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Original Article

Sustainable and Efficient Wastewater Treatment: A Novel Alginate Bead Membrane Solution

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Abstract: *Alginate, a natural biopolymer, has gained significant attention as a versatile material for developing sustainable and efficient membranes for wastewater treatment. This paper explores the recent advancements in fabricating and optimizing alginate membranes for enhanced performance. Various techniques, including casting, electrospinning, and 3D printing, are discussed for creating alginate membranes with tailored properties. To further optimize the performance of alginate membranes, strategies such as crosslinking, incorporation of porogens, and surface functionalization are employed. These modifications aim to improve mechanical strength, porosity, selectivity, and antifouling properties. Response Surface Methodology (RSM) has emerged as a powerful tool for optimizing the fabrication process, enabling the identification of optimal conditions for specific applications. The integration of alginate membranes with biological treatment processes, such as phycoremediation and mycoremediation, holds great promise for sustainable wastewater treatment. By immobilizing microorganisms on alginate membranes, enhanced biodegradation and pollutant removal can be achieved. Overall, this study provides a comprehensive overview of the state-of-the-art in alginate membrane technology for wastewater treatment. It highlights the potential of alginate membranes as a sustainable and effective solution for addressing global water pollution challenges.*

Keywords: *Alginate, Membrane, Wastewater, Optimization, Mycoremediation, Phycoremediation.*

I. INTRODUCTION

Alginate membranes have emerged as promising materials for wastewater treatment due to their unique properties. As a natural biopolymer derived from brown algae, alginate exhibits biocompatibility, biodegradability, and excellent gel-forming ability [1]. These characteristics make it suitable for various wastewater treatment applications. Alginate membranes can be employed in different configurations, including beads, fibers, and films. These membranes can effectively remove heavy metals, organic pollutants, and suspended solids from wastewater. Additionally, they can serve as immobilization matrices for microorganisms, enhancing biological treatment processes. The versatility and environmental friendliness of alginate membranes make them a potential alternative to conventional synthetic materials in wastewater treatment. However, challenges such as mechanical strength and cost-effectiveness need to be addressed for wider practical application [2]. Alginate membrane have a lot of advantages.

In the first place, they are biocompatible and biodegradable. Alginate is a natural polymer derived from brown algae, making it inherently safe for the environment. Its biodegradability ensures that it does not persist in the environment, reducing potential long-term impacts. A study by [3] demonstrated the successful degradation of alginate membranes in soil, highlighting their environmental friendliness.

Alginate membranes also possess a high porous structure, allowing for efficient diffusion of pollutants and water molecules. This high porosity enhances the contact area between the membrane and the contaminants, leading to improved adsorption and removal efficiency. [4] investigated the effect of pore size on the adsorption capacity of alginate membranes for heavy metals, confirming the positive correlation between porosity and removal efficiency. In addition, alginate can be modified through various techniques to tailor its properties for specific wastewater treatment applications. For instance, crosslinking with calcium ions can improve the mechanical strength of the membranes, while incorporating functional groups can enhance their affinity for specific pollutants. A study by [5] successfully modified alginate membranes with amino groups to improve their adsorption capacity for dyes.

Alginate also exhibits a strong affinity for a wide range of pollutants, including heavy metals, dyes, and organic compounds. This high adsorption capacity is attributed to the presence of functional groups within the alginate structure that can interact with pollutants through various mechanisms. [6] demonstrated the exceptional adsorption capacity of alginate membranes for removing lead ions from wastewater. Lastly, alginate readily forms hydrogels, enabling the creation of three-dimensional structures with high water retention capacity. This characteristic allows for the immobilization of microorganisms within the membrane, facilitating biological treatment processes. A research by [7] successfully encapsulated bacteria within alginate beads for the removal of organic pollutant

While alginate membranes offer several advantages, they also have certain limitations that hinder their widespread application in wastewater treatment. Alginate membranes are generally weak and susceptible to damage under harsh operating conditions due to their low mechanical strength. This limits their durability and lifespan, requiring frequent replacement. Another challenge is that the porous structure of alginate membranes can easily become clogged with suspended solids and organic matter, reducing their permeability and efficiency over time. Another challenge is that alginate membranes may degrade in certain chemical environments, such as those with high acidity or alkalinity, reducing their effectiveness.

In addition, balancing high selectivity for target pollutants with good water permeability remains a challenge. [8] explored the development of advanced alginate membrane structures to achieve enhanced selectivity and permeability for efficient wastewater treatment. Finally, it is biodegradable in complex wastewater. The presence of complex organic matter in wastewater can hinder the biodegradation rate of alginate membranes. [9] investigated strategies to improve biodegradability in complex wastewater environments.

Traditional wastewater treatment methods frequently fail to eliminate persistent pollutants and emerging contaminants [10]. Mycoremediation and Phycoremediation present promising alternatives by taking advantage of the natural metabolic abilities of fungi and microalgae, respectively, for treating wastewater [11]. This literature review aims to understand the latest developments in fabricating and using alginate membranes for wastewater treatment, particularly for slaughterhouse wastewater, assess the potential of combining mycoremediation and phycoremediation with alginate membranes to improve treatment efficiency, and identify knowledge gaps and future research directions in this area.

II. ALGINATE-BASED MEMBRANE TECHNOLOGY: A BREAKTHROUGH IN WASTEWATER TREATMENT AND REUSE

Alginate, a natural biopolymer sourced from brown algae, has proven to be a promising material for developing membranes for wastewater treatment, thanks to its inherent benefits. This section explores the essential properties of alginate membranes that make them ideal for wastewater treatment applications.

A. Properties of Alginate Membranes for Wastewater Treatment

Here, we focus on some of the properties of alginate membranes. *Biocompatibility and biodegradability:* Alginate, being a natural material, breaks down under certain environmental conditions. This biodegradability reduces the environmental impact of the membranes compared to synthetic options. Furthermore, alginate's biocompatibility ensures minimal environmental harm during membrane disposal or accidental release [12]. *Tailorable Properties:* Alginate membranes are notably versatile allowing their properties to be adjusted through different methods to optimize their effectiveness for particular wastewater treatment needs. For instance, crosslinking with cations such as calcium can enhance mechanical stability and adding nanoparticles can boost selectivity and adsorption capacity for specific pollutants [13]. *Chemical Functionality:* Lastly, alginates contain functional groups (carboxylate) that can engage with different pollutants via electrostatic interactions or complexation [14]. This natural chemical functionality enables alginate membranes to eliminate specific contaminants without requiring further modifications.

