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Incorporation of Kappa-Carrageenan as Additive for Morphological and Performance Enhancement of Nanohybrid Polysulfone / Silver-Graphene Oxide Membranes

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ABSTRACT

Membranes have been widely used in the process of treatment of water and wastewater. PSf membranes exhibit robustness and flexibility. Nevertheless, the hydrophobic nature of PSf impedes the flow of water and reduces the effectiveness of membrane filtration. Hence, the properties of PSf membranes can be enhanced with the incorporation of kappa-carrageenan (k-car), an extremely hydrophilic biopolymer. This study examined the use of k-car, a biopolymer made up of anionic polysaccharides derived from certain species of ocean red algae. The goal was to address issues connected to the membrane's hydrophilicity and selectivity. The membranes produced with various percentages of k-cars (0.1 wt%, 0.25 wt%, 0.5 wt%, 0.75 wt%, and 1.0 wt%) are identified as C1, C2, C3, C4, and C5, respectively. The PSf/k-car membranes underwent characterization using FTIR, water contact angle (WCA) goniometer, FESEM, salt and dye rejection. The inclusion of k-car substantially enhanced the hydrophilic properties of PSf membranes. The results indicated that the 0.25 wt.% k-car addition resulted in the maximum porosity, reaching 79%. The presence of an extra -OH signal at 3385.31 cm⁻¹ in the nanohybrid membrane's FTIR spectra suggests an enhanced hydrophilicity, possibly due to the hydroxyl (-OH) groups of k-car. The water contact angle of the manufactured membranes reduced from 68.52° to 43.28°, indicating an improvement in their hydrophilicity. Compared to the pure PSf membrane, the arrangement of the finger-like structure of the manufactured nanohybrid membrane is slightly curved with a bigger lower section. Out of all the artificial membranes, C2 demonstrated the highest level of salt removal, reaching up to 97%. This discovery demonstrated that the inclusion of 0.25 wt% k-cars significantly improved both the water permeability of the membrane and its ability to reject salt and dye. Overall, the addition of k-car as a substance that creates pores in the PSf membrane has significantly affected its ability to attract water, its ability to selectively allow certain substances to pass through, and its physical structure.

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1. Introduction

Water is a crucial resource for the development of both farming and commercial goods and services. Approximately 2.7% of the total global water supply is classified as freshwater, and out of that, only 30% is safe for human use [1]. Considering these circumstances, countries that experience arid and semi-arid climates have limited access to freshwater, which significantly hinders their socio-economic progress. In addition, the freshwater resources of the region have been subjected to increased demand due to factors such as fast population growth [2], economic development, urbanization [3], industrialization [4], and changes in land use [5]. The discharge of chemical waste into freshwater systems reduces the accessibility of fresh water [6]. The main water pollutants can be classified into three categories: pathogens, organic chemicals, and inorganic chemicals. According to Yaashikaa et al., [7] inorganic chemicals encompass heavy metals [8], colorants [9], organic volatile compounds (VOC), plastics [10], oil [11], herbicides [12], pesticides [13], and insecticides [14]. Diverse water treatment techniques have been employed to eliminate harmful pollutants from the water [15]. There are found three distinct categories of water treatment technologies: physical, chemical, and biological methods. The major physical methods used for controlling water pollution are sedimentation, degasification, and filtration. Filtration is the method of eliminating impurities by considering their dimensions. Eliminating pollutants from wastewater enables the recycling of water for many purposes. The filters used in the procedure differ depending on the specific contaminants found in the water. There are two primary methods of wastewater filtration: particle filtration [16] and membrane filtration [17].

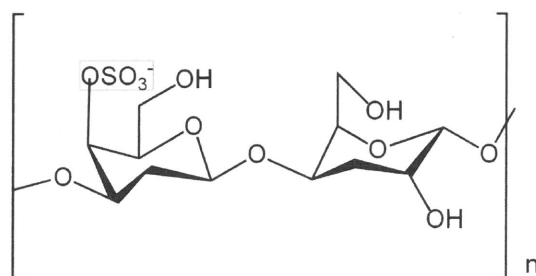


Fig. 1. The chemical structure of kappa-carrageenan

2. Methodology

2.1 Materials

The pelletized form of polysulfone (PSf), kappa carrageenan (*k*-car) powder, sodium sulphate (Na₂SO₄), calcium chloride (CaCl₂) and methylene blue dye were obtained from Sigma (Darmstadt, Germany). The solvent employed was N-methyl-2-pyrrolidone (NMP) acquired from R & M Chemicals in Kuala Lumpur, Malaysia.

2.2 Methods

The PSf/ *k*-car films were produced using the phase inversion approach. The polymer utilized for making the casting solution was PSf, while the solvent employed was NMP. The objective of

employing k-car, a hydrophilic modifier/additive, was to enhance the flow rate of the membrane. Table 1 shows that different amounts of k-car were added to membranes C0 (as controlled film), C1, K2, K3, K4, and K5. These amounts ranged from 0.0% to 1.0%.

