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Research Paper

Fabrication and Performance Evaluation of CA–PEG–PVC/GO Nanocomposite Membranes Prepared by Phase Inversion for Desalination in Drinking Water Treatment

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Abstract

The global clean water shortage has driven the development of more efficient desalination technology, particularly reverse osmosis (RO) membrane-based. However, conventional CA membranes still exhibit low permeability, fouling vulnerability, and weak mechanical properties. This study aims at the preparation and the performance characterization of CA–PEG–PVC composite membranes with incorporated graphene oxide (GO) nanoparticles through the phase inversion method. The major materials utilized were cellulose acetate (CA), polyvinyl chloride (PVC), polyethylene glycol (PEG) as a pore former, N-methyl-2-pyrrolidone (NMP) as a solvent, and GO at various concentrations. The membrane was characterized through salt rejection and permeate flux measurements in cross-flow mode using feed water of 241 ppm total dissolved solids (TDS). The results show that membranes without PVC registered 2.07% salt rejection with high flux of 825.33 $L \cdot m^{-2} \cdot h^{-1}$, while the addition of 0.01 g PVC increased salt rejection to 4.15% but decreased flux to 300.12 $L \cdot m^{-2} \cdot h^{-1}$. The results draw the conclusion that PVC adds structural stability and ion rejection but decreases water permeability as it is hydrophobic. Overall, this study demonstrates the compromise between permeability and selectivity in CA–PEG–PVC/GO membranes and suggests that it is necessary to further balance the composition of PVC and GO in order to achieve more balanced RO membrane performance in drinking water treatment applications.

Keywords: *Cellulose Acetate (CA), Phase Inversion, Reverse Osmosis (RO)*

INTRODUCTION

Water is a natural resource that is vital for human survival. However, in the modern era, the world is facing an increasingly alarming water crisis. The shortage of clean water supply has become one of the biggest global problems today. According to the latest report from WHO and UNICEF in 2024, around 2.1 billion people still do not have access to safely managed drinking water, and around 3.4 billion people do not have access to safely managed sanitation (WHO & UNICEF, 2025). Desalination technology can be used to produce alternative water supplies. The most widely used desalination technology today is Reverse Osmosis (RO).

Reverse Osmosis (RO) is a filtration method that can separate large molecules and ions from a solution. This process works by applying pressure to the solution so that only smaller molecules can pass through the filter membrane (Chairunissa et al., 2021). To work properly, RO (Reverse Osmosis) membranes must meet several criteria, namely: the ability to absorb water and better select the particles to be filtered, resistance to dirt, sufficient strength to withstand high pressure, and sufficient thinness to maximize the filtration area (How RO membrane permeability and other performance factors affect process cost and energy use: A review – ScienceDirect (Okamoto & Lienhard, 2019).

The most commonly used method for producing porous polymer membranes is phase inversion. Phase inversion is a mixing process in which a homogeneous polymer solution is

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converted from a liquid phase to a solid phase in a controlled manner (Purkait et al., 2018). The phase inversion method is widely used in the manufacture of polymer membranes because of its simple process, relatively low production costs, and compatibility with various types of polymers and additives (Geleta et al., 2023). In addition, in the phase inversion method, the morphology of the membrane can be manipulated by adding a pore-forming agent. Pore-forming agents are additives in the membrane fabrication process (usually via the phase inversion method) that serve to help form pores in the membrane structure. When the polymer solution (dope solution) is molded into a membrane and then dipped into a non-solvent (usually water), the pore-forming agent will dissolve/wash out, leaving empty spaces (voids/pores) in the membrane (Fathanah & Meilina, 2021).

CA-based RO membranes are commonly used in industry due to their inherent properties, namely low cost, non-toxicity, higher hydrophilicity, environmental friendliness, biodegradability, and sustainability (Vatanpour et al., 2022). However, cellulose acetate (CA)-based membranes have limitations such as low flux, susceptibility to bacterial and chemical degradation, and a narrow pH and temperature operating range. In addition, the phase inversion process in CA produces a solid skin layer with low porosity, which can reduce separation performance. Therefore, to overcome this, organic or inorganic additives are added and the solvent system is modified, such as DMAc, DMF, NMP, and others (Vatanpour et al., 2022).

This study focuses on the fabrication of CA–PEG–PVC membranes with the addition of GO nanoparticles using the phase inversion method. The initial stage of the research still focuses on evaluating the basic properties of the membrane, including water flux performance, permeability, salt rejection capability, and resistance to operating pressure. The results of this study are expected to provide an understanding of the potential development of CA–PEG–PVC/GO-based thin film composite (TFC) membranes for drinking water treatment applications based on RO technology.

