

Silver Nanoparticle-Engineered Sodium Alginate Nanocomposite Membranes for Enhanced Gas Separation Performance

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HIGHLIGHTS

- Silver nanoparticle-engineered sodium alginate (SA) nanocomposite membranes were successfully fabricated via solution casting followed by CaCl_2 crosslinking.
- AgNP incorporation (0.5–2.0 wt.%) effectively tailored the membrane microstructure and polymer free-volume characteristics.
- Nanocomposite membranes exhibited enhanced CO_2 permeability with preferential CO_2 transport over O_2 and N_2 .
- An optimum AgNP loading achieved the best balance between gas permeability and ideal CO_2/N_2 and CO_2/O_2 selectivity.
- Improved gas separation performance was attributed to homogeneous nanoparticle dispersion and strong polymer-AgNP interactions following the solution–diffusion mechanism.

ABSTRACT

Silver nanoparticle (AgNP)-engineered sodium alginate (SA) nanocomposite membranes were created by solution casting followed by CaCl_2 crosslinking utilizing a fixed sodium alginate concentration (5 wt.%) and varied AgNP loadings (0.5–2.0 wt.%). The membranes were tested for single-gas permeation of O_2 , N_2 , and CO_2 at a 2-bar supply pressure. The incorporation of AgNPs considerably altered the membrane microstructure, increased polymer-nanoparticle interactions, and adjusted free-volume properties, resulting in improved gas transport compared to pure SA membranes. Because of homogeneous nanoparticle

dispersion and little agglomeration within the polymer matrix, optimal AgNP loading achieved the best balance of gas permeability and perfect selectivity. The nanocomposite membranes exhibited preferential CO_2 permeability and increased CO_2/N_2 and CO_2/O_2 selectivity, resulting in gas transport via solution-diffusion. The increased structural stability and separation performance show that AgNP inclusion is a useful method for adjusting the transport properties of sodium alginate membranes. These sustainable nanocomposite membranes hold great promise for energy-efficient industrial gas separation and carbon capture applications.

Keywords: Carbon dioxide separation; Gas permeability; Nanocomposite membranes; Silver nanoparticles

1. Introduction

The rapid expansion of industrial activities and the corresponding increase in global energy consumption have intensified the demand for efficient and sustainable gas separation technologies. Traditional separation processes such as cryogenic distillation, pressure swing adsorption (PSA), and solvent-based absorption are widely used at industrial scale; however, they are typically associated with high energy requirements, complex operational setups, and significant capital costs. In contrast, membrane-based gas separation has emerged as a promising alternative owing to its lower energy consumption, modular design, ease of operation, and scalability, making it suitable for both large-scale and niche applications in environmental and energy sectors [1,2]. Polymeric membranes dominate current gas separation technologies due to their relatively low cost, good mechanical properties, and ease of fabrication. Despite these advantages, conventional polymeric materials often exhibit an inherent permeability–selectivity trade-off commonly described by Robeson’s upper bound, which limits their overall separation efficiency. In addition, issues such as plasticization under high-pressure conditions, physical aging, and limited thermal and chemical stability further restrict their long-term industrial applicability [3,4].

In recent years, increasing attention has been directed toward the development of sustainable and bio-based polymeric membranes as environmentally benign alternatives to conventional petroleum-derived membrane materials. Biopolymers such as chitosan, cellulose, alginate, gelatin, and starch are particularly attractive because of their renewable origin, biodegradability, low toxicity, and potential for functional modification. These materials can be further enhanced through blending, cross-linking, or incorporation of inorganic and organic nanofillers to improve their mechanical strength, thermal stability, permeability, and selectivity. Consequently, bio-

based membranes are emerging as promising materials for applications in gas separation, water purification, pervaporation, energy conversion, and environmental remediation, while contributing to the development of more sustainable and circular membrane technologies. Polymeric membranes have emerged as promising materials for the efficient separation of gases due to their low energy consumption, simple operation, compact design, and scalability. Gas separation occurs primarily through the solution–diffusion mechanism, in which gas molecules selectively dissolve in the polymer matrix and subsequently diffuse across the membrane. The separation performance depends on factors such as polymer structure, free volume, chain mobility, permeability, and gas–polymer interactions. Common polymeric materials include polysulfone, cellulose acetate, polyimides, polycarbonates, and emerging bio-based polymers. Recent research focuses on developing nanocomposite and mixed-matrix polymeric membranes to overcome the permeability–selectivity trade-off and enhance separation performance for applications such as CO₂/CH₄, CO₂/N₂, H₂/CO₂, and O₂/N₂ separation.