Table 1
Composition of fabricated membranes

Membrane	PSf (% wt)	k-car (% wt)	NMP solvent (% wt)
C0	20	0.0	80
C1	19.9	0.1	80
C2	19.75	0.25	80
C3	19.5	0.5	80
C4	19.25	0.75	80
C5	19.0	1.0	80

In order to achieve a uniform casting solution, the k-car compound was initially dissolved in the N-methyl-2-pyrrolidone (NMP) solvent and went through sonication for a duration of 30 minutes. The solution containing the k-car /Ag-GO/NMP was stirred for 24 hours while the PSf was slowly added. Next, the mixed casting solution was carefully spread onto a pristine glass plate, which was subsequently immersed in deionized water (DI) for a duration of 15 seconds before it was separated. After the fabrication process, the completed films k-car were immersed in a container filled with deionized water.

2.3 Characterizations

Porosity is an essential element of the membrane's structure, as it directly influences the rate at which water flows through it. The equation provided below outlines the gravimetric method employed for determining the porosity (ε) of the membrane:

$$\varepsilon, \% = \frac{W_w - W_d}{\rho \cdot A \cdot \ell_m} \times 100 \quad (1)$$

where A is the membrane area, ρ is the water density, ℓ_m is the membrane thickness, and W_w and W_d are the membrane's weights when wet and dry, respectively.

The membranes were assessed using a Perkin Elmer Frontier Fourier-transform infrared (FTIR) spectroscopy to identify the functional groups present. Before assessment, the samples were dried in a desiccator to guarantee that the membrane coupons are devoid of contaminants and in an intact state. Every membrane went through 3 rounds of analysis.

The surface wettability/hydrophilicity of a membrane was assessed using a contact angle measurement goniometer (L2004A1, Ossila BV), which quantifies the contact angle. Prior to measurement, each newly produced membrane was subjected to a 24-hour drying process in a desiccator. The tensiometer was assembled by placing a glass slide on the PSf/ k-car /Ag-GO film membranes after it had undergone drying at room temperature in desiccator. In order to ascertain the angle of contact, a 3 μ L droplet of deionized water, was applied to 3 distinct spots on the dry membrane surface.

The cross-sectional and surface structure of the membranes that were created were analyzed by Field Emission Scanning Electron Microscopy (FESEM) via a Gemini SEM 500 apparatus from Zeiss, that is located in Oberkochen, Germany. The pristine membranes were filled using ultra-pure water and left to desiccate overnight prior to measurement. The porous membrane samples used in the

FESEM investigations were fragmented using liquid nitrogen and subsequently coated with platinum. Afterward, the membrane was affixed to the 3.0 mm × 4.0 mm measurement, where is set up on the FESEM sample holder.

2.3 Performance of membranes

Filtration tests are performed utilizing a small-scale dead end filtration system equipped with a stirred cell made of stainless steel. The system has a functional membrane surface area of 14.6 cm². The tests are performed at room temperature and at a pressure of 3 bar, as shown in Figure 2. The membranes' distinguishing features are their water permeability and capacity to remove dye. The permeability was determined using the following formula:

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

The pure water flux (J) in units of (L/m².h) is calculated by considering the permeate volume (ΔV) in liters, the effective membrane area (A) in square meters, and the duration (Δt) in hours. The performance study for solute removal used feed solutions with a dye concentration of 10 mg/L and both salts concentration of 1000mg/L. The rejection of solutes of Na₂SO₄ and CaCl₂ salts and methylene blue (MB) dye were estimated using the following equation:

$$Ro = 1 - \left(\frac{c_p}{c_f}\right) \times 100\% \quad (3)$$

Where Ro represents the percentage of rejection, c_f represents the concentration of the feed, and c_p represents the concentration of the permeate. The salt content is evaluated through assessing its conductivity with a conductivity meter equipped with a pH probe (Hanna HI-5521-02 Research Grade Bench Meter). The dyes concentration is evaluated by measuring its absorbance at the relevant wavelength using a UV-spectrophotometer, namely the Thermo Scientific GENESYS 180 UV-VIS spectrophotometer.

