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Sustainable Desalination Through Eco-Friendly Membrane Technology: Enhancing Performance with Biodegradable Polymers and Green Solvents

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Abstract The integration of green concepts into membrane technology remains a key challenge. Among various fabrication methods, non-solvent-induced phase separation (NIPS) is the most widely used technique. However, concerns regarding secondary pollution present significant drawbacks. This study aims to replace the NIPS method with a more sustainable approach by utilizing polylactic acid (PLA) as a biodegradable polymer, dimethyl sulfoxide (DMSO) as a green solvent, and deep eutectic solvents (DES) as environmentally friendly additives.

A full characterization was performed to assess the structural and functional properties of the fabricated membranes. The transition to eco-friendly materials led to physical modifications in the membrane structure while maintaining its chemical integrity. Filtration tests demonstrated that membranes composed of 20 wt% PLA, DMSO, and 1 wt% choline chloride: ethylene glycol (ChCl:EG) (1:2) exhibited significantly enhanced water flux (1138 L/m².h) compared to membranes prepared with conventional solvents (554 L/m².h). Additionally, the modified membranes achieved a high oil rejection rate of 96% and improved anti-fouling properties, with a flux recovery ratio (FRR) of 80%.

These findings confirm that the novel combination enables the fabrication of an environmentally friendly membrane through a sustainable process.

Keywords: Membrane Technology, Sustainable Membrane Fabrication, Biodegradable Polymer, Anti-Fouling Membrane

1.Introduction

The constant demand for water drives the development of practical water treatment technologies. Membrane-based technologies, including reverse osmosis (RO), ultrafiltration (UF), and nanofiltration (NF), are among the most widely adopted methods for water treatment. However, there are still challenges in effectively incorporating sustainable and environmentally friendly principles into membrane technologies. The non-solvent-induced phase inversion technique is the most adaptable fabrication method used for membrane fabrication. Nevertheless, the chances of secondary contamination present a major drawback for this method. Therefore, using an eco-friendly fabrication technique in membrane manufacture is a must. The focus of this work was to substitute the conventional dope solution constituents with eco-friendly material to tailor the structure and filtration performance of PLA membranes[1]. A series of modified membranes were fabricated to study the effect of switching each constituent into a more eco-friendly one. In the beginning, two membranes were fabricated to investigate the influence of substituting the conventional solvent e.g. DMAc with an environmentally friendly solvent like DMSO[2]. Then, the influence of incorporating DES as an additive was assessed by fabricating membranes composed of a mixture of PLA, DMSO as a dissolving solvent, and ChCl:EG (1:2) DES with various concentrations. The membranes were tested according to the water permeation and oil rejection.

2.Methods

2.1. Membrane fabrication/characterization

The PLA membranes were fabricated using the NIPS method [9]. Initially, PLA polymer beads were dried overnight at 70 °C. To prepare the casting solutions, the dried PLA beads were mixed with the solvent at 70 °C, after which DES was added and dispersed into the solvent. The mixture underwent sonication for 20 min to achieve a uniform dispersion. Then, the solution was magnetically stirred at 70 °C and 300 rpm for 24 h to ensure complete polymer dissolution. Afterthat, the dope solutions were degassed and aerated using a sonicator and vacuum oven for 4 h at 30 °C. The prepared solutions were then casted onto a dry glass plate using a casting knife with a 200 µm gap. Immediately after casting, the membranes were immersed in a coagulation bath containing DI water at room temperature and kept for 24h. Finally, the membranes were washed and soaked in water to remove any residual solvents and impurities.

Various characterization techniques were utilized to analyze the chemical structure, morphology, and properties of each membrane such as ATR-FTIR spectroscopy (Vertex 80/80v, Bruker, Germany), TGA

analyzer (PerkinElmer - TGA 4000), and scanning electron microscope (SEM Quanta 250, USA).