LITERATURE REVIEW

Reverse osmosis (RO) membranes are a key component in the desalination process, functioning as semi-permeable filters to separate water molecules from dissolved ions and contaminants. Compared to heat-based desalination methods such as multi-stage flash (MSF) or multi-effect distillation (MED), RO technology is more efficient because it only requires about 3–6 kWh/m^3 of energy, which is much lower than the energy requirements of MSF, which can reach 80–120 kWh/m^3 (Shannon et al., 2008). Modern RO membranes can retain up to 99% of salt ions and produce water with a TDS quality of < 500 mg/L, in accordance with WHO standards for drinking water (Elimelech & Phillip, 2011). However, the performance of RO membranes is highly dependent on the polymer materials used in their composition, where the intrinsic properties of the polymer, such as hydrophilicity, chemical stability, mechanical strength, and the ability to form suitable pore morphology, greatly determine the final performance of the membrane.

Cellulose acetate (CA) is one of the classic polymers widely used in reverse osmosis (RO) membranes due to its hydrophilic, biodegradable, non-toxic, environmentally friendly properties, and relatively low production costs. These advantages enable CA to reduce fouling and increase water transport through the membrane (Koriem et al., 2023). Quantitatively, pure CA has a water contact angle (WCA) of approximately 52°, indicating good hydrophilicity; this value can be reduced to 36° by adding hydrophilic additives such as polyethylene glycol (PEG) or polyvinyl alcohol (PVA) (Azhar et al., 2021). The separation performance of CA is also quite good, as evidenced by a pure water flux that can reach 42.4 $L \cdot m^{-2} \cdot h^{-1}$ and a rejection rate of 95% for BSA protein, 93% for urea, and 89% for creatinine after modification (Koriem et al., 2023). However, pure CA has serious drawbacks, including low mechanical strength (tensile strength 2–4.5 MPa), a narrow operating pH range (4–6.5), and sensitivity to high temperatures (<35 °C), so it cannot be used independently for high-pressure and long-term desalination applications (Koriem et al., 2023).

To overcome these limitations, polyvinyl chloride (PVC) is widely chosen as an additional polymer. PVC is known to be inexpensive, widely available, resistant to wear, acids and bases, and organic solvents, and has good mechanical and chemical stability (Zhang et al., 2021). Mechanically, PVC exhibits a tensile strength of 1.2 MPa with an elongation at break of 15%, which is higher than CA, which only reaches 1.0 MPa with an elongation of 5%. Therefore, PVC plays an important role in strengthening the membrane structure (Azhar et al., 2021). However, pure PVC is highly hydrophobic with a WCA of ~86°, low porosity (0.13), and limited flux (36 $L·m^{-2}·h^{-1}$), despite its high BSA rejection (91.7%) (Aji et al., 2020). This makes PVC difficult to use alone as an RO membrane material. The CA–PVC combination has been shown to produce synergy that overcomes the weaknesses of each polymer. Aji et al. (2020) showed that adding only 5 wt% CA to PVC was able to reduce the WCA from 86° to 64.7°, increase porosity from 0.13 to 0.58, and increase flux from 36 to 85 $L· m^{-2}·h^{-1}$, with an increase in flux recovery ratio (FRR) from 56% to 78%, indicating better antifouling performance (Aji et al., 2020). Furthermore, El-Gendi et al. (2017) reported that a 16% PVC–3% CA membrane (plus 1% PEG) was able to operate stably at high pressures up to 50 bar, with a tensile strength of 283 $kg·cm^{-2}$ (~2.77 MPa) and elongation of 11%, and showed salt rejection of 99.99% for 5120 ppm NaCl and 99.95% for Red Sea water (TDS 38.528 ppm). The resulting flux is also high, reaching 40–90 $kg·m^{-2}·h^{-1}$ depending on the pressure and concentration of the test solution, and its performance is proven to be stable during 36 days of continuous operation (El-Gendi et al., 2017). In addition, research by Zhang et al. (2021) also reinforces that hydrolysis treatment of PVC/CA membranes can increase hydrophilicity, increase porosity (up to 82%), and increase pure water flux to 792 $L·m^{-2}·h^{-1}·bar^{-1}$ without reducing mechanical strength (Zhang et al., 2021). Overall, CA contributes to hydrophilicity and ion selectivity, while PVC provides mechanical stability and chemical resistance. With the right combination of proportions, especially at low CA fractions (~2–3%), PVC/CA membranes are able to achieve a balance between permeability, rejection, mechanical strength, and fouling resistance, making them promising candidates for RO-based desalination applications.