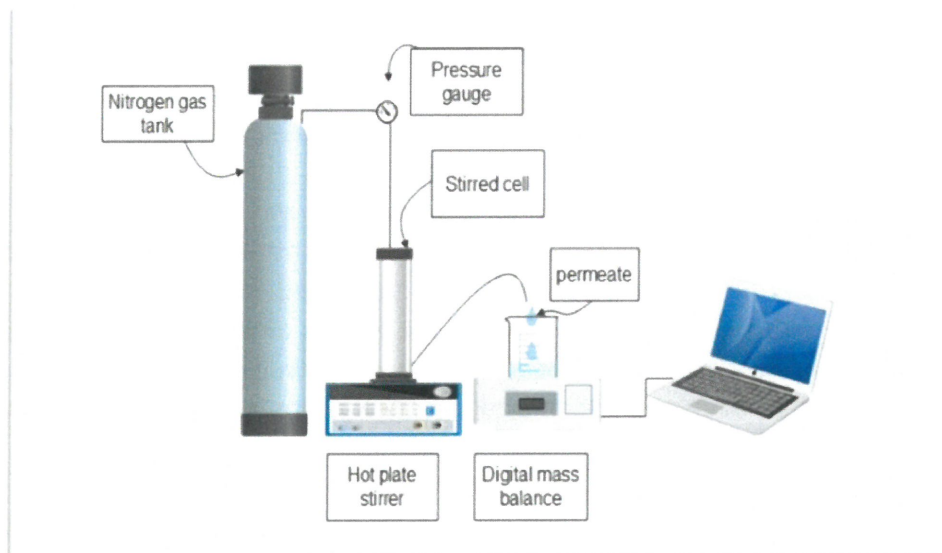


Fig. 2. Illustration shows the arrangement of components in a filter system

3. Results

3.1 Porosity

The incorporation of diverse k-car into polysulfone membranes can have a substantial impact on their porosity and efficiency. High porosity membranes exhibit greater hydrophilicity [18]. Figure 3 displays the findings of an investigation on membrane structure elements, specifically porosity, which has a substantial impact on the water flux. Based on the results of this research, augmenting the amount of k-car within the PSf composition induces the development of the PSf membrane, resulting in the creation of an increasingly porous and permeable configuration. The porosity of the fabricated membranes originally experienced a rise from 69.70% to 79.25%, but then decreased to 75.61%. Afterwards, the porosity remained consistent even when the k-car concentration reached 1.0%. The porosity of C2 membranes, which contain 0.25 wt.% of k-car, increased by 79.25% compared to the C0 membranes. Nevertheless, the inclusion of k-car content in C3 membranes led to a significant reduction of 75.61% in the porosity value. The addition of additional k-car to the C4 and C5 membranes did not affect the porosity percent values, which maintained at 75.71% and 75.67%, respectively. These findings suggest that the pattern exhibited a correlation between hydrophilic properties and the functional group analysis. These results clearly demonstrate that the hydrophilicity of the membrane and the O-H bond are greatly modified by the introduction of k-car. This is further supported by the observation that C2 membranes exhibited the smallest contact angle measurement, indicating an augmentation in the porosity of the films. In addition, the introduction of k-car has led to an increase in the porosity of polymer membrane surfaces, allowing for a greater influx of water molecules into the matrix. The presence of O-H groups on the surfaces of polymers significantly impacts the porosity of manufactured polymer membranes, particularly when combined with low contact angles. The increased hydrophilicity caused by the presence of hydroxyl (-OH) bonds promotes the formation of interconnected voids and porosity in the membrane structure, leading to higher porosity.

Incorporating kappa-carrageenan (k-car) into membrane formulations has a substantial impact on both porosity and performance. According to Alam et al.[19], the addition of k-car to polyvinylidene fluoride (PVDF) membranes enhances their hydrophilicity, resulting in faster separation and the creation of asymmetric structures that have better water permeability. According to El-Aassar et al.,[20] membranes made of k-car/hyaluronic acid exhibit greater porosity and drug release when they contain higher amounts of hyaluronic acid. As shown by Olay et al., [21] the pore diameters and water permeability of composite membranes constructed from k-car and tilapia fishbone fluctuate depending on the ratio of k-car to fishbone. In a study conducted by Yadav et al., [22] it was shown that incorporating kappa-carrageenan and graphene oxide into a nanofiltration membrane resulted in enhanced wettability, selectivity, and antifouling qualities. The investigations illustrate that the addition of k-car and the conditions under which it is processed are vital factors in defining the porosity of the membrane and its performance characteristics.

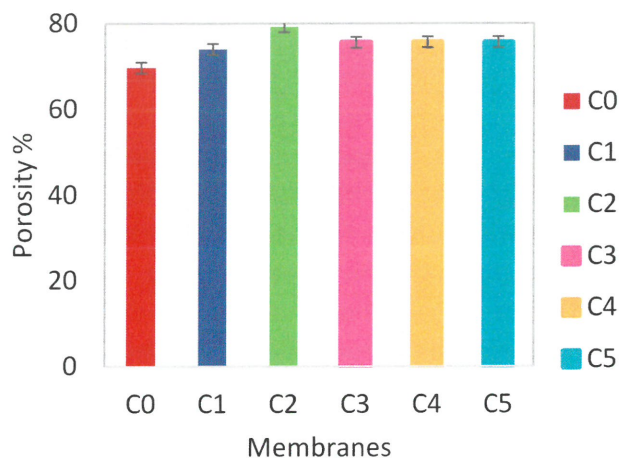


Fig. 3. Membranes porosity

3.2 Functional group of membranes

The fabricated membranes were analyzed for their functional groups using FTIR spectroscopy. In the present study, we performed characterization of all PSf membranes, whether fabricated with or without Ag-GO NPs. Figure 4 displays the FT-IR spectra of C0 and modified membranes (C1 - C5) in the range of 3000 to 4000 cm^{-1} . Table 2 presents a compilation of O-H peak vibrational frequencies for membrane samples. Figure 4 demonstrates that the C0 membrane does not exhibit any visible peaks (3350.45 cm^{-1}) indicating O-H peak vibrations. However, the C1 to C5 membranes showed a distinct peak ranging from 3379.62 cm^{-1} to 3379.97 cm^{-1} . Table 2 shows that the frequency of O-H stretching bonds rose from 3379.62 cm^{-1} to 3385.31 cm^{-1} for membrane C1 and C2, respectively. These reasons explain how the addition of k-car significantly alters the hydrophilicity and structure of the membrane. The introduction of k-car at a greater concentration for the C3 membrane resulted in a decrease of 3379.87 cm^{-1} . The frequency then stabilized at 3379.81 cm^{-1} for the C4 membrane and 3379.97 cm^{-1} for the C5 membrane. Concisely, the results of the FT-IR spectra confirm the theory that the appearance of an O-H bond causes a shift in the water contact angle, which initially decreased and subsequently increased once more.