Among these, sodium alginate (SA), a naturally derived polysaccharide extracted from brown seaweed, has gained considerable interest. It is composed of β -D-mannuronic acid (M) and α -L-guluronic acid (G) residues arranged in varying sequences. The presence of abundant hydroxyl (-OH) and carboxylate (-COO⁻) functional groups in its structure provides strong coordination sites for metal ions and nanoparticles, while also facilitating intermolecular interactions with gas molecules, particularly those having polar or quadrupolar characteristics such as CO₂ [5,6]. Silver nanoparticles (Ag NPs) have attracted significant attention in membrane science due to their unique physicochemical and surface properties, including high surface area-to-volume ratio, catalytic activity, and affinity

toward π -electron-rich species. When incorporated into polymer matrices, Ag NPs can influence polymer chain packing, disrupt dense chain ordering, and thereby enhance fractional free volume, which in turn improves gas diffusion characteristics. Furthermore, their interaction with gas molecules can introduce additional selective transport pathways, thereby improving overall membrane performance [7,8].

Recent studies on silver-incorporated alginate-based membranes have demonstrated enhanced separation performance, particularly in olefin/paraffin systems, where Ag^+ species exhibit reversible π -complexation interactions with unsaturated hydrocarbons such as ethylene. This selective interaction leads to significantly improved ethylene/ethane selectivity while maintaining reasonable permeability, highlighting the potential of silver-functionalized biopolymer systems for targeted gas separations [9,10]. Motivated by these advancements, the present study focuses on the fabrication of sodium alginate–silver nanoparticle (SA–Ag NP) nanocomposite membranes via a solution casting method. The work systematically investigates their structural, morphological, and gas transport properties, with particular emphasis on evaluating their performance for CO_2 , O_2 , and N_2 separation. The overall objective is to develop a sustainable, high-performance, and cost-effective membrane system for advanced gas separation applications.

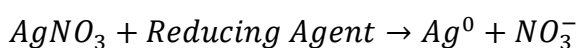
2. Materials and Methods

2.1. Materials

Sodium alginate, Calcium chloride, and sodium borohydrates of AR grade were purchased from S.D. Fine Chemicals, Mumbai, India. Silver nitrate was purchased from Sigma-Aldrich, India. All the reagents were used as such without any purification.

2.2. Synthesis of Silver Nanoparticles

Silver nanoparticles were prepared by the chemical reduction method.



A calculated amount of silver nitrate solution was added dropwise into the reducing solution under constant stirring. Formation of Ag nanoparticles was confirmed by the appearance of a yellow-brown colour due to surface plasmon resonance.

2.3. Preparation of Sodium Alginate–Silver Nanoparticle Nanocomposite Membranes

Sodium alginate (Na-Alg) solution was prepared by dissolving the required amount of sodium alginate in distilled water under continuous magnetic stirring until a homogeneous and clear polymer solution was obtained. Subsequently, the predetermined concentration of silver nanoparticle (AgNP) suspension (previously evaluated at different concentrations as shown in Table 1) was gradually introduced into the sodium alginate solution while maintaining continuous stirring to ensure uniform mixing. The resulting mixture was further subjected to ultrasonication for an appropriate duration to achieve homogeneous dispersion of the AgNPs throughout the polymer matrix and to minimize nanoparticle agglomeration. The well-dispersed nanocomposite solution was then cast onto clean, leveled glass plates using the solution-casting technique to obtain membranes of uniform thickness. The cast films were dried in a hot-air oven at 50–60 °C until complete evaporation of the solvent and the formation of free-standing membranes. The dried membranes were carefully peeled from the glass plates and subsequently immersed in an aqueous calcium chloride (CaCl_2) solution to induce ionic crosslinking between the alginate chains. The crosslinked membranes were washed thoroughly with distilled water to remove excess calcium ions and then dried at room temperature before further characterization and gas separation studies.

