Frontiers in Sustainable Science and Technology
E-ISSN: 3089-2767
DOI: https://doi.org/10.69930/fsst.v3i1.767
Research Article

Vol. 3 (1), 2026
Page: 01-06

Synthesis of Chitosan, Carboxymethyl Cellulose, and Silica Membrane for Seawater Desalination as a Clean Water Source

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Abstract. *This research is driven by the high salinity of seawater, which limits its use as a clean water source, necessitating eco-friendly desalination technology,. The objective was to synthesize a composite membrane based on chitosan (CS), carboxymethyl cellulose (CMC), and silica (SiO_2) and evaluate its effectiveness in seawater desalination,. The research employed a solution casting technique using 0.15 g chitosan, 0.05 g CMC, and 0.05 g silica, which were mixed homogeneously and dried at room temperature,. The results showed successful membrane formation with Si–O–Si and Si–O–C chemical bonds and electrostatic interactions between the polymers,. SEM analysis revealed a relatively homogeneous surface, while EDX confirmed a silicon composition of 2.23%,,. Desalination tests demonstrated a drastic reduction in TDS from 38,000 mg/L to meet clean water standards, with salinity dropping to 3.138 ppt and a stable pH of 7.8,. It is concluded that the CS-CMC/SiO_2 composite membrane is an effective and sustainable solution for seawater desalination in accordance with Permenkes No. 2 of 2023.*

Keywords: *Membrane; Chitosan; Carboxymethyl Cellulose; Silica; Desalination*

1. Introduction

Clean water is essential for life, yet population growth and climate change have triggered a global water crisis affecting more than 2 billion people worldwide (Maro et al., 2023). For coastal communities in Indonesia, seawater with an average salinity of approximately 3.5% represents an abundant but unusable water resource without desalination treatment (Anawai et al., 2023). Among desalination technologies, reverse osmosis (RO) is widely applied due to its high efficiency; however, the system remains relatively expensive and is susceptible to membrane fouling problems that reduce operational performance (Islam *et al*., 2023; Shokri et al., 2023).

This study proposes a sustainable membrane synthesized from natural biopolymers consisting of Chitosan (CS) derived from shrimp shell waste, Carboxymethyl Cellulose (CMC) obtained from cellulose derivatives, and Silica (SiO_2) extracted from rice husk ash (Sulistyawati et al., 2022). The combination of cationic chitosan and anionic CMC forms a stable polyelectrolyte complex (PEC) through electrostatic interactions, while silica incorporation enhances membrane mechanical strength, thermal stability, and permeability (He et al., 2015; Malis et al., 2022; Spoială et al., 2021). Therefore, this research aims to characterize the CS-CMC/SiO_2 composite membrane and evaluate its effectiveness in reducing seawater salinity through desalination processes.

Received: 20 May 2026 / Accepted: 25 June 2026 / Available online: 30 June 2026

2. Methods

The membrane was synthesized using a multi-pot solution casting method. Specifically, 0.05 g of CMC was dissolved in warm water, 0.15 g of chitosan was dissolved in 2% acetic acid, and 0.05 g of SiO_2 was dispersed in distilled water for 30 minutes. These solutions were blended until homogeneous, poured into a 90 mm petri dish, and dried at room temperature (±25°C) for 24 hours to form a film with a thickness of 30-50 μm,,. Characterization was performed using FTIR (Shimadzu) for functional group identification and SEM-EDX (Coxem) for surface morphology and elemental composition,. Desalination performance was tested by measuring TDS, pH, salinity, BOD, and COD against the Permenkes No. 2 Year 2023 standards.

3. Results and Discussion

This section provides an in-depth description of the experimental results of the synthesis of CS-CMC/SiO_2 composite membranes, their physicochemical characterization, and performance analysis in the seawater desalination process.

3.1. CS-CMC/SiO_2 Material Synthesis and Chemical Interactions

The membrane was synthesized using a solution blending method followed by casting to produce a homogeneous structure. The combination of cationic chitosan (CS) and anionic carboxymethyl cellulose (CMC) produces a stable Polyelectrolyte Complex (PEC) through electrostatic interactions between protonated amine ($-NH_3^+$) and carboxylate ($-COO^-$) groups. In addition to these charge interactions, the addition of silica (SiO_2) strengthens the polymer matrix through chemical integration at the interface. The silanol (Si–OH) groups in the silica form hydrogen bonds with the hydroxyl (–OH) and amine ($-NH_2$) groups in the CS-CMC chains. This integration was validated by the appearance of Si–O–C vibrations, indicating that the silica is chemically bonded and not simply physically dispersed.