The research conducted by Sinha et al., [23] and Kanehashi et al., [24] emphasizes the use of -OH groups in adamantane-containing polymer substances and alcohols as modifications that increase the hydrophilicity of membranes. The substitution of functional groups in k-car structures boosts their electronegative characteristics, resulting in enhanced interaction with ions and greater electrical conductivity [25]. The study conducted by Fathanah et al., [26] found that the inclusion of hydroxyl groups from additives such as $\text{Mg}(\text{OH})_2$ enhances the hydrophilicity and antifouling capabilities of the modified PES membranes. The alterations made to the O-H functional groups of k-car within the membrane lead to enhanced membrane performance, rendering it a highly promising material for augmenting the properties of polymer membranes.

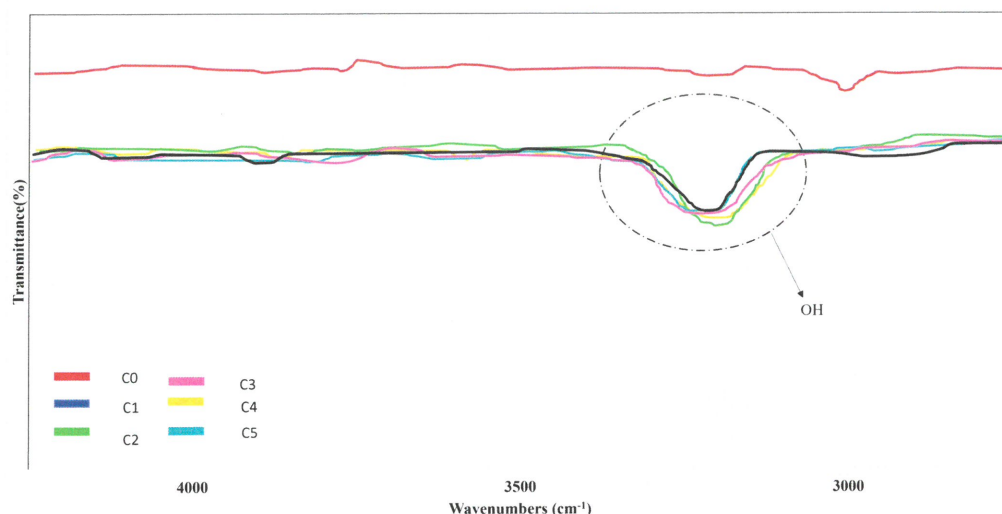


Fig. 4. FTIR Spectra of produced membranes

Table 2

Assignment spectra of membranes C0, C1, C2, C3, C4 and C5

No. assignment	FTIR Frequency(cm^{-1})					
	C0	C1	C2	C3	C4	C5
O-H stretching bonds	3350.45	3379.62	3385.31	3379.87	3379.81	3379.97

3.3 Hydrophilicity

Incorporating kappa-carrageenan, k-car into polymer membranes greatly improves their hydrophilicity and overall performance. The hydrophilic property of membranes, often assessed using contact angle measurements, affects their flow rate, ability to reject certain substances, and tendency to accumulate fouling [27]. The data presented in Figure 5 demonstrates that the higher concentration of k-car in the membrane fabrication process has resulted in an improved contact angle, leading to increased hydrophilicity of the composite membranes. Specifically, the contact angle has decreased from 68.52° to 43.28° . The contact angle decreased to 68.52° , 59.48° , and 43.28° for C0, C1, and C2 membranes, respectively. The contact angle for the C3 membrane has been increased to a value of 58.09° . However, the contact angles at which the C4 and C5 membranes remain still are 58.64° and 58.22° , respectively. The results suggest that the initial reduction in contact angles is likely due to the formation of a more even and hydrophilic surface layer as the result of carrageenan molecule absorption. When the amount of carrageenan reaches a particular limit, additional molecules may disrupt the uniformity of the surface barrier. This disturbance leads to an elevation of the contact angle and a subsequent decrease in the hydrophilicity of the surface. Therefore, it was discovered that the inclusion of k-car during the preparation of C2 membrane is the optimum quantity that significantly enhanced the hydrophilic properties of polymeric PSf membranes. There is an anticipated point of saturation for the hydrophilic parts on PSf/ k-car membranes, beyond which further additions do not provide any further effects.

A study conducted by Liew et al., [28] found that phosphorylation of k-car improves the conductivity of proton and hydrophilic properties of the resultant polymer membrane. While studies conducted by Zeinali et al., [29] and Alam et al., [19] found that phosphorylation of k-carrageenan improves the conductivity of proton and hydrophilic properties of the resultant polymer membrane.

These results show that by adding k-car, the hydrophilicity of the membrane can be increased, resulting in a considerable improvement in membrane performance.