3. Results and Discussion

3.1. FTIR Analysis

The FTIR spectra of pristine sodium alginate (SA), SA–Ag (0.5 wt.%), and SA–Ag (2 wt.%) nanocomposite membranes are shown in Fig. 1. The spectra reveal that the characteristic absorption bands of sodium alginate are retained

after the incorporation of AgNPs, indicating that the fundamental polysaccharide backbone remains chemically intact during membrane fabrication. However, slight shifts in peak positions, changes in band intensity, and peak broadening are observed with increasing AgNP loading, suggesting the formation of strong intermolecular interactions between the hydroxyl and carboxylate functional groups of sodium alginate and the surface of AgNPs. A broad absorption band centered at 3420 cm^{-1} for pristine SA corresponds to the stretching vibration of hydroxyl (-OH) groups originating from the abundant hydrogen-bonded polysaccharide chains. Upon incorporation of AgNPs, this band gradually shifts to 3416 cm^{-1} for SA-Ag (0.5 wt.%) and 3412 cm^{-1} for SA-Ag (2 wt.%), accompanied by slight broadening. This shift indicates enhanced hydrogen-bonding interactions and coordination between the -OH of sodium alginate and the silver nanoparticles, resulting in restricted mobility of the polymer chains. Similar observations have been reported for silver nanoparticle-incorporated polysaccharide membranes, where metal-polymer interactions improve structural stability and interfacial compatibility [11-12]. The weak absorption band appearing around $2923\text{--}2925\text{ cm}^{-1}$ is assigned to the asymmetric stretching vibration of aliphatic C-H groups. This peak exhibit only marginal changes after AgNP incorporation, suggesting that the hydrocarbon backbone of SA remains unaffected during nanocomposite formation. The absence of new absorption bands in this region further confirms that AgNP incorporation occurs predominantly through physical interactions rather than the formation of new covalent bonds.

The characteristic asymmetric stretching vibration of the carboxylate group (vs COO^-) appears at 1602 cm^{-1} in pristine SA and shifts slightly to approximately 1600 cm^{-1} in both AgNP-loaded membranes. Likewise, the symmetric stretching vibration (vs COO^-) observed at 1417 cm^{-1} for pure SA shifts to 1412 cm^{-1} and 1411 cm^{-1} for SA-Ag (0.5 wt.%) and SA-Ag (2 wt.%), respectively. These spectral shifts indicate coordination interactions between AgNPs and the negatively charged carboxylate

groups of alginates. Such interactions reduce the electron density around the carboxylate oxygen atoms, leading to slight changes in vibrational frequencies. The interaction between AgNPs and alginate carboxylate groups contributes to improved nanoparticle dispersion and enhanced mechanical integrity of the membrane matrix [13-14]. The fingerprint region between 1200 and 900 cm^{-1} exhibits prominent absorption bands characteristic of the polysaccharide structure. The peak at approximately 1092 cm^{-1} corresponds to the C-O-C stretching vibration of the glycosidic linkage, while the band around 1024 cm^{-1} is attributed to C-O stretching vibrations of pyranose rings. Following AgNP incorporation, these peaks exhibit slight shifts toward lower wavenumbers ($1089\text{--}1087\text{ cm}^{-1}$ and $1022\text{--}1018\text{ cm}^{-1}$, respectively), accompanied by a modest reduction in intensity. These observations suggest that the AgNPs influence the local molecular environment surrounding the ether and hydroxyl groups through intermolecular interactions rather than altering the primary chemical structure of sodium alginate. Similar spectral behavior has been widely reported for polysaccharide-based nanocomposite membranes reinforced with metallic nanoparticles [15-16].

The absorption band located near 819 cm^{-1} , corresponding to the β -glycosidic linkage of the alginate backbone, remains nearly unchanged after AgNP addition, confirming that the saccharide framework is preserved during membrane preparation. The retention of this characteristic peak demonstrates that the solution-casting process and subsequent calcium ion crosslinking do not induce degradation of the polymer backbone [17]. FTIR results confirm the successful incorporation of silver nanoparticles into the sodium alginate matrix through non-covalent interactions, primarily involving hydroxyl and carboxylate functional groups. The absence of new characteristic absorption bands indicates that no new chemical species are formed during membrane fabrication, while the observed peak shifts and broadening provide clear evidence of strong polymer-nanoparticle interactions. These interactions are expected to modify polymer chain packing,

reduce chain mobility, and regulate the free-volume distribution within the membrane, thereby influencing gas diffusion pathways. Such structural modifications are anticipated to contribute to the enhanced gas permeability and selectivity observed for the SA–Ag nanocomposite membranes, particularly at the optimum AgNP loading, consistent with the solution–diffusion mechanism governing gas transport in dense polymeric membranes.