B. Fabrication Methods for Alginate Membranes

The method of fabrication is vital in defining the properties and performance of alginate membranes for wastewater treatment. Various techniques can be used to create alginate membranes, each offering its own benefits and drawbacks.

Solvent casting/evaporation: This commonly used method involves casting an alginate solution onto a mold and letting it evaporate to form a thin membrane film. The membrane’s properties, such as porosity and thickness, can be regulated by altering the concentration of the alginate solution and the casting parameters [15]. Another technique is the immersion precipitation. This technique involves immersing a sodium alginate solution in a calcium chloride ($CaCl_2$) bath, causing gelation through ionic crosslinking with calcium ions (Ca_{2+}). The membrane properties can be customized by adjusting the concentration of the alginate solution, the immersion time, and the bath composition. This straightforward method is suitable for large-scale membrane production [15].

Electrospinning: This technique uses an electric field to produce thin alginate fibers, which are then collected to form a non-woven membrane structure. Electrospinning enables the creation of membranes with highly interconnected pores and a large surface area, making it advantageous for wastewater treatment applications [15]. Spray coating: This method involves applying an alginate solution onto a substrate through spraying, followed by drying or gelation to create a membrane layer. Spray coating allows for precise control over membrane thickness and can be used to coat different types of support materials [15].

Dissolution-Gelation: This involves dissolving alginate in water, then adding a cross-linking agent (usually a divalent cation like calcium) to induce gelation and form the membrane. This process is straightforward and cost-effective, allowing control over membrane properties by adjusting the alginate concentration, type and concentration of the cross-linking agent, and casting conditions. However, the membranes produced may have limited mechanical strength, especially for high-pressure wastewater treatment applications [15]. Bioprinting: This innovative technique uses 3D printing technology to fabricate complex alginate membrane structures with specific shapes and channels. It allows for precise control over membrane architecture, which can improve performance in specific wastewater treatment processes. However, bio-printing is still in development and requires specialized equipment, making it a less commonly used fabrication method at present [15].

a) Cross-Linking Fabrication Technique: A Fabrication Method for Alginate Membranes

Cross-linking is an essential step in creating alginate membranes for wastewater treatment. It involves forming covalent or ionic bonds between alginate chains, enhancing the membrane's mechanical strength and stability [16]. There are some common cross-linking agents for alginate membranes include: *Divalent Cations:* Calcium ions (Ca^{2+}) are the most commonly used cross-linking agents for alginate due to their availability and ease of application [17]. The cross-linking process involves immersing the sodium alginate membrane in a $CaCl_2$ solution, which forms ionic bonds between Ca^{2+} and the carboxylate groups of alginates. The density of crosslinking can be adjusted by varying the concentration of the $CaCl_2$ solution and the immersion time. *Multivalent Metal Ions:* Other metal ions, such as aluminum (Al^{3+}) and iron (Fe^{3+}), can also be used for crosslinking alginate membranes [12]. These multivalent ions can provide stronger crosslinking compared to Ca^{2+}, but they may pose additional challenges, such as potential toxicity or compatibility issues with wastewater. *Chemical Crosslinkers:* Synthetic agents like glutaraldehyde can be employed to create covalent bonds between alginate chains [18]. Covalent crosslinking typically offers better mechanical stability than ionic crosslinking, but it may also raise concerns regarding environmental impact and potential toxicity.

This research centers on the crosslinking technique, specifically using calcium chloride and a combination of calcium chloride and sodium tetraborate as crosslinking agents. By optimizing the parameters of the crosslinking process, the goal is to achieve an ideal balance of mechanical strength, porosity, and biodegradability for alginate membranes used in treating slaughterhouse wastewater. The choice of fabrication method greatly impacts the properties and performance of alginate membranes.

II. MEMBRANE MODIFICATION FOR WASTEWATER TREATMENT

Alginate membranes have significant potential for wastewater treatment, but their properties and limitations can be improved through various modification techniques. This section examines different methods for modifying alginate membranes, including the use of porogens, stabilizers, and anti-fouling agents, to enhance their performance in wastewater treatment applications.

A. Porogen Modification for Alginate Membranes

A key strategy to enhance alginate membranes for wastewater treatment is through membrane modification. This section examines different modification techniques, with a focus on porogen modification to control the pore structure and improve the membranes' permeability and selectivity. Porosity is vital for wastewater treatment, affecting water flow and pollutant rejection. Porogen modification involves adding foreign materials to the alginate solution during membrane fabrication, which form pores in the membrane after their removal. This affects pore size, distribution, and the overall performance of the membrane. The pore structure is essential for the effectiveness of alginate membranes in wastewater treatment, influencing water permeation and contaminant rejection [19]. We will now review various types of porogens used to modify alginate membranes.

a) Types of Porogens Used to Modify Alginate Membranes

The types of porogens used to modify alginate membranes are explained below:

Inorganic Porogens: Enabling precise control over pore structure. When compared to other inorganic porogens, calcium carbonate ($CaCO_3$) is widely used, biocompatible, and easily removable porogen. By adjusting the size and concentration of $CaCO_3$ particles, the pore size and distribution can be controlled. However, residual $CaCO_3$ may impact membrane performance, necessitating thorough washing.

Natural Polymers: An attractive alternative as a sustainable material. These include: Starch: Starch is a biocompatible and easily accessible natural polymer used as a porogen. It creates interconnected pores in the membrane after removal, which can improve permeability. However, starch can degrade under specific wastewater conditions, potentially compromising membrane stability. Cellulose: Cellulose, another widely available and biocompatible natural polymer, can serve as a porogen to form well-defined pores in alginate membranes. The pore structure is influenced by the size and shape of the cellulose particles. However, fully removing cellulose from the membrane can be difficult. Lignin: Lignin, a natural biopolymer derived from wood, is attracting attention as a porogen because of its biocompatibility and ability to creat hierarchical pore structures. However, research on using lignin as a porogen for alginate membranes is still preliminary, and more studies are required to enhance its effectiveness.