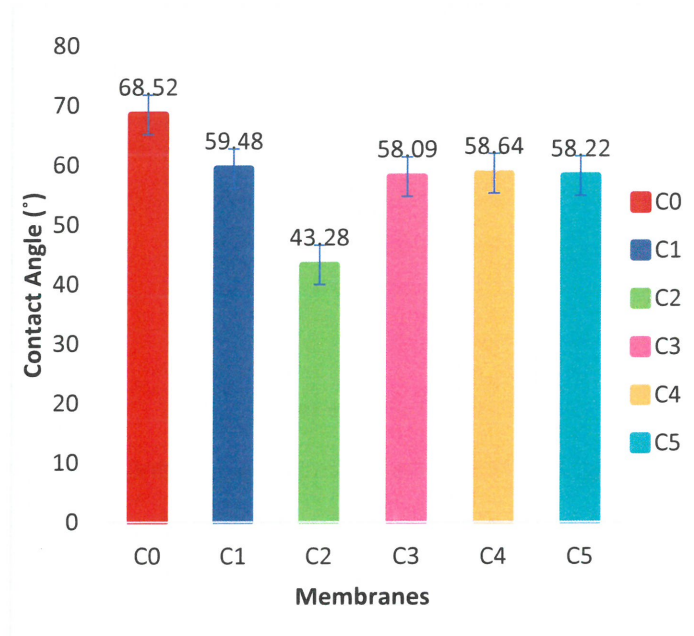


Fig. 5. Contact angle for fabricated membranes

3.4 Membranes Morphology

The cross-sectional images exhibit a significant differentiation. The structures of the PSf membrane and PSf/k-car membranes were examined by FESEM characterisation. Figure 6 presents FESEM images of the cross-sectional views of membranes C0, C1, C2, C3, C4, and C5. The cross-sectional pictures obtained from the Field Emission Scanning Electron Microscope (FESEM) show a minor difference between the C0 and C1 membranes. The finger-like structure of K0 membranes was replaced by membranes that included a porous sublayer with non-uniform thumb-like pores, as depicted in the FESEM image of the C1 membrane. However, when the concentration of k-car was increased to 0.25%, it was replaced by a continuous porous membrane that exhibited uniformly distributed pores. Figure 6 (d-f) demonstrates that the finger-like structure decreased in length with the increasing inclusion of k-cars. Furthermore, the lower section underwent a transformation, underwent enlargement and closure, accompanied by the formation of tiny holes as a result of the saturation and clumping of k-car throughout the fabrication procedure. Alam et al., [19] stated that the PVDF/ k-car exhibited a wide bell-shaped surface and open macrovoids that were dispersed unevenly over the entire cross-sectional region. Suhaim et al., [30] reported that the finger-like structure formed with increasing amounts of Ag-GO NPs.

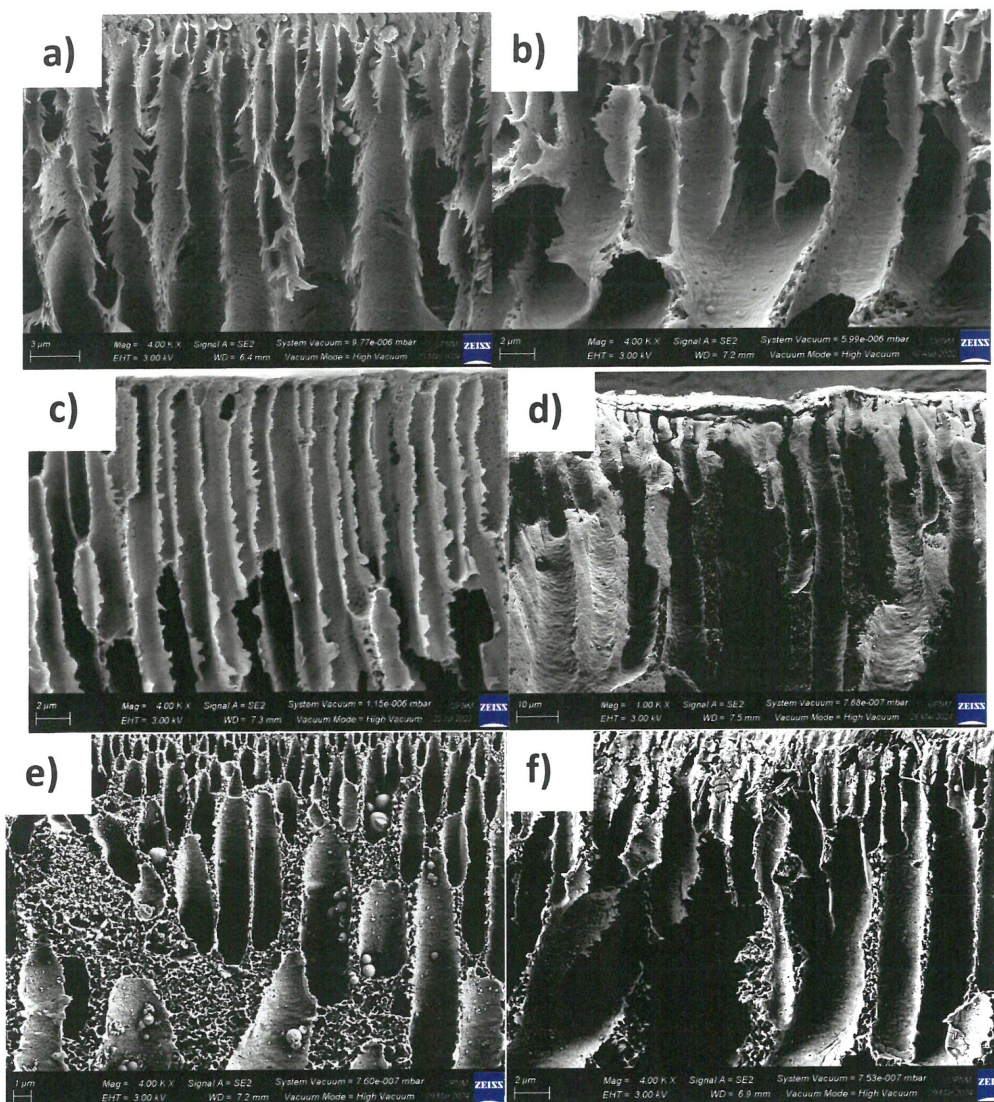


Fig. 6. Cross-sectional morphology for a) C0, b) C1, c) C2, d) C3, e) C4, and f) C5