3.2. X-ray diffraction (XRD) Studies

The XRD patterns of pristine sodium alginate, AgNPs, and SA–Ag nanocomposite membranes containing 0.5 wt.% and 2 wt.% AgNPs are presented in Fig. 2. The diffraction profiles clearly demonstrate the successful incorporation of crystalline silver nanoparticles into the sodium alginate matrix while preserving the structural integrity of the polymer. The progressive appearance and enhancement of characteristic Ag diffraction peaks with increasing nanoparticle loading confirm the formation of well-dispersed AgNPs within the biopolymer matrix. Pristine sodium alginate exhibits two broad diffraction halos centered at approximately $2\theta = 13.5^\circ$ and 22.1° , which are characteristic of the semi-crystalline nature of sodium alginate. The broadness of these reflections indicates the predominance of amorphous regions associated with the random arrangement of polymer chains interconnected through extensive hydrogen bonding. Such a semi-crystalline morphology is typical of alginate membranes prepared by solution casting and provides sufficient chain flexibility required for gas transport through the polymer matrix. Similar diffraction features have been consistently reported for sodium alginate and calcium-crosslinked alginate membranes in the literature. The XRD pattern of the synthesized Ag nanoparticles displays four sharp and intense diffraction peaks located at 38.1° , 44.3° , 64.5° , and 77.4° , corresponding to the (111), (200), (220), and (311) crystallographic planes of face-centered cubic (fcc) metallic silver, respectively. These diffraction peaks agree well with the standard diffraction data for crystalline Ag (JCPDS Card No. 04-0783), confirming the successful formation of highly crystalline

metallic silver nanoparticles without detectable impurity phases such as silver oxide. Among these reflections, the (111) plane exhibits the highest diffraction intensity, indicating preferred crystal growth along with energetically favorable orientation, which is commonly observed for chemically synthesized Ag nanoparticles [14][18][19].

Following the incorporation of 0.5 wt.% AgNPs into the sodium alginate matrix, the characteristic broad reflections of sodium alginate remain visible, while additional diffraction peaks corresponding to metallic silver emerge at 38.1° , 44.3° , 64.5° , and 77.4° . The relatively lower intensity of these peaks reflects the limited concentration of AgNPs dispersed within the polymer matrix. Simultaneously, the alginate halo becomes slightly broader with a marginal reduction in intensity, indicating partial disruption of the polymer chain ordering due to nanoparticle incorporation. This behavior suggests that AgNPs act as nanoscale fillers that interfere with intermolecular hydrogen bonding and modify the packing density of the polymer chains without inducing crystallization of the alginate phase. For the SA–Ag (2 wt.%) membrane, the diffraction peaks corresponding to crystalline Ag become considerably sharper and more intense, reflecting the higher concentration of dispersed nanoparticles. Nevertheless, the broad amorphous halos associated with sodium alginate are still preserved, confirming that the polymer retains its predominantly amorphous structure despite nanoparticle reinforcement. The simultaneous presence of both the amorphous polymer halo and the crystalline Ag reflections demonstrates the successful formation of a polymer–metal nanocomposite consisting of crystalline Ag domains uniformly embedded within the alginate matrix. The absence of additional diffraction peaks further indicates that no undesirable secondary crystalline phases or silver oxide species were generated during membrane preparation [17][20].

The increase in Ag diffraction intensity with nanoparticle loading confirms efficient nanoparticle incorporation and good phase purity. At the same time, the persistence of the

broad alginate diffraction bands indicates that AgNP addition does not significantly alter the fundamental molecular structure of sodium alginate. Instead, the nanoparticles are physically embedded and interact primarily through coordination with hydroxyl and carboxylate groups, as supported by the FTIR analysis. Such polymer-nanoparticle interactions are expected to reduce excessive chain aggregation, slightly increase the interchain free volume, and generate additional diffusion pathways to penetrant gas molecules. Consequently, the structural modifications observed in the XRD patterns provide a strong structural basis for the enhanced gas permeation characteristics of the SA-Ag nanocomposite membranes [21]. From the perspective of membrane science, the coexistence of a semi-crystalline polymer phase and highly crystalline Ag nanoparticles is particularly advantageous for gas separation. The amorphous regions of sodium alginate primarily govern gas diffusion, whereas the uniformly dispersed crystalline Ag nanoparticles modify the microstructure by altering chain packing, increasing tortuosity in a controlled manner, and generating polymer-particle interfacial free volume. These interfacial regions facilitate selective gas transport according to the solution-diffusion mechanism while suppressing the formation of non-selective voids. At moderate nanoparticle loading, this synergistic effect can simultaneously enhance gas permeability and maintain or improve ideal selectivity. Conversely, excessive nanoparticle loading may promote local particle aggregation, reduce the continuity of selective transport pathways, and potentially diminish membrane performance. Therefore, the XRD results indicate that AgNP incorporation effectively tailors the microstructure of sodium alginate membranes, providing the structural foundation for their improved gas separation behavior.