Other Porogens includes ice crystals. This technique involves forming ice crystals within the membrane structure, which are then melted to create well-defined pores. The size and distribution of these pores can be adjusted by changing the freezing conditions, such as temperature and duration. Although this method provides precise control over pore structure, it can be difficult to scale up for industrial use. Naphthalene. Naphthalene is frequently used as an organic porogen in alginate membranes, as it forms a highly interconnected pore structure that can enhance water permeability. However, naphthalene is a volatile organic compound (VOC) with potential environmental and health concerns. Residual naphthalene can adversely affect the membrane's performance and pose safety risks. Consequently, ensuring complete removal of naphthalene is essential, which may involve additional steps and could increase the environmental impact of the process.

b) Optimizing Alginate Membrane Development: Identifying The Ideal Porogen

Selecting an appropriate porogen depends on several factors. First, the *pore characteristics*: The size, distribution, and connectivity of the pores should be tailored to target pollutants. *Biocompatibility and Environmental Impact:* Biocompatible natural polymers are preferred for eco-friendly applications, minimizing environmental impact. *Removal Method:* The method for removing the porogen should be effective, avoid damaging the alginate structure, and minimize harsh chemicals. *Ease of Removal:* Porogens should be easily and completely removed from the membrane. *Cost and Availability:* Economic feasibility and accessibility of the porogen are also important.

Future Considerations: Ongoing research is focused on developing new porogens for alginate membranes, including stimuli-responsive porogens that can be removed under specific conditions (such as temperature or pH) and sustainable or recyclable options to reduce environmental impact.

B. Stabilizers for Alginate Membrane: Boosting the Mechanical Strength and Stability

While alginate membranes offer many benefits, they can sometimes show limited mechanical stability, especially in harsh wastewater conditions. Stabilizers are additives added to the membrane to improve its mechanical strength and reduce degradation. This section explores various stabilizers that are commonly used to reinforce alginate membranes. *Cross-linking Agents for Improved Stability:* Cross-linking is a key process in the fabrication of alginate membranes using the dissolution-gelation method. While calcium ions (Ca^{2+}) are commonly used, alternative cross-linking agents can enhance stability. For example, research by [20] explored zirconium ions (Zr^{4+}) as a cross-linking agent, showing that it provides better mechanical strength and stability than calcium-cross-linked membranes. *Polymers:* Adding synthetic or natural polymers to the alginate matrix can strengthen its mechanical properties. [19] studied the blending of alginate with polyvinyl alcohol (PVA), resulting in composite membranes with improved mechanical strength and better resistance to degradation in saline conditions. *Clay Minerals:* Clay minerals, like montmorillonite, can serve as stabilizers for alginate membranes. These clays enhance the mechanical strength and barrier properties of the membranes.

a) Choosing the Right Stabilizer for Alginate Membranes

The selection of a suitable stabilizer depends on the following several factors. *Desired Improvement:* The choice of stabilizer should align with the main objective, whether it's to enhance mechanical strength, resistance to degradation, or achieve particular functional properties. *Biocompatibility:* For applications focused on environmental friendliness, stabilizers that are biocompatible are preferred. *Compatibility with Alginate:* The stabilizer must be compatible with the alginate matrix to ensure effective integration and performance. *Cost and Availability:* Consideration should be given to the economic feasibility and accessibility of the stabilizer.

C. Anti-Fouling Agents for Alginate Membranes

Membrane fouling is a significant issue in wastewater treatment, where organic and inorganic materials build up on the membrane surface, reducing its effectiveness. Anti-fouling agents are additives added to the membrane to reduce fouling and enhance long-term performance. This section reviews some frequently used anti-fouling agents for alginate membranes. *Hydrophilic Modifiers:* Adding hydrophilic groups, such as polyethylene glycol, to the membrane surface can form a water-repellent layer that reduces the adhesion of foulants [17]. *Nanoparticles:* Integrating specific nanoparticles, like silica nanoparticles, into the membrane structure can act as a physical barrier against foulants and enhance membrane hydrophilicity [12]. *Zwitterionic Materials:* These materials, which have both positive and negative charges, create repulsive forces that reduce the attachment of organic foulants [19]. *Clay Minerals:* Clay minerals, such as kaolin, can also serve as anti-fouling agents. They create a physical barrier and improve the surface properties of the membrane, similar to their role as stabilizers [18].

a) Selecting Effective Anti-Fouling Agents: A Crucial Step in Membrane Maintenance

Selection of suitable anti-fouling agent depends on the type of wastewater being treated, and the dominant fouling mechanisms. Here are some considerations: *Effectiveness Against Specific Foulants:* The anti-fouling agent should effectively target the primary foulants present in the specific wastewater stream. *Compatibility with Alginate:* The agent must be compatible with the alginate matrix to ensure proper integration and minimal interference with membrane properties. *Durability:* The anti-fouling properties should be long-lasting and maintain their effectiveness throughout extended periods of operation.

b) Future Consideration

Research is continuously investigating new anti-fouling agents that offer enhanced effectiveness and long-term stability to tackle the persistent issue of membrane fouling in wastewater treatment. The following are some promising areas of exploration:

i) Self-Cleaning Membranes:

These membranes are designed with mechanisms that allow them to periodically cleanse themselves of foulants. Strategies include surface modifications to create a slippery surface, incorporating enzymes to break down foulants, or using responsive materials that trigger self-cleaning under specific conditions such as changes in light or pH.

ii) Stimuli-Responsive Anti-Fouling Agents:

These agents are engineered to react to external triggers like light, pH changes, or electric fields. For instance, light-responsive agents can be activated periodically to either release foulants or increase their hydrophilicity, thereby reducing the adhesion of contaminants. Such agents provide the benefit of controlled release and precise anti-fouling actions.

iii) Biomimetic Approaches:

Drawing inspiration from nature, researchers are examining the anti-fouling characteristics of marine organisms like barnacles and mussels. This research aims to create biomimetic surface modifications for alginate membranes, emulating the natural defenses these organisms use to prevent fouling.

iv) Combined Approaches:

Utilizing multiple anti-fouling methods together may enhance effectiveness and offer more comprehensive protection against different fouling mechanisms. This could include blending hydrophilic polymers with charged components or incorporating nanoparticles that have self-cleaning properties.

v) Sustainable and Eco-Friendly Antifouling Agents:

Are essential for advancing environmentally responsible wastewater treatment methods. This involves investigating the potential of natural resources such as biopolymers, plant extracts, and other accessible, low-impact materials. By focusing on these avenues, researchers seek to develop alginate membranes with enhanced antifouling capabilities, resulting in improved durability and decreased maintenance needs for wastewater treatment systems.

III. RESPONSE SURFACE METHODOLOGY (RSM) FOR OPTIMIZATION OF ALGINATE MEMBRANE FABRICATION AND ITS APPLICABILITY IN WASTEWATER TREATMENT

Optimizing the fabrication of alginate membranes for targeted wastewater treatment applications is essential for ensuring high performance and efficiency. Response Surface Methodology (RSM) stands out as an effective statistical tool to accomplish this objective [21]. This section examines the use of RSM in refining alginate membrane fabrication and highlights its benefits for wastewater treatment.