3.2. Physical Characteristics of the Membrane

The membrane produced by the casting method exhibits a visual appearance in the form of a homogeneous, flexible, thin film with a smooth surface texture, as shown in Figure 1. Visually, the CS-CMC/SiO_2 membrane is transparent or semi-transparent (see Figure 1), maintaining clarity even though the addition of silica increases the turbidity of the solution before drying. Dimensional control was performed using a 90 mm diameter Petri dish with a solution volume of approximately 10 mL, resulting in a uniform membrane thickness ranging from 30–50 μm. These dense physical characteristics and minimal cracking were achieved through a controlled drying process at room temperature for 24 hours, which allows for self-assembly of the polymer chains (Figure 1).

Figure 1. Physical photo of the synthesized CS-CMC/SiO_2 membrane.

3.3. Fourier Transform Infrared (FTIR) Characterization

Analysis using Fourier Transform Infrared Spectroscopy confirmed the formation of the Polyelectrolyte Complex (PEC), as shown in Figure 1. A significant shift in the Amida I (C=O) and carboxylate (COO^-) peaks from 1649.14 cm^{-1} to 1624.06 cm^{-1} indicated strong electrostatic interactions between the positive charge of chitosan (–NH_3^+) and the negative charge of carboxymethyl cellulose (CMC) (–COO^-), which can be clearly observed in the spectra (see Figure 1). The integration of silica into the polymer matrix was further validated through the appearance of Si–O–Si stretching at 1080.14 cm^{-1} and Si–O–C vibrations at 459.06 cm^{-1} (Figure 2), proving that chemical bonding occurred through condensation reactions rather than mere physical dispersion.

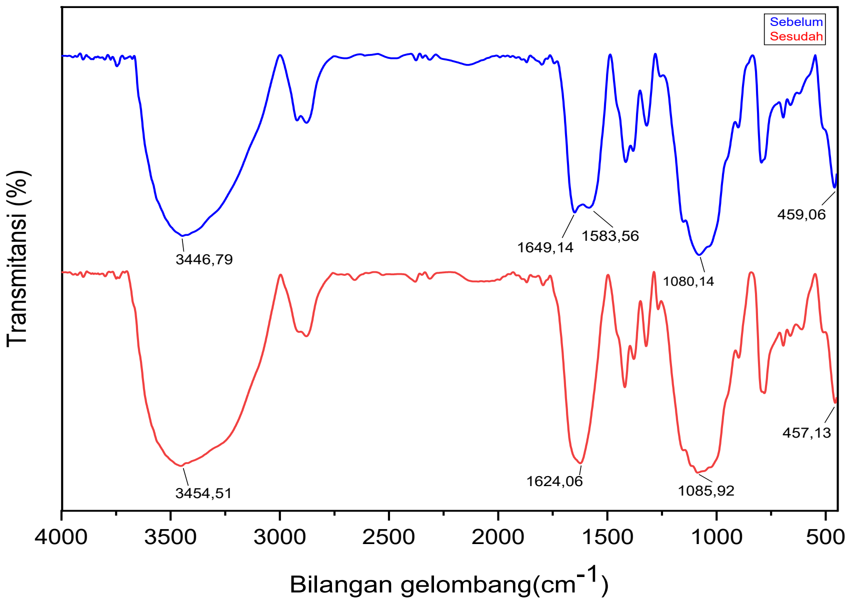

Figure 2. FTIR spectra before and after use

3.4. SEM-EDX Characterization (Morphology and Composition)

Observations using Scanning Electron Microscopy (SEM) at 500× magnification showed that the membrane surface had a dense and homogeneous structure, as shown in Figure 3(a). However, at higher magnifications, namely 10,000× and 20,000×, silica microaggregates were observed dispersed within the polymer network (see Figures 3(b) and 3(c). Observations using Scanning Electron Microscopy (SEM) at 500× magnification showed that the membrane surface had a dense and homogeneous structure, as shown in Figure 3(a). However, at higher magnifications, namely 10,000× and 20,000×, silica microaggregates were observed dispersed within the polymer network (see Figures 3(b) and 3(c).