One of the main drawbacks of using membranes in water desalination and purification processes is their low mechanical resistance, which can lead to clogging and limited permeability, thereby affecting the efficiency of the process of removing contaminants or other impurities (Wang et al., 2024). Therefore, manipulation through the addition of nanomaterials or variations in polymer use is needed to overcome the aforementioned weaknesses. One nano material that can improve morphology and performance is graphene oxide (GO) (An et al., 2023a). Graphene oxide is a derivative of graphene that can be manipulated in terms of its physical and chemical properties (Tene et al., 2023; Mahmun & Deoghare, 2024). This manipulation can result in changes in electronic, mechanical, biocompatible, and water dispersibility properties (An et al., 2023b). In its application for reverse osmosis membranes, GO is usually used as a thin film laminate layer or mixed in polymers to improve antifouling and prevent contaminant buildup (Rashidi et al., 2022; Nawi et al., 2024). In addition, the addition of GO can also manipulate the hydrophilic properties of water so that water flow can more easily penetrate the membrane (Zhang et al., 2025). Apart from the addition of nano-materials, the use of pore-forming agents such as PEG-400 is also commonly used to increase hydrophilicity and improve anti-fouling properties. PEG-400 works by dissolving when immersed in a non-solvent, leaving pores or empty spaces in the membrane and giving the membrane a porous structure (Chen et al., 2019). Fabrication with the addition of PEG-400 and GO has the effect of reducing the water contact angle and water flux, especially for use in desalination and water purification, because it is important to have good hydrophilic properties. (Rashidi et al., 2022).

RESEARCH METHOD

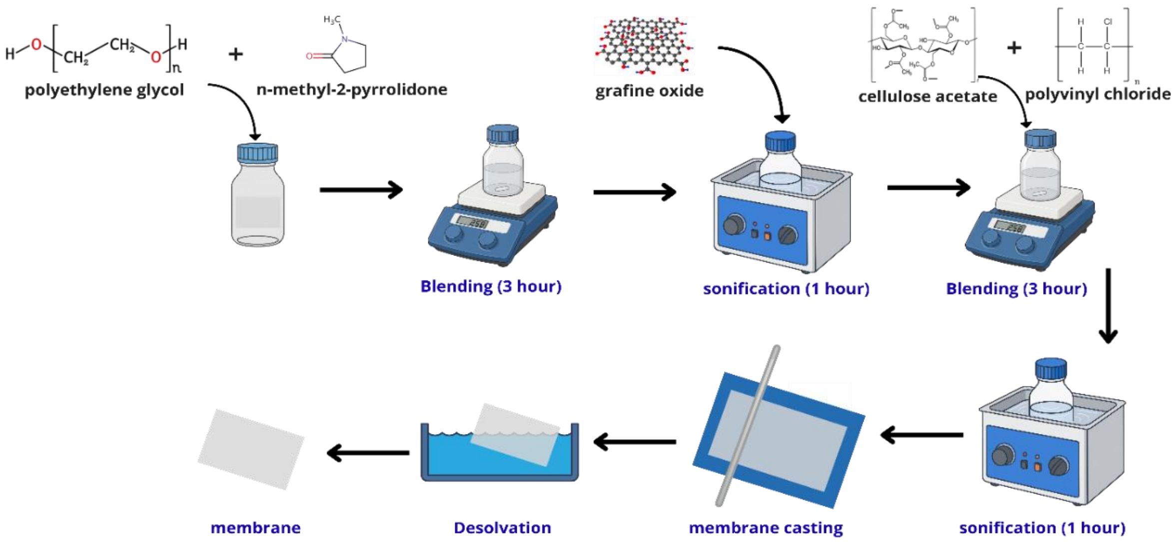

Figure 1. Schematic diagram of the membrane fabrication process using the phase inversion method

The main materials used in this study were n-methyl-2-pyrrolidone (NMP, 17 mL) as a solvent, polyethylene glycol (PEG, 0.5 g) as a pore-forming agent, cellulose acetate (CA 2 g), polyvinyl chloride (PVC, 0.01 g), and graphene oxide (GO) with varying concentrations (0; 0.1; 0.5; and 1% w/w). The main equipment used included an ultrasonic sonicator, magnetic stirrer, glass plate, and coagulation tank containing distilled water. The membranes were synthesized using the phase inversion technique with three different formulas, namely:

