.153.
[19] C. J. N. Buisman, H. V. M. Hamelers, and M. Tedesco, "Salinity gradient energy: Sustainable power from oceans, rivers, and wastewater," Environ. Sci. Technol., vol. 47, no. 3, pp. 1191–1195, Feb. 2013, doi: 10.1021/es3045774.
[20] W. W. Li et al., "From wastewater to bioenergy and biochemicals via microbial fuel cells," Renew. Sustain. Energy Rev., vol. 45, pp. 540–555, May 2014, doi: 10.1016/j.rser.2014.04.009.
[21] Y. Wang et al., "Vibration-induced membrane cleaning in electrodialysis," Desalination, vol. 450, pp. 48–55, Jan. 2019, doi: 10.1016/j.desal.2018.10.010.
[22] Q. Zhao, L. Liu, and J. Wang, "Piezoelectric vibration as an anti-biofouling strategy in electrochemical systems," ACS Appl. Mater. Interfaces, vol. 12, no. 4, pp. 4892–4900, Jan. 2020, doi: 10.1021/acsami.9b19276.
[23] Z. Fangchao et al., "Increasing the vibration frequency to mitigate reversible and irreversible membrane fouling using an axial vibration membrane in microalgae harvesting," J. Membr. Sci., vol. 541, pp. 76–85, May 2017, doi: 10.1016/j.memsci.2016.11.031.
[24] Y. Park et al., "Effect of vibration on fouling propensity of hollow fiber membranes in microfiltration and membrane distillation," Desalination and Water Treatment, vol. 192, pp. 11–18, Jul. 2020, doi: 10.5004/dwt.2020.25151.
[25] C. Wang et al., "Insights on fouling development and characteristics during different fouling stages between a novel vibrating MBR and an air-sparging MBR for domestic wastewater treatment," Water Research, vol. 212, p. 118098, Apr. 2022, doi: 10.1016/j.watres.2022.118098.
[26] X. Liu, Y. Wang, and Z. Zhang, "Crossflow-induced membrane vibration and its effects on fouling and scaling in direct contact membrane distillation," J. Membr. Sci., vol. 694, p. 122410, Feb. 2024, doi: 10.1016/j.memsci.2023.122410.
[27] "Membrane Fouling Mitigation in Water Filtration Using Piezoelectrics," Purdue University Thesis Repository, Hammer Purdue.



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