A. Central Composite Design In RSM

Response Surface Methodology (RSM) employs various statistical and mathematical methods to explore the relationship between multiple independent variables (factors) and a target response (output) [22]. Central Composite Design (CCD) is one of the most widely used designs within RSM, providing a systematic approach for conducting optimization experiments. [23] gave a detailed explanation of CCD as it applies to alginate membrane fabrication.

Factors: These represent the various parameters you can control during membrane fabrication, such as alginate concentration, crosslinking agent type and concentration (e.g., calcium chloride concentration), porogen type and concentration (if applicable), curing time or temperature, and stirring speed (during membrane casting).

Response: This is the desired outcome you want to optimize, which could be pure water permeability (measures water flux through the membrane), rejection rate of specific pollutants (e.g., organic matter, heavy metals) and mechanical strength of the membrane.

Advantages of optimizing alginate membranes: Central Composite Design (CCD) enables efficient exploration of the factor space with fewer experimental runs compared to traditional one-variable-at-a-time methods. Secondly, CCD not only highlights the individual effects of each factor on the response but also uncovers interactions between them. For instance, the impact of alginate concentration on permeability might vary depending on the concentration of the crosslinking agent used. Finally, RSM produces a mathematical model that predicts the response within the studied factor space, allowing researchers to pinpoint the optimal combination of factors to achieve the desired membrane properties.

IV. MYCOREMEDIATION AND PHYCOREMEDIATION FOR WASTEWATER TREATMENT

Traditional wastewater treatment methods, though effective, frequently produce secondary waste and demand significant energy. Biological treatment methods, such as mycoremediation and phycoremediation, present promising alternatives for more sustainable and efficient wastewater treatment.

In mycoremediation, **f**ungi exhibit bio-sorption abilities that allow them to degrade a broad spectrum of pollutants, such as organic matter, pharmaceuticals, and heavy metals. For example, [11] showcased the effectiveness of fungal strains in breaking down organic pollutants in slaughterhouse wastewater. In phycoremediation, microalgae provide several benefits for wastewater treatment, including nutrient removal, pollutant degradation, and biomass production for biofuel applications. Recent research by [6] investigated the potential of microalgae to remove nitrogen and phosphorus from various wastewater sources.

This section examines the use of fungi (mycoremediation) and microalgae (phycoremediation) in wastewater treatment.

A. Fungal Applications in Mycoremediation

Mycoremediation employs fungi to degrade, transform, or immobilize pollutants in contaminated environments. These fungi provide several benefits for wastewater treatment.

- Biodegradation: Fungi have a range of enzymes capable of breaking down complex organic pollutants in wastewater, such as hydrocarbons, pharmaceuticals, and pesticides.
- Bio-sorption: The cell walls of fungi can serve as biosorbents, binding pollutants through physical and chemical interactions.
- Bioaccumulation: Certain fungi can accumulate heavy metals and other contaminants in their biomass, effectively concentrating and removing these pollutants from wastewater.
- Stress tolerance: Fungi can tolerate various environmental conditions, including high organic loads and toxic compounds, making them effective for treating different types of wastewater.

a) Fungal Applications in Mycoremediation

There is need to experiment for better alternatives for wastewater treatment with the advantage of reducing energy consumption and reduce sludge generation. *White-rot fungi:* These fungi are highly effective at degrading complex organic pollutants due to their production of ligninolytic enzymes, such as laccase and peroxidase [24]. They are particularly useful for treating industrial wastewater containing dyes, textiles, and pharmaceuticals. *Brown-rot fungi:* These fungi are specialized in breaking down cellulose and hemicellulose. Although they are not directly used for removing organic pollutants, they can be applied for the pretreatment of wastewater with high organic matter content. *Metal-accumulating fungi:* These fungi are selected for their capacity to biosorb or bioaccumulate heavy metals from wastewater, making them valuable for treating industrial wastewater with heavy metal contaminants.

b) Challenges and Future Considerations

A lot of challenges face the applications of fungi in Mycoremediation. Effective mycoremediation involves choosing the right fungal strains that possess the necessary degradation or biosorption capabilities for the specific pollutants present in the wastewater. Secondly, factors such as nutrient supplementation, aeration, and pH control must be optimized to support efficient fungal growth and pollutant removal. Finally, mycoremediation can be combined with physical or chemical treatments for comprehensive wastewater treatment, depending on the complexity of the wastewater.

B. Microalgae Applications in Phycoremediation

Phycoremediation uses microalgae, microscopic photosynthetic organisms, for wastewater treatment. Microalgae provide several benefits for this process.

- Nutrient Removal: Microalgae effectively remove excess nutrients like nitrogen and phosphorus from wastewater as they use these nutrients for their growth, helping to prevent eutrophication in receiving water bodies [25].
- Organic Pollutant Degradation: Certain microalgae can degrade complex organic pollutants, such as hydrocarbons and pharmaceuticals, through their metabolic processes [26].
- Biomass Production: The biomass generated by microalgae during wastewater treatment can be repurposed for

various uses, including biofuel production or as fertilizer, adding value to the treatment process.
- CO_2 Fixation: Microalgae use CO_2 in photosynthesis, aiding in greenhouse gas reduction while treating wastewater.

a) Microalgae Applications in Wastewater Treatment

Here are some potential applications of microalgae in wastewater treatment.

- Municipal wastewater treatment: Microalgae can remove excess nutrients and organic matter from municipal wastewater prior to its discharge.
- Industrial wastewater treatment: Certain microalgae strains can be selected to address pollutants specific to various industrial wastewater streams.
- Combined treatment with bacteria: Combining microalgae with bacterial cultures can form a synergistic treatment system, where bacteria break down complex organic matter, and microalgae use the resulting by-products for growth.

VI. REVIEW OF RELEVANT LITERATURE

A. Alginate Membrane Modification for Wastewater Treatment

Alginate membranes, made from the naturally sourced alginate biopolymer, have gained attention as an effective technology for wastewater treatment because of their natural benefits. However, to overcome certain limitations and boost their efficiency, different modification techniques have been investigated. This section provides an overview of recent studies on the modification of alginate membranes to enhance their performance in wastewater treatment applications.

a) Porogen Modification

Porogens are substances added to the membrane during fabrication that form pores once they are removed. The characteristics of these pores, such as their size, distribution, and connectivity, are vital in influencing water permeability, contaminant filtration, and overall membrane effectiveness. Researchers are investigating innovative porogens, including those that respond to stimuli and can be removed under particular conditions like temperature or pH [19]. Moreover, there is increasing interest in using sustainable and recyclable porogens to reduce environmental impact [18].

i) Efficiency and Selectivity of Porogens

The choice of porogens is essential in shaping the pore structure of alginate membranes, which directly impacts their permeability and selectivity for specific pollutants. The size, distribution, and connectivity of these pores greatly affect how well the membrane can permeate water and selectively filter out target pollutants [19]. Research by [27] and [18] highlights the successful use of porogens like calcium carbonate, natural polymers (such as starch and cellulose), and ice crystals in forming well-defined pores. This results in improved water permeability and better rejection of organic pollutants from wastewater.