- PVC/PEG/NMP: PVC, PEG, and NMP were mixed using a magnetic stirrer for 4 hours until homogeneous, followed by ultrasonication.
- CA/PVC/PEG/NMP: The mixture of CA, PVC, PEG, and NMP was stirred using a magnetic stirrer for 4 hours until homogeneous, then ultrasonicated.
- CA/PVC/PEG/NMP with GO: Variations of GO (0; 0.1; 0.5; and 1% w/w) were added to the polymer solution. The polymer mixture (CA, PVC, PEG, and NMP) was stirred for 1 hour, then GO was dispersed using an ultrasonic sonicator for 1 hour until a stable suspension was formed. The GO suspension was then mixed into the polymer solution and ultrasonicated again for 1 hour so that the GO was evenly dispersed in the polymer matrix.

Each sonicated formula was then cast using square glass plates of a predetermined thickness and immediately dipped into a coagulation bath containing distilled water to trigger the phase inversion process. Next, the formed membranes were soaked in distilled water for 15 minutes to remove any remaining solvent, resulting in solvent-free membranes that were ready for further characterization.

FINDINGS AND DISCUSSION

Finding

Membrane performance was evaluated based on salt rejection and permeate flux parameters using a cross-flow system. The feed water was obtained from the water utility company (PDAM) at the Antasari Building, Yogyakarta Veteran University, with a total dissolved solids (TDS) concentration of 241 ppm. The membranes tested were flat-sheet type (4 × 4 cm) with an effective membrane area of 16 cm^2. Four membrane variations were examined:

1. Non-PVC membrane,
2. PVC membrane with 0.01 g PVC,
3. CA/GO membrane with 0.5 wt% GO, and
4. CA/GO membrane with 1 wt% GO.

The salt rejection percentage (R) was determined by calculating the difference in concentration between the feed solution (Cf) and permeate (Cp) to the feed concentration, according to the following equation:

$$\%R = \left(\frac{Cf - Cp}{Cf}\right) \times 100\% \quad (1)$$

Meanwhile, the permeate flux value is shown in the following equation:

$$J = \frac{Q}{A \times \Delta t} \quad (2)$$

Where Q is the quantity of permeate (L), A is the effective membrane area (m^2) and Δt is the sampling time (h) (Nyamiati et al., 2021).

Discussion

The results showed that the addition of PVC increased salt rejection from 2.074% (non-PVC) to 4.149%, indicating improved membrane stability due to the superior mechanical properties of PVC compared to CA. However, this improvement was accompanied by a decrease in flux from 825.330 L/(m^2·h) to 300.120 L/(m^2·h), mainly due to the hydrophobic nature of PVC that limits water transport. This finding is consistent with reports that PVC provides high mechanical and chemical stability (Azhar et al., 2021), although pure PVC membranes generally exhibit low porosity and limited flux (Aji et al., 2020). Blending CA with PVC has been shown to balance hydrophilicity, permeability, and mechanical strength, as demonstrated by El-Gendi et al. (2017) and Zhang et al. (2021), who reported improved membrane performance after optimizing composition and applying surface modification treatments. The performance test results for both membrane variations are shown in Table 1.

Table 1. The performance test results for both membrane variations

Membrane Variation	Feed Concentrate (ppm)	Permeate Concentration (ppm)	Salt Rejections (%)	Permeat Fluxs L/(m^2·h)
Non-PVC	241	236	2.074	8253.30
PVC 0.01 g	241	231	4.149	300.12
GO 0.5%	241	-	-	9003.60
GO 1%	241	-	-	4501.80

In contrast, the incorporation of graphene oxide (GO) significantly increased water flux, with 0.5wt% GO achieving 9003.60 L/(m^2·h). This improvement is mainly due to the hydrophilic functional groups of GO (–OH, –COOH, and epoxy), which enhance water affinity and reduce the contact angle, as well as the lamellar structure that forms selective nanochannels for water transport. At higher concentrations (1wt%), however, flux decreased to 4501.80 L/(m^2·h), likely due to GO agglomeration blocking membrane pores. These observations are consistent with prior studies showing GO's dual role in boosting permeability while requiring careful optimization (Rashidi et al., 2022; Dahanayaka et al., 2020).