Unlike the cross-sectional images, Figure 7 displays the surface of the produced membranes using microscope pictures. From the provided photos, it can be observed that there is minimal differentiation between the pure PSf membrane (depicted in Figure 7a) and the nanohybrid membrane that was created (depicted in Figure 7b–f). The photos depict a transition from a smooth and uniform surface to a rough surface with an increased number of embedded k-cars. This roughness is accompanied by an increase in the number of pores on the surface membrane, indicating the aggregation and saturation of k-car. The current finding corresponds to a study conducted by Selvakumaran et al., [31], which examined the surface morphology of hydrogels containing k-car/ NaHCO_3 . The results showed that the hydrogels exhibited a rough, compact, fragile, denser, undulating, and non-uniform surface structure. While the study conducted by Rudhzhiah et al., [32] said that the k-car material has an irregular and rough surface for applications involving polymer electrolytes. When comparing with other additives such as zinc oxide [33] and titanium dioxide (TiO_2) [34]. According to study that conducted by Mataram et al., [34] it is observed that there is a notable occurrence of agglomeration and the creation of irregular pore diameters. The reason for this occurrence is the migration of nanoparticles to the surface of the membranes [35]. Consequently, the membrane's porosity was increased, resulting in a beneficial effect on the

membrane's pure water flow. The introduction of k-car has been discovered to modify the shape of the PSf the membranes and leading to the development of a structure resembling fingers shape. This design will showcase the exceptional porosity and selectivity of the films.

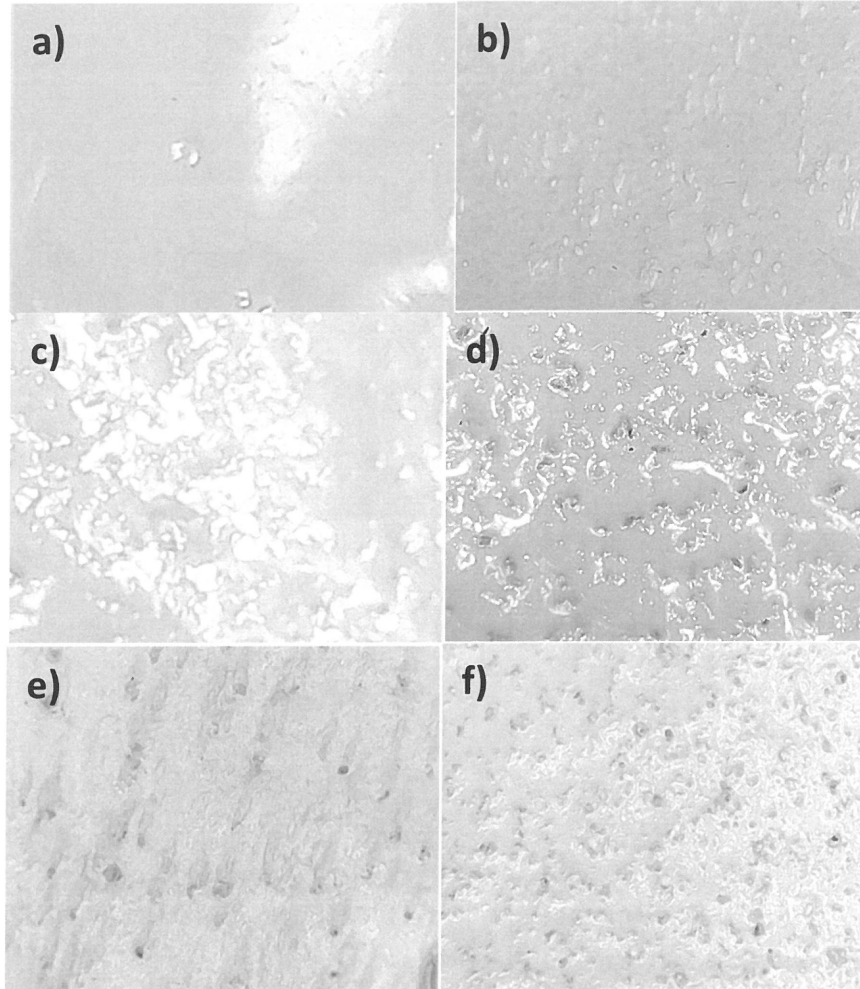


Fig. 7. Surface Images of a) C0, b) C1, c) C2, d) C3, e) C4, and f) C5

3.5 Salt Rejection

The salt rejection tests utilized feed solutions containing 1000 mg/L of Na_2SO_4 and CaCl_2 . The studies were performed in a dead-end stirred cell, repeated three times, under a constant pressure of 3 bar. Continuous stirring was employed to reduce concentration polarization, and the resulting mean values were recorded. Figure 8 illustrates the removal of salt for Na_2SO_4 and CaCl_2 , respectively. The nanohybrid membrane demonstrated greater salt rejection, above 80%, when subjected to a pressure of 3 bar, in comparison to the pure PSf membrane which only achieved 20% salt rejection at a pressure level of 7 bar. The pure PSf membrane is unable to accomplish full salt rejection at 3 bar pressure, which is why the C0 membrane at 7 bar pressure can only remove both salts at a rate of 20%. The reason for these observations is that nanohybrid membranes are more hydrophilic compared to pure PSf membranes. However, this result can also be attributed to the growing permeability caused by the introduction of k-cars. Specifically, the porosity of C0 was measured at 69.70%, whereas C2 had a porosity of 79.25%. According to the graph in Figure 8, the rejection of