- Inorganic Porogens: Calcium carbonate ($CaCO_3$) is a commonly used inorganic porogen because of its biocompatibility, ease of removal, and ability to control pore size [19]. However, any leftover $CaCO_3$ particles can impact the membrane's performance, necessitating thorough washing.
- Natural Polymers: Biocompatible and easily accessible natural polymers such as starch, cellulose, and lignin are becoming increasingly popular as porogens [12;18]. These materials provide benefits like environmental sustainability and the formation of hierarchical pore structures. However, challenges arise with the incomplete removal of certain natural polymers like cellulose and the potential degradation of starch in specific wastewater conditions.
- Ice Crystals: The use of ice crystals, which form and then melt within the membrane structure, provides effective control over pore size but poses challenges when scaling up for larger applications [19].
- Naphthalene: Naphthalene is highly effective at forming interconnected pores, but as a volatile organic compound (VOC), it poses environmental and health risks. Ensuring its complete removal is essential but can also raise the environmental impact of the process [17].
- Biocompatibility And Sustainability: With increasing emphasis on sustainable and eco-friendly methods, there is a rising interest in using biocompatible porogens such as natural polymers. [12] explored the potential of lignin, a widely available biopolymer, as a porogen for alginate membranes. However, additional research is required to enhance its effectiveness.

b) Stabilizers For Mechanical Strength

Alginate membranes often have limited mechanical strength, especially under harsh wastewater conditions. To address this, stabilizers are added to the membrane structure to increase its durability and prevent degradation. Current research is aimed at creating innovative, biocompatible, and sustainable stabilizers, such as those derived from natural sources like cellulose nanofibers [12]. Moreover, researchers are also investigating stabilizers that provide extra benefits, such as enhanced antifouling properties [28].

i) Crosslinking Optimization:

Crosslinking with cations, such as calcium, is a common technique for improving mechanical strength. The choice and concentration of crosslinking agents, like calcium chloride, can also affect properties like porosity and selectivity [17]. However, recent research has focused on alternative crosslinking agents and their effects on other membrane properties.

[20] explored new crosslinkers derived from natural resources, aiming to enhance mechanical strength while preserving biocompatibility and came up with some conclusions.

1. Incorporation of Reinforcing Agents:

Adding materials such as cationic polymers (e.g., chitosan) or clay minerals can further strengthen mechanical stability. Cationic polymers like chitosan interact with the negatively charged groups of alginates, enhancing membrane stability [19]. [28] showed that chitosan improves both the strength and antifouling properties of alginate membranes. Similarly, [18] explored the use of clay minerals to enhance barrier properties. Clay minerals like montmorillonite can boost mechanical strength and provide physical barriers for better contaminant rejection [18]. However, it is important to carefully evaluate the impact on permeability during the optimization process.

2. Biocompatible Reinforcements:

Using biocompatible reinforcing agents such as cellulose nanofibers provide a sustainable way to enhance strength while maintaining biodegradability [12]. [29] investigated the application of cellulose nanofibers to create durable and biocompatible alginate membranes for wastewater treatment.

c) Anti-Fouling Agents for Long-Term Performance

Membrane fouling presents a significant challenge in wastewater treatment, as organic and inorganic substances build up on the membrane surface, obstructing flow and diminishing performance. Anti-fouling agents, which are additives introduced into membranes, aim to reduce fouling and preserve their efficiency over time. Ongoing research is focused on developing innovative anti-fouling agents that offer enhanced effectiveness and durability. This includes the investigation of self-cleaning membranes and stimuli-responsive agents that can be activated by external factors, such as light or pH changes, to enable controlled release and targeted effects [19].

- Hydrophilic Surface Modification: By integrating hydrophilic polymers such as polyethylene glycol (PEG), a water-attracting surface is formed, which minimizes the attachment of organic foulants. [30] showed that PEG modification significantly improves the antifouling capabilities of alginate membranes in the treatment of oily wastewater.
- Charged Polymers for Repulsion: Charged polymers, like zwitterionic polymers, provide a wide range of anti-fouling effects by repelling both organic and inorganic contaminants. [31] investigated the use of zwitterionic polymers to create alginate membranes with enhanced antifouling properties for treating municipal wastewater.
- Nanoparticles for Antimicrobial Properties: The integration of nanoparticles with antimicrobial characteristics, such as silver nanoparticles, can provide targeted anti-fouling effects. Nonetheless, the possible environmental implications of using nanoparticles must be carefully evaluated.
- Natural Anti-foulants: Natural extracts, like those from seaweed or plants, are being studied for their potential as anti-fouling agents because of their biocompatibility and eco-friendly properties. [19] emphasized the need for additional research to assess their effectiveness across various wastewater streams.

i) Future Perspective and Recommendations

The future perspective for anti-fouling agents are listed below. The development of new biocompatible and sustainable porogens and stabilizers; The Investigation of advanced anti-fouling agents with enhanced effectiveness and durability, including self-cleaning membranes and stimuli-responsive agents; The combination of multiple modification techniques to achieve synergistic effects and broader protection against various fouling mechanisms; and the leveraging of artificial intelligence and machine learning to further optimize membrane fabrication processes.

d) Relevant Studies on Porosity Modification Using Naphthalene

Alginate membranes hold great potential for wastewater treatment due to their biocompatibility and biodegradability. However, their performance can be significantly enhanced by adjusting their porosity. Naphthalene, a widely accessiblearomatic hydrocarbon, has been investigated as a porogen in alginate membranes. This review examines studies that explore the use of naphthalene for modifying porosity in alginate membranes for wastewater treatment applications.

[17] detailed the preparation and characterization of innovative PVDF/alginate composite ultrafiltration membranes using a novel non-solvent induced phase separation (NIPS) technique. Their research demonstrates the application of

naphthalene for porosity modification in PVDF/alginate composite membranes for microfiltration. The study found that water permeability increased with higher naphthalene content, but the authors warned against using excessive amounts due to the risk of membrane defects. [12] published a review on alginate-based microfluidic devices for environmental monitoring and pollutant removal. This review discusses the use of various porogens, including naphthalene, in alginate membranes, emphasizing the need to optimize porogen concentration and removal processes to achieve the desired pore characteristics.

i) Advantages of Naphthalene as a Porogen

The advantages of naphthalene as a porogen are explained in this subsection.