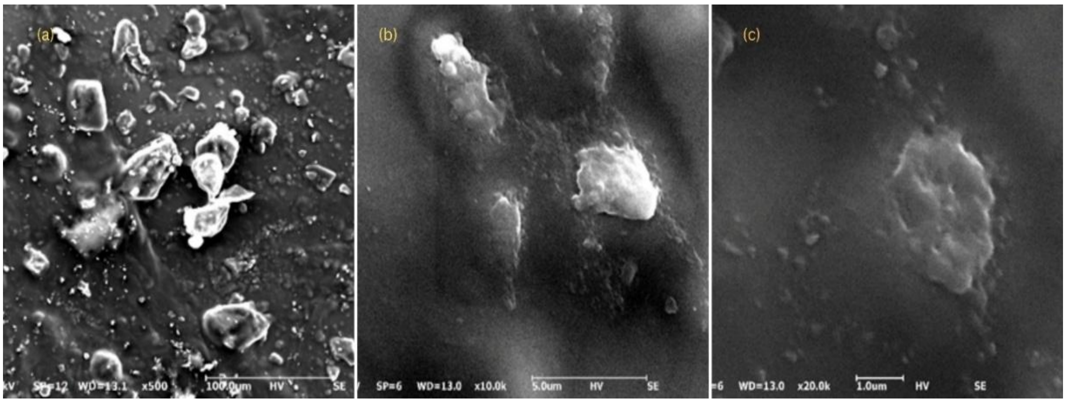

Figure 3. SEM images of CS–CMC/SiO_2 membrane: (a) 500× magnification; (b) 10,000× magnification; (c) 20,000× magnification**.**

Energy Dispersive X-Ray (EDX) analysis results confirmed the elemental composition of the membrane, as detailed in Table 1. Energy Dispersive X-Ray (EDX) analysis results confirmed the elemental composition of the membrane, as detailed in Table 1. Carbon (C) was the component with the highest percentage, at 55.02%, originating from the organic polymer matrix of chitosan (CS) and carboxymethyl cellulose (CMC). Oxygen (O) was detected at 41.59%, representing the presence of hydroxyl, carboxylate, and siloxane groups in the composite network. Meanwhile, the Silicon (Si) content of 2.23% provides scientific evidence for the successful integration of silica into the membrane matrix.

Table 1. EDX reading results of CS-CMC/SiO2 composite membrane

Element	*Weight %*	*Weight % Sigma*	*Atomic %*
C	55.02	0.74	62.70
O	41.59	0.73	35.58
Si	2.23	0.08	1.08
Total	98.84		99.36

3.5. Membrane Performance Analysis in Desalination Process

Performance tests were conducted to evaluate the effectiveness of the CS-CMC/SiO_2 composite membrane in filtering salt ions and pollutants, with the results summarized in Table 2. The test results indicate that the membrane effectively transforms seawater into clean water. The most significant achievement was the drastic reduction in Total Dissolved Solids (TDS) from an initial seawater level of 38,000 mg/L to meet the threshold of <300 mg/L as stipulated in Minister of Health Regulation No. 2 of 2023 (see Table 2). This success was supported by the abundant density of active hydroxyl (–OH) and amine (–NH_2) groups in the membrane matrix. Although the salinity remained at 3.138 ppt and required further optimization, the membrane maintained a stable pH of 7.8, within the ideal standard range of 6.5–8.5. Furthermore, the low BOD (0.375 mg/L) and COD (4 mg/L) values, as listed in Table 2, indicate that the membrane has good resistance to organic pollutants, thus minimizing the risk of fouling during the filtration process. Overall, the integration of CS, CMC, and silica creates a matrix with a high density of active groups that offers great potential for sustainable desalination applications.

Table 2. Analytical Results of CS-CMC/SiO_2 Membrane Desalination

Parameter	Unit	Result	Permissible Limit	Methods
pH	-	7.8	6.5–8.5	SNI 6989.11-2019
Salinity	%	3.138	-	Salinometer
TDS	mg/L	38000	< 300	SNI 6989.27:2019
BOD	mg/L	0.375	10	SNI 6989.72:2009
DO	mg/L	1,25	< 5	SNI 6989.72:2009
COD	mg/L	4	-	SNI 6989.15-2019

Conclusions

CS-CMC/SiO_2 composite membrane was successfully synthesized using the solution casting method, resulting in a homogeneous and stable structure. The integration of organic and inorganic materials through Si-O-C bonds and electrostatic interactions has been proven effective in reducing salt levels and organic pollutants in seawater, making it an environmentally friendly alternative desalination technology.

Funding

This research received no external funding

Acknowledgments

The authors would like to thank the Chemistry Laboratory of ISTEK 'Aisyiyah Kendari, UPA Integrated Laboratory of UHO, and the Integrated Chemistry Laboratory of Hasanuddin University for their research facility support.

Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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