Overall, the XRD analysis confirms the successful fabrication of sodium alginate-silver nanocomposite membranes comprising a semi-crystalline biopolymer matrix reinforced with highly crystalline face-centered cubic silver nanoparticles. The preservation of the alginate structure, together with the progressive increase

in Ag diffraction intensity, demonstrates excellent nanoparticle incorporation without altering the chemical identity of the polymer. These structural characteristics are expected to enhance membrane stability, optimize free-volume distribution, and improve gas transport properties, making the SA-Ag nanocomposite membranes promising candidates for sustainable gas separation applications.

3.3. FESEM Analysis

The FESEM micrographs of (a) Ag nanoparticles, (b) pristine sodium alginate, (c) SA-Ag (0.5 wt.%), and (d) SA-Ag (2 wt.%) are presented in Fig. 3. The synthesized Ag nanoparticles (Fig. 3a) exhibit a predominantly spherical morphology with a relatively narrow particle size ranging from 35-40 nm distribution and slight agglomeration, which is commonly attributed to the high surface energy of metallic nanoparticles. The pristine sodium alginate membrane (Fig. 3b) displays a dense, continuous, and relatively smooth surface without observable pores or defects, indicating the formation of a homogeneous polymer matrix through the solution-casting process. Upon incorporation of 0.5 wt.% AgNPs (Fig. 3c), the nanoparticles are uniformly dispersed throughout the alginate matrix with minimal aggregation, confirming good interfacial compatibility between AgNPs and the polymer. This homogeneous dispersion is expected to modify the polymer chain packing and generate additional interfacial free volume, thereby facilitating selective gas transport. With a further increase in AgNP loading to 2 wt.% (Fig. 3d), the membrane surface becomes comparatively rougher with a higher density of embedded nanoparticles and the appearance of localized nanoparticle clusters, suggesting the onset of partial agglomeration at higher filler concentrations. Nevertheless, no obvious cracks, voids, or phase separation are observed, indicating successful fabrication of structurally stable nanocomposite membranes. The FESEM observations demonstrate that silver nanoparticles are effectively incorporated into the sodium alginate matrix, where controlled nanoparticle dispersion can tailor the membrane microstructure and contribute to enhanced gas

permeability and selectivity by regulating diffusion pathways and free-volume characteristics [18][22].

3.4. Gas Separation Behaviour

Gas separation using polymeric membranes is governed by the solution–diffusion mechanism. According to this model, gas molecules first dissolve into the membrane surface, diffuse through the polymer matrix, and finally desorb at the opposite side.

The permeability of a gas is expressed as:

$$P_i = D_i \times S_i$$

where:

- P_i = permeability of gas i
- D_i = diffusion coefficient
- S_i = solubility coefficient

The ideal selectivity between two gases is:

$$\alpha_{A/B} = \frac{P_A}{P_B}$$

where A is the faster-permeating gas

B is the slower gas.

In NaAlg–AgNP membranes, gas transport is controlled by:

- Interaction between gas molecules and alginate functional groups
- Silver nanoparticle-induced free-volume changes
- Molecular size difference
- Gas polarity and solubility

Nanoparticle dispersion inside the polymer matrix.

Units: Barrer

(1 Barrer = $10^{-10} \text{ cm}^3(\text{STP}) \cdot \text{cm} / \text{cm}^2 \cdot \text{s} \cdot \text{cmHg}$)