- Effective Pore Formation: Naphthalene shows strong compatibility with alginate and effectively forms well-defined, interconnected pores after sublimation (removal through heating) [17]. This results in a porous structure that improves water permeability and supports the transport of water and small molecules through the membrane.
- Tunable Pore Size: The pore size and distribution in alginate membranes can be customized by varying the concentration of naphthalene during fabrication [17]. This enables the adjustment of membrane properties to suit specific applications.
- Relatively Simple Removal: Naphthalene can be removed through sublimation at moderate temperatures, making it a more convenient porogen compared to some alternatives [19]. This process minimizes the risk of damaging the membrane structure during removal.

ii) Challenges of Naphthalene as a Porogen

Some of the challenges observed from the application of naphthalene as a porogen are explained below.

- Environmental Concerns: Naphthalene is a volatile organic compound that poses potential environmental and health risks. Strict safety measures are essential during its handling and disposal to mitigate its environmental impact.
- Potential Membrane Defects: Using high concentrations of naphthalene can result in large and irregular pores, which may compromise the membrane's mechanical strength and selectivity [12].
- Residual Naphthalene: Incomplete removal of naphthalene from the membrane can impair its performance and raise environmental concerns. It is crucial to optimize the removal process to address this issue.

iii) Future Directions for the Choice of a Porogen

These include:

- Exploration of alternative porogens: Research is underway to find more environmentally friendly and sustainable porogen materials that can provide similar advantages to naphthalene for alginate membrane fabrication.
- Combined porogen techniques: Combining naphthalene with other porogens or employing multi-step porogen strategies may allow for more precise control of pore size distribution and improved membrane properties.
- Development of efficient naphthalene removal techniques: Enhancing the sublimation process or investigating alternative removal methods can reduce residual naphthalene content and address environmental concerns.

e) Studies on Kaolin as an Anti-Fouling Agent for Alginate Membrane

Membrane fouling continues to be a major issue in wastewater treatment, affecting membrane performance and necessitating frequent cleaning. Anti-fouling agents are additives used in membranes to reduce the accumulation of organic and inorganic contaminants on their surfaces. Kaolin, a layered silicate clay mineral, has been identified as a promising anti-fouling agent for alginate membranes. This review examines studies that explore the use of kaolin to reduce fouling in alginate membranes for wastewater treatment.

i) Potential Benefits of Kaolin as an Anti-Fouling Agent

The benefits of the use of kaolin as an anti-fouling agent as explained here.

- Physical Barrier Effect: The layered structure of kaolin can function as a physical barrier, preventing the attachment and build-up of organic and inorganic foulants on the membrane surface surface [18]. This helps reduce the initial adsorption of organic molecules and microorganisms that can lead to biofilm formation.
- Improved Membrane Selectivity and Hydrophilicity: Incorporating kaolin into alginate membranes may enhance their selectivity for specific pollutants by blocking larger foulants while allowing water to pass through [32]. Additionally, kaolin can increase the membrane's hydrophilicity, decreasing interactions with hydrophobic foulants [19].
- Enhanced Mechanical Strength: The addition of kaolin may also strengthen alginate membranes due to its reinforcing effect within the membrane structure [17;20]. This improvement in mechanical strength could enhance the membrane's resistance to fouling and cleaning processes [20].

ii) Kaolin as an Anti-Fouling Agent: Considerations and Challenges

The challenges are explained below.

Trade-off between Permeability and Fouling Reduction. Too much kaolin may reduce membrane permeability by clogging pores. It is important to optimize kaolin concentration to balance anti-fouling properties with water flow [18].

Potential for Caking. Kaolin particles can aggregate and form cakes on the membrane surface, which may inadvertently contribute to fouling if they are not well dispersed within the membrane matrix [19].

Long-term Stability and Fouling Removal. Additional research is needed to assess the long-term stability of kaolin's anti-fouling effects and to develop effective cleaning methods for kaolin-modified membranes after fouling occurs.

The review by [18] explores different modification techniques for polysaccharide-based membranes, including the application of kaolin in treating oily wastewater. It stresses the need to optimize kaolin levels to balance fouling reduction and membrane permeability. [33] examined kaolin/sodium alginate composite membranes for removing humic acid, showing enhanced selectivity and anti-fouling properties compared to pure alginate membranes. The review by [12] addresses various challenges with alginate membranes, including fouling, and emphasizes the need for further research on anti-fouling methods, suggesting that kaolin could be a promising option.

iii) Kaolin as an Anti-Fouling Agent: Future Directions

Some of the future directions are explained here.

- Surface Modification of Kaolin: Treating kaolin particles with hydrophilic groups could improve their compatibility with alginate and enhance their dispersion within the membrane matrix, potentially reducing caking and boosting anti-fouling performance.
- Optimizing Kaolin Incorporation: Research is needed to determine the ideal kaolin content and incorporation techniques that balance anti-fouling effectiveness with membrane permeability and long-term stability.
- Combined Strategies: Investigating the combined effects of kaolin with other anti-fouling agents, such as polymers or nanoparticles, could lead to advanced alginate membranes with enhanced anti-fouling properties.
- Modelling and Simulation: Creating models to simulate interactions between kaolin and foulants on the membrane surface could help refine kaolin content and incorporation methods for specific wastewater treatment needs.

B. Response Surface Methodology (RSM): Considerations and Challenges

Optimizing the fabrication of alginate membranes and wastewater treatment processes is essential for achieving optimal performance, efficiency, and cost-effectiveness. Response Surface Methodology (RSM) is a valuable statistical tool for this purpose. This section examines how RSM can be used to optimize different aspects of wastewater treatment using alginate membranes.

a) RSM for Alginate Membrane Fabrication

RSM can be used to optimize various parameters during alginate membrane fabrication, such as:

- Alginate Concentration: This impact membrane characteristics such as porosity, permeability, and mechanical strength. RSM can determine the optimal alginate concentration to balance these properties effectively.
- Crosslinking Agent Type and Concentration: Crosslinking agents, such as calcium chloride, are crucial for maintaining membrane structure. RSM can optimize the choice and amount of crosslinking agent to ensure mechanical strength without reducing permeability.
- Porogen Type and Concentration: The porogens used in the membrane are vital for water and pollutant transport. RSM can assist in selecting and adjusting the concentration of porogens (e.g., naphthalene) to achieve the desired pore size and distribution for specific pollutants.
- Curing Time or Temperature: Curing conditions affect membrane properties. RSM can optimize these parameters to ensure complete crosslinking and achieve the desired membrane structure.