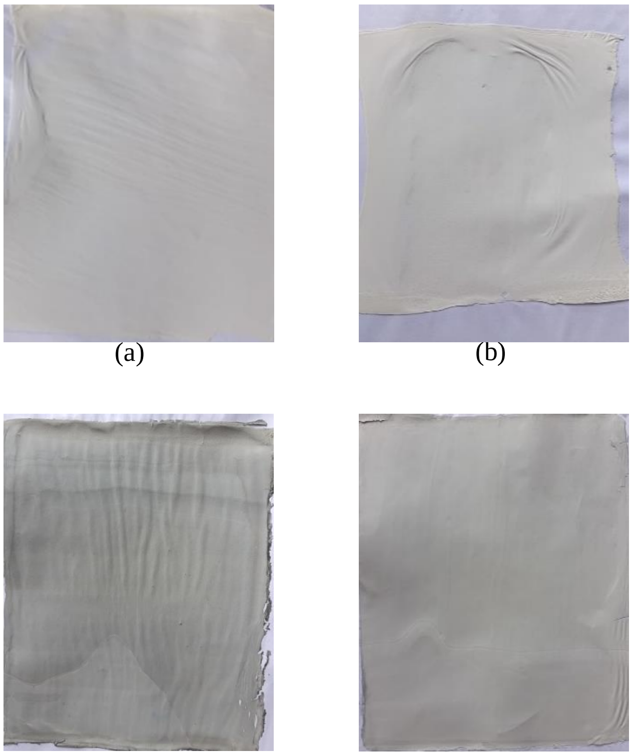

Figure 2. Membrane (a) PVC, (b) non-PVC, (c) GO 0.5%, and (d) GO 1%

Figure 2 shows membranes produced with different compositions, where visual inspection reveals variations in surface homogeneity, smoothness, and the presence of folds or lines. Membranes with smoother surfaces indicate better casting quality and more uniform polymer distribution, while folds or irregularities suggest instability during solvent evaporation or phase inversion. In addition, differences in membrane color also reflect the influence of additives: the incorporation of CA into PVC generally enhances hydrophilicity, which is often indicated by a brighter surface and higher porosity, whereas the addition of GO tends to result in a slightly darker appearance due to the dispersion of carbon nanosheets within the polymer matrix, which simultaneously contributes to improved hydrophilicity and permeability.

Overall, the findings highlight a clear trade-off between permeability and selectivity depending on the chosen additive. PVC enhances salt rejection but reduces flux, while GO dramatically increases flux at optimal loading but risks aggregation at higher concentrations. The novelty of this study lies in demonstrating the contrasting effects of polymer blending (PVC) versus nanomaterial incorporation (GO) on CA membranes, showing that even small modifications can significantly alter performance. Future research should explore hybrid strategies combining these approaches to achieve a better balance between salt rejection and water permeability.

CONCLUSIONS

The addition of PVC to the membrane layer enhances mechanical resistance, as indicated by an increase in salt rejection from 2.074% in membranes without PVC to 4.149% in membranes with the incorporation of 0.01 g PVC. However, this improvement in selectivity was accompanied by a significant reduction in permeate flux, from 825.330 L/m²·h to 300.120 L/m²·h. These findings highlight the inherent trade-off between membrane selectivity and permeability, whereby PVC incorporation improves salt rejection efficiency but reduces water transport. In contrast, the incorporation of graphene oxide (GO) into the membrane was found to enhance permeate flux, with GO at 0.5% achieving 9003.60 L/m²·h, while a higher loading of 1% resulted in a decrease to 4051.80 L/m²·h due to agglomeration. To overcome these limitations, optimization of PVC composition within the polymer blend, in combination with careful adjustment of GO concentration, is necessary to achieve a more favorable balance between permeability and selectivity. Furthermore, future studies should assess the long-term stability of these membranes under operating conditions that more closely simulate real-world applications and explore potential polymer combinations to further enhance overall performance.

LIMITATIONS & FURTHER RESEARCH

This study is subject to several limitations. First, the concentration of polymers and additives employed in membrane fabrication was restricted to relatively simple variations, and therefore does not capture the broader range of complex formulations that may yield different performance outcomes. Second, the performance evaluation was limited to permeability, salt rejection, and pressure resistance using feed water from the local utility (PDAM). Consequently, the findings may not be directly comparable when applied to brackish water or wastewater containing higher levels of ions and organic compounds. Third, although pressure resistance was assessed, other critical aspects, such as resistance to biological fouling and long-term chemical stability, were not evaluated, indicating that further research is required to ensure the durability of the membranes under real operating conditions. Fourth, the present work was conducted at the laboratory scale using flat-sheet membranes with a small effective area (4 × 4 cm), which necessitates further investigation at the pilot or industrial scale to obtain more representative performance data.

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