both salts exhibited an increase from C1 to C2, followed by a slight decline for C3, and then stayed constant for C4 and C5. The observed trend can be attributed to saturation and agglomeration occurring at the C3, C4, and C5 membranes. Furthermore, the graph analysis reveals that Na_2SO_4 exhibits better rejection capabilities for nanohybrid membranes in comparison to CaCl_2 .

The rejection process is influenced by Donnan exclusion. Membranes possessing negative charge provide selectivity for positive ions, enabling them to pass through the membrane while resisting negative ions. When comparing them, sulfate ions have greater charges, which is why Na_2SO_4 is rejected more strongly than CaCl_2 . The exclusion of ions is intensified by co-ions with higher charges and diminished by counter-ions with higher charges. The work developed a negatively charged nanohybrid membrane with co-ions consisting of chloride ions (Cl^-) and sulphate ions (SO_4^{2-}). CaCl_2 maintains a high rejection rate of over 80% due to concentration of Ca^{2+} ions formation at the surface. As proposed by Mi et al., [36], the presence of a negatively charged membrane can result in the attraction of Ca^{2+} ions to its surface, leading to an increased concentration of Ca^{2+} ions at the surface. Basically, C2 membranes provide notable advantages for membrane filtering applications that require immediate results, as they are highly efficient in eliminating salt.

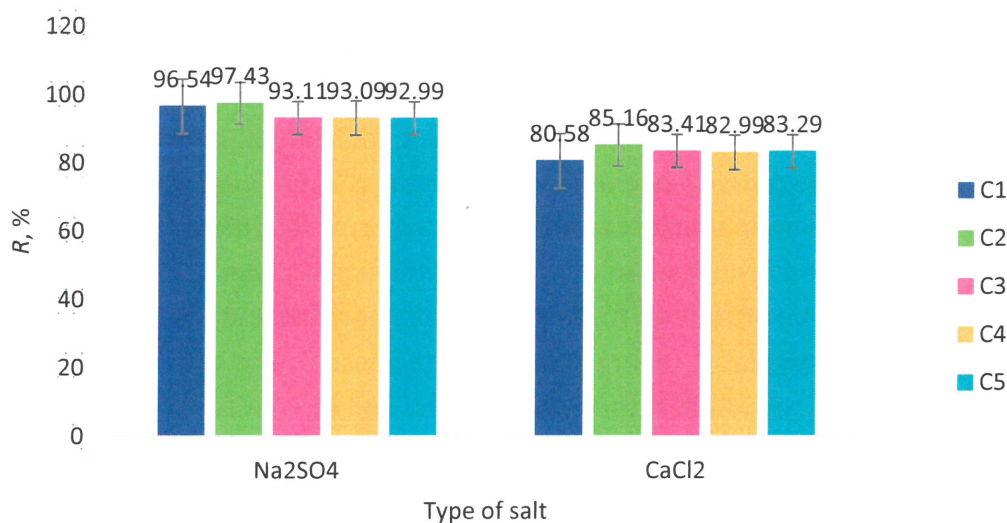


Fig. 8. Salt removal of Na_2SO_4 and CaCl_2 of concentration 1000 mg/L at 3 bar pressure

3.6 Methylene blue Rejection

Methylene blue (MB) is a positively charged dye. Excessive exposure to MB can lead to jaundice, nausea, tissue necrosis, elevated heart rate, and other significant impacts on human health [37]. Basic dyes, which include basic red, basic blue 9, and methylene blue (MB), are regarded as one of the troublesome dye classes. MB is a basic dye that's commonly used to dry wood, cotton, and silk. The molecules that comprise up MB generally soluble in water and very stable. This basic dye is categorized as a hazardous colorant and has the potential to cause cancer and mutagenesis [38]. Sewage discharges containing MB are both visually vibrant and pose a significant threat to aquatic species. Therefore, it is necessary to treat the colored water before disposing of it [37]. The problem of contamination produced by colorant material can be mitigated through many methods including oxidation from chemicals, coagulation, membrane separations, and microbial degradation processes

[39]. Employing affordable, eco-friendly techniques and biocompatible substances can serve as efficient means to mitigate the environmental impact caused by dye producers and the waste generated by the textile sector. Composite membranes have emerged as a highly promising platform for effectively removing dyes from both water and wastewater.