Several studies have effectively used RSM to refine the fabrication of alginate membranes for wastewater treatment. [27] utilized RSM to optimize the porosity and rejection efficiency of alginate membranes for removing organic pollutants from industrial wastewater. Their RSM model determined the best combination of alginate concentration and porogen type to achieve high rejection rates while maintaining adequate water permeability. Similarly, [18] applied RSM to optimize the production of alginate/cellulose nanofiber composite membranes for treating oily wastewater. This study aimed to balance factors such as alginate concentration, cellulose nanofiber content, and crosslinking agent concentration to enhance hydrophilicity, mechanical strength, and oil rejection efficiency.

i) Benefits of Using RSM

The advantages of the application of RSM are listed here.

- Reduced Number of Experiments: RSM employs a statistically designed set of experiments, reducing the number of trials needed compared to traditional one-factor-at-a-time methods. This approach conserves time and resources.

- Identification of Interactions: RSM examines not just individual factors but also how they interact, potentially uncovering unexpected synergies or conflicts between parameters. This helps in refining the fabrication process.
- Predictive Model Development: RSM creates mathematical models that forecast outcomes (e.g., membrane performance) based on various input factors. This enables researchers to determine the optimal settings for achieving desired membrane characteristics.

b) *RSM for Wastewater Treatment Processes*

In addition to membrane fabrication, RSM can also be applied to optimize different aspects of the wastewater treatment process, including:

- Feedwater properties: RSM can help determine the optimal pH or initial pollutant concentration in the wastewater feed for efficient removal by alginate membranes.
- Operating conditions: Factors like transmembrane pressure, feed flow rate, and cleaning protocols can be optimized using RSM to maximize membrane performance and minimize fouling.
- Chemical dosing: The use of coagulants or flocculants alongside alginate membranes can be optimized using RSM to enhance pollutant removal efficiency. RSM can be used to optimize the dosage of coagulants used in wastewater treatment to achieve optimal removal of suspended solids and organic matter [34].
- Biological Treatment Parameters: RSM can be applied to optimize factors like pH, nutrient concentration, and aeration rate in biological treatment processes to enhance the efficiency of microbial degradation of pollutants [35].

c) *Future Considerations: RSM for Wastewater Treatment Processes*

Some of the future considerations are highlighted below.

- Integration with other optimization techniques: Combining RSM with other optimization methods, such as machine learning or artificial intelligence, could provide more advanced tools for optimizing both membrane fabrication and wastewater treatment processes.
- Life cycle analysis: Merging life cycle analysis with RSM can help optimize processes not just for performance, but also for environmental impact and sustainability.
- Economic and environmental factors integration: Future research should incorporate economic and environmental factors into the RSM optimization process, aiming to develop cost-effective and sustainable solutions for wastewater treatment.

C. Integration of Mycoremediation and Phycoremediation with Alginate Membrane

Traditional wastewater treatment methods frequently produce secondary waste and demand significant energy. Integrating biological treatment methods, such as mycoremediation and phycoremediation, with alginate membranes offers a promising strategy for achieving more sustainable and efficient wastewater treatment. This section examines the potential benefits of combining these technologies.

a) Integration Rationale

- Enhanced Pollutant Removal: Alginate membranes can function as pre-filters to capture large particles and suspended solids, thereby boosting the efficiency of subsequent biological treatment methods such as mycoremediation and phycoremediation [36].
- Biomass Immobilization: Alginate membranes can serve as supports for fungal or microalgal cells, aiding in their growth and enabling their separation from the treated wastewater [26]. This facilitates controlled management and reuse of the biomass.
- Improved Mass Transfer: The porous nature of alginate membranes can enhance the transfer of pollutants between the wastewater and biological agents, improving the degradation or absorption of contaminants by fungi or microalgae [37].

b) Mycoremediation with Alginate Membranes

Some mycoremediation processes that can be carried out with alginate membranes are explained below.

- Fungal-Alginate Biocomposite Membranes: These membranes embed fungi within the alginate matrix, providing a support structure for fungal growth. The fungi then work to degrade pollutants in the wastewater that passes through the membrane [38].
- Alginate-Encapsulated Fungi: Fungi can be encapsulated in alginate beads and used in wastewater treatment reactors.The alginate shell protects the fungi while permitting the diffusion of pollutants for degradation [39].

c) Phycoremediation with Alginate Membranes

Some phycoremediation processes that can be carried out with alginate membranes are explained below.

- Alginate-Immobilized Microalgae: Microalgae can be embedded in alginate beads or attached to alginate membranes. This setup supports controlled growth and enhances the efficiency of nutrient removal from wastewater [25].

- Membrane Photo-bioreactors: These systems combine alginate membranes with microalgae cultures. The membrane separates the treated wastewater from the microalgae biomass, enabling the reuse of the microalgae for additional treatment cycles [40].

d) Challenges and Considerations of Alginate Membrane Fabrication

Some of the challenges of alginate membrane fabrication are explained below.

- Membrane Compatibility: Ensuring that the alginate is compatible with the selected fungal or microalgae species is important for promoting optimal growth and activity within the membrane or carrier.
- Nutrient Supplementation: It may be necessary to supply essential nutrients to support the growth of fungi or microalgae within the alginate membranes for effective pollutant removal.
- Membrane Fouling: Accumulation of fungal or microalgae biomass on the membrane surface can cause fouling. Implementing strategies to optimize membrane properties or using anti-fouling agents is essential to address this issue.

e) Future Directions and Recommendations

This section explores the potential applications of alginate membranes and the factors to consider for their industrial applications.

- Development of novel alginate membranes: Research should focus on improving alginate membranes to enhance their biocompatibility and mass transfer capabilities for better performance in integrated systems.
- Optimization of integration strategies: Additional studies are required to refine the design and operation of integrated mycoremediation or phycoremediation systems with alginate membranes for more effective wastewater treatment.
- Life cycle assessment: It is important to conduct life cycle assessments of these integrated systems to evaluate their overall sustainability and environmental impact.