2.2. Membrane testing

The membranes' performance was evaluated based on membrane permeability, and its ability to reject oil from oily wastewater. The experimental tests were conducted at room temperature using a dead-end stirred filtration cell (UHP 4370). Initially, all membranes were compacted by applying a hydrostatic pressure of 2 bar for 50 min until a stable flux was established. The DI water flux of each membrane was then measured under an applied pressure of 1 bar. After that, the water permeability (J_w) of each membrane was calculated using the following expression:

$$J_w(\text{LMH}) = \frac{V}{A.\Delta t} \qquad (1)$$

where V (L) is the collected volume, A (m²) is the membrane area; 15.20 cm². and Δt (h) is the time required to collect the permeate. The water permeability flux was obtained by replicating each membrane sample three times under identical conditions and the average water permeability flux was calculated. Next, the DI water was substituted with a 1000 ppm oil-water emulsion, serving as a model for simulating oily wastewater. Throughout the experiment, the as-prepared solution was filtered through the membrane at a constant pressure of 1 bar for 30 min. Samples from feed and permeate were collected and their respective concentrations were quantified using a total organic carbon (TOC) analyzer (TOC-L series from Shimadzu, Japan). Then, the oil rejection percentage (R) was calculated using equation[3]:

$$R(\%) = \frac{C_f - C_p}{C_f} \times 100 \qquad (2)$$

where C_f and C_p are the protein concentration in the feed and permeate, respectively.

3.Results and Discussion

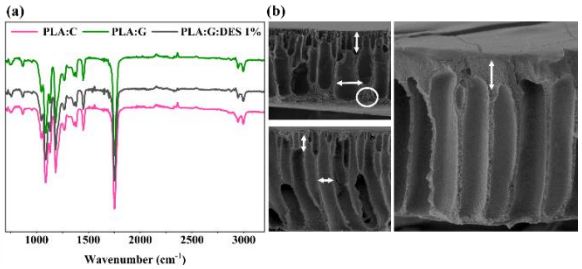

Figure 1: Chemical and physical charectors of fabricated membranes; (a) FTIR spectra, and (b) the SEM images.

Figure 1(a) represents the ATR-FTIR spectra of PLA:C compared to PLA:G and PLA:G:DES membranes, where no change in the chemical structure was detected. Hence, no alterations in the chemical characteristics of the base membrane was detected by solvent substitution. On the other hand, the membranes exhibited physical changes where DMAc resulted in an asymmetric structure (PLA:C) consisting of two distinct layers; a dense top layer, and a large proportion of sponge-like microporous structure in the sublayer, whereas PLA:G membrane showed a more symmetric structure with longer finger-like macro-voids[4]. The addition of DES resulted in increasing the thickness of the top active porous layer of membranes formed[5].

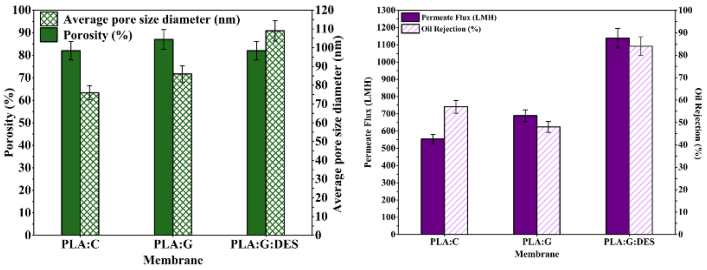

Figure 2: (a) Porosity and average pore size diameter, and (b) Pure water flux (L/m².h) and oil rejection (%) of PLA:C, PLA:G, and PLA:G:DES membranes.

The results demonstrated that the membrane fabricated using DMSO as the solvent (PLA:G) achieved a DI water flux of approximately 700 L/m²·h, higher than that of PLA:C. Further increase was noticed when DES was added where the water flux reached 1138 L/m²h. The notable increase in flux can be attributed to structural modifications in the membrane, which enhanced water permeation (see Figure 2 (a))[6]. The oil rejection exhibited an inverse trend to water flux, with the PLA:C membrane achieving higher rejection compared to the PLA:G membrane. The addition of DES resulted in increasing the membrane rejection. This can be attributed to differences in membrane pore size, as larger pores lead to lower rejection due to the size exclusion mechanism in addition to an increase in membrane top layer thickness resulting in enhancing the membrane rejection abilities.

4.Conclusion

This study investigates the use of innovative material combinations to develop an eco-friendly membrane fabrication approach, highlighting their enhanced compatibility with sustainable practices.

5.References

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