Figure 9 depicts the water permeability and methylene blue rejection of the fabricated membranes. The PSf composite membranes, when blended with k-car, exhibited increased permeability and water flux in comparison to the original PSf membrane. The PSf membrane, in its original condition, needed a pressure of 7 bar to obtain a water flux of 8.53 L/m².h in a span of 30 minutes. Additionally, it demonstrated a remarkable ability to eliminate 90.21% of a cationic methylene blue dye. The k-car -blended polymer membranes have shown comparable properties with notably higher hydrophilicity, even at a minimal concentration of k-car. The results showed that the membranes made with the hybrid of PSf/ k-car had the greatest volume of water flux. Figure 9 showed that the introduction of the k-car starts to the membrane at C1 resulted in an increase in water flux from 8.53 L/m².h to 30.81 L/m².h, compared to the original PSf membrane. Nevertheless, the elimination of MB experiences a gradual decrease from 90.21% to 89.27%. However, amazingly, the elimination of MB significantly increased as the concentration of k-car started to rise at the C2 membrane, reaching a level of 95.29% with a water recovery rate of 64.31 L/m².h. However, when the k-car is increased, the K3 membranes are unable to remove the dye as effectively as the C2 membranes. C3 membranes are able to remove dye up to 69.39% with a recovery water rate of 14.21 L/m².h. Subsequently, the removal of dye reached a state of stagnation when additional k-car were added to the C4 and C5 membranes, resulting in a dye removal efficiency of 70.06% and 69.15% respectively. The observed result can be attributed to the aggregation of particles at K3, K4, and K5. The observed result can be attributed to the decrease in porosity and the increase of contact angle at K3, K4, and K5. Consequently, this resulted in a decrease in the hydrophilicity of three of the membranes, leading to a reduction in their permeability and selectivity.

In this study, the C2 membrane is regarded as the most effective membrane for eliminating cationic dye from synthetic dye water. However, future work will include determining the optimal rejection that may be accomplished by analyzing the amount of Ag-GO NPs embedded in the nanohybrid PSf/Ag-GO membranes. In future research, the study will explore the potential of attaining complete rejection (100%) of anionic dyes and divalent ions in order to improve membrane performance and ensure the production of safe drinking water.

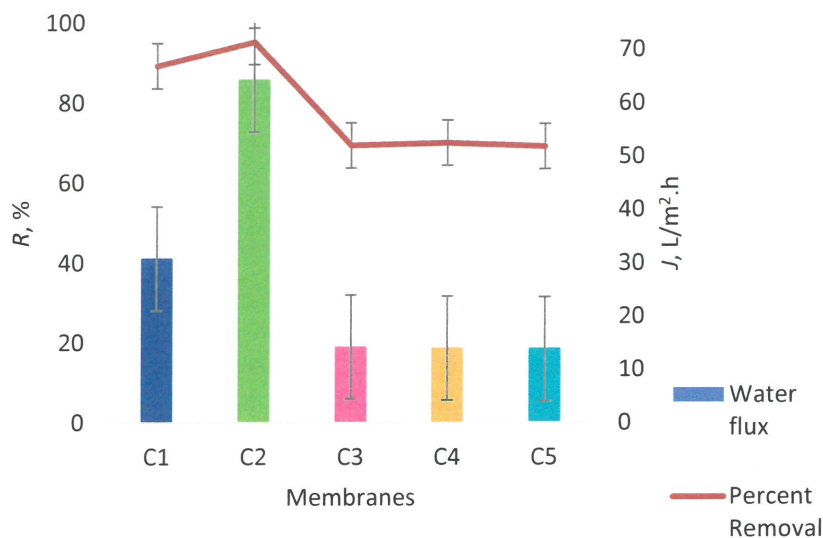


Fig. 9. Removal of methylene blue and water flux of prepared membranes

4. Conclusions

This study effectively created nanohybrid polysulfone membranes by incorporating kappa-carrageenans (PSf/k-car) into the PSf casting solution. The nanohybrid film was fabricated using the phase inversion approach. The inclusion of k-cars led to enhancements in the properties of the produced membrane, including increased porosity, hydrophilicity, and selectivity. The presence of many hydrophilic -OH functional groups on k-car/PSf membranes is responsible for this. The contact angle results indicate that increasing the number of integrated k-cars from C1 to C2 leads to a decrease in the contact angle of the produced membrane. This suggests that the hydrophilicity of the membranes has been improved. The porosity of the produced membranes in C2 increased due to the increased water flux. Nevertheless, the introduction of a greater concentration of k-car into the polymeric solution led to a decrease in the hydrophilicity and porosity of the membranes. As a result, this circumstance led to an accumulation and clumping of k-car occurring throughout the fabrication process. In addition, the inclusion of k-car in C2 led to a continuous finger-like membrane structure, enhancing its hydrophilicity and porosity. Moreover, the inclusion of k-car in C2 membranes resulted in an augmentation of hydrogen bonding, which consequently enhanced the affinity of water towards the lower part of the finger-like structure, thus elevating the hydrophilicity of the membrane.

The permeability and efficiency of the produced membranes were enhanced. The nanohybrid membrane effectively removes salt, with a C2 rise of over 85% compared to the pure PSf membrane (20%). In addition, C2 membranes have the capability to remove cationic dye by more than 95%, while recovering 64.31 L/m².h of water. However, it is advisable to further explore the effectiveness of the C2 membrane compared to other membranes by including Ag-GO NPs. Additionally, it is recommended to analyze the elimination of divalent ions in order to determine if drinking water regulations can be met or if complete removal is practicable. The next objective of this study is enhancing the efficiency and expanding the size of the PSf/Ag-GO membrane for anti-biofouling experiments in order to examine the antibacterial characteristics of the PSf/Ag-GO membrane. In

summary, this work provides valuable information on how to improve the design and efficiency of nanohybrid membrane technology for sustainable processes. Future research can use these findings as a foundation to develop even more sophisticated membrane technologies.

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