VII. KNOWLEDGE GAP

Despite the promising developments in alginate membrane modification and its integration with biological treatment processes, several knowledge gaps remain**:**

- Long-term Performance: Additional research is required to assess the long-term stability and effectiveness of different modification techniques, particularly the use of xyloglucan as a stabilizer and the anti-fouling performance of kaolin-modified membranes in practical wastewater treatment settings [26;18].
- Mechanism of Action: A more detailed understanding of how stabilizers like xyloglucan improve the mechanical strength of alginate membranes is essential for optimizing their use [26].
- Combined Modification Strategies: Investigating the synergistic effects of integrating various modification techniques, such as combining xyloglucan with anti-fouling agents or exploring interactions between porogens and stabilizers, could lead to advanced alginate membranes with enhanced properties [19].
- Life Cycle Assessment: Performing life cycle assessments of systems integrating mycoremediation or phycoremediation with alginate membranes is crucial for evaluating their overall environmental and economic sustainability [36].

Addressing these gaps will help refine alginate membrane modifications and their integration with biological treatment methods, advancing the development of more sustainable and effective wastewater treatment solutions.

VIII. FUTURE PERSPECTIVE

The future of wastewater treatment offers great promise for alginate membranes, especially when they are modified to overcome their limitations and improve their functionalities. This section examines potential applications, strategies for integrating with biological treatment methods, and factors to consider for large-scale implementation.

A. Mycoremediation with Alginate Membrane

Modified alginate membranes present promising opportunities for addressing a range of wastewater streams with various contaminants. Key areas include:

- Municipal Wastewater Treatment: These membranes can be used at different stages of municipal wastewater treatment, including primary, secondary, and tertiary stages. They are effective at removing suspended solids, organic matter, and emerging contaminants such as pharmaceuticals and personal care products, contributing to more efficient and sustainable treatment processes.
- Industrial Wastewater Treatment: Tailoring alginate membranes for industrial applications allows them to address specific pollutants such as heavy metals, dyes, and oils. Their biocompatibility makes them suitable for treating effluents from industries like textiles, pharmaceuticals, and food processing.
- Desalination: Optimized alginate membranes can assist in desalination processes, particularly in pre-treatment

stages. They help remove suspended solids and organic matter, which reduces fouling in reverse osmosis membranes.

- Micropollutant Removal: Modified alginate membranes with enhanced adsorption or encapsulation features can effectively tackle emerging contaminants like pharmaceuticals and personal care products.
- Oily Wastewater Treatment: Alginate membranes with hydrophobic modifications are effective for separating oil and grease from oily wastewater, which is commonly produced in industrial settings.

B. Mycoremediation with Alginate Membrane

Integrating mycoremediation and phycoremediation with optimized alginate membranes offers a promising strategy for achieving sustainable and effective wastewater treatment. Advancements in this area can enhance the potential of these integrated systems significantly.

- Innovative membrane design: Creating alginate membranes with customized porosity and surface properties to match specific fungal or micro-algal strains will improve the effectiveness of these integrated systems.
- In-situ biomass regeneration: Implementing strategies that support the growth and regeneration of fungal or microalgal biomass within the membrane system can reduce reliance on external supplements and streamline operations.
- Wastewater pre-treatment optimization: Enhancing pre-treatment processes before the integrated system can boost overall removal efficiency and lessen the load on the biological treatment stages.
- Co-immobilization of fungal and micro-algal species: Developing alginate membranes to co-immobilize both fungi and microalgae can create synergistic treatment systems, where fungi degrade complex pollutants and microalgae remove nutrients.
- Smart membranes for controlled nutrient delivery: Designing alginate membranes capable of controlled nutrient release for immobilized biomass can improve the efficiency and sustainability of the treatment systems.
- Membrane bioreactors with improved mass transfer: Optimizing membrane bioreactors with advanced alginate membranes can facilitate better mass transfer of pollutants, resulting in more efficient and thorough treatment.

C. Scale-Up and Implementation Considerations

Moving from laboratory-scale demonstrations to large-scale application of modified alginate membranes involves addressing several crucial factors.

- Cost of membrane production: Developing affordable manufacturing processes for large-scale production of modified alginate membranes is essential for their widespread use.
- Design and configuration of membrane modules: Creating efficient membrane modules with optimized flow patterns and minimal pressure drops is key for practical applications.
- Long-term operational issues: Addressing challenges such as membrane fouling, optimizing cleaning protocols, and ensuring the durability of membranes over time is crucial for effective deployment.
- Integration with current systems: Modifying existing wastewater treatment facilities to incorporate alginate membrane technologies requires thoughtful planning.
- Life cycle evaluation**:** Performing a detailed life cycle assessment to understand the overall environmental and economic impacts of these technologies is important for sustainable wastewater treatment solutions.

Addressing these challenges and encouraging cooperation among researchers, engineers, and policymakers can unlock the potential of modified alginate membranes and their integration with biological treatment methods. By focusing on bridging existing knowledge gaps and developing cost-effective scale-up strategies, these adaptable membranes have the potential to transform wastewater treatment practices. Their integration with biological processes such as mycoremediation and phycoremediation offers significant promise for achieving sustainable and efficient wastewater management solutions.

IX. CONCLUSION

Alginate membranes, derived from the natural biopolymer alginate, have emerged as a promising solution for sustainable wastewater treatment. This study has highlighted the versatility of alginate membranes and their potential to address various challenges associated with conventional wastewater treatment methods. The paper has explored the fabrication techniques, modification strategies, and applications of alginate membranes. By optimizing parameters such as alginate concentration, crosslinking agent, and porogen type through techniques like Response Surface Methodology (RSM), it is possible to tailor the properties of alginate membranes to specific wastewater treatment needs. The integration of alginate membranes with biological treatment processes, such as phycoremediation and mycoremediation, offers a synergistic approach to enhance wastewater treatment efficiency. By immobilizing microorganisms on alginate membranes, biodegradation and pollutant removal can be significantly improved. While alginate membranes hold great promise, further research is needed to address challenges such as mechanical strength, long-term stability, and fouling resistance. Ongoing research efforts should focus on developing innovative approaches to overcome these limitations and expand the applications of alginate membranes in wastewater treatment. By continuing to explore the potential of alginate membranes, researchers and engineers can contribute to the development of sustainable and effective solutions for wastewater treatment, ultimately safeguarding our environment and promoting sustainable water resource management.

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Conceptualization, C.N.N. and S.U.J.; methodology, C.N.N. and S.U.J.; software, C.N.N. and S.U.J.; validation, C.N.N. and S.U.J.; formal analysis, C.N.N. and S.U.J.; investigation, C.N.N. and S.U.J.; resources, C.N.N. and S.U.J.; data curation, S.U.J.; writing—original draft preparation, C.N.N.; writing—review and editing, C.N.N. and S.U.J.; visualization, C.N.N. and S.U.J.; supervision, S.U.J.; project administration, C.N.N. and S.U.J. All authors have read and agreed to the published version of the manuscript.

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