The single-gas permeability results of pure sodium alginate (SA) and SA–Ag nanocomposite membranes (0–2 wt.% Ag) demonstrate a clear dependence of gas transport

properties on nanoparticle incorporation. Pure SA exhibits comparatively low permeability for all tested gases, with values of 4.0 Barrer for O_2 , 1.2 Barrer for N_2 , and 25.0 Barrer for CO_2 (Table 2). This behavior shows the characteristic of dense hydrophilic biopolymer matrices, strong intermolecular hydrogen bonding and a compact chain packing structure significantly restrict gas diffusion pathways and limit overall permeability. With the incorporation of Ag nanoparticles, a pronounced enhancement in gas permeability is observed up to 1.5 wt.% loading. Specifically, O_2 permeability increases from 4.0 to 7.2 Barrer, N_2 from 1.2 to 2.0 Barrer, and CO_2 from 25.0 to 45.0 Barrer. This improvement can be attributed to the disruption of polymer chain packing induced by well-dispersed nanoparticles, which increases the fractional free volume within the membrane matrix. Additionally, the formation of polymer–nanoparticle interfacial regions introduce microvoid-like transport pathways that facilitate enhanced diffusion of gas molecules. Such behavior is consistent with established transport models for polymer nanocomposites, where the incorporation of nanoscale fillers modifies chain dynamics and increases diffusivity.

Among the tested gases, CO_2 consistently exhibits the highest permeability across all membrane compositions. This trend is primarily attributed to its higher condensability and stronger affinity toward the polar functional groups of sodium alginate, such as hydroxyl and carboxylate groups. As a result, CO_2 transport is governed by a combination of solubility and diffusivity effects, with solubility playing a dominant role in hydrophilic polymer systems. Similar solubility-controlled CO_2 transport behavior has been widely reported in biopolymer-based membranes. At the highest Ag loading (2 wt.%), a slight deviation from the increasing trend is observed, particularly for O_2 permeability, which marginally decreases from 7.2 to 7.0 Barrer, while N_2 and CO_2 show only minor increases. This phenomenon is commonly associated with nanoparticle agglomeration at elevated filler concentrations, leading to partial blockage of transport pathways and reduced effective interfacial area. Consequently, the

creation of additional free volume becomes less efficient, resulting in a saturation or slight decline in permeability enhancement. Overall, the SA–Ag nanocomposite membranes exhibit an initial enhancement in gas permeability with increasing Ag content, followed by a mild saturation at higher loading. This indicates the existence of an optimal nanoparticle concentration, where the balance between increased free volume and nanoparticle dispersion is most favorable for gas transport. The observed trends suggest that SA–Ag membranes are promising candidates for CO₂-selective separation applications due to their comparatively higher CO₂ permeability relative to O₂ and N₂, combined with tunable transport properties induced by nanoparticle incorporation.

3.5. Selectivity

The calculated selectivity data clearly demonstrate that incorporation of Ag nanoparticles into the sodium alginate matrix significantly influences the gas transport behavior, particularly enhancing the preferential permeability of CO₂ over N₂ and O₂ (Table 3). The CO₂/N₂ selectivity increases from 20.83 (pure SA) to ~22.50 (SA–Ag 1.5 wt.%), indicating improved discrimination between condensable CO₂ and non-condensable N₂. This trend is primarily attributed to the higher condensability and quadrupole moment of CO₂, which leads to stronger interactions (e.g., Lewis's acid–base and dipole–induced dipole interactions) with polar functional groups in alginate and modified free volume created by Ag nanoparticle dispersion. Similar enhancements in CO₂/N₂ selectivity in biopolymer-based nanocomposites have been widely reported in the literature due to increased diffusivity selectivity and solubility. The CO₂/O₂ selectivity (5.82–6.71) shows a modest but consistent improvement with increasing Ag loading, suggesting that Ag nanoparticles contribute to a more favorable microenvironment for CO₂ transport, likely by increasing polymer chain packing irregularities and enhancing CO₂ sorption sites. Meanwhile, the O₂/N₂ selectivity remains relatively low (3.33–3.78) with only slight variation, indicating that size-sieving

effects are less dominant in this system compared to solubility-driven transport mechanisms. This behavior is typical of hydrophilic polymer membranes where gas separation is governed more by solubility differences than kinetic diameter discrimination. The observed selectivity enhancement aligns with previously reported findings on metal nanoparticle-modified polymer membranes, where nanoparticles improve gas solubility selectivity without severely compromising diffusivity selectivity, leading to improved CO₂-philic behavior.

4. Conclusion

Silver nanoparticle-engineered sodium alginate (SA) nanocomposite membranes were successfully fabricated by a solution casting method and evaluated for single-gas separation performance. The incorporation of Ag nanoparticles improved the membrane morphology and gas transport characteristics by enhancing polymer–filler interactions and optimizing the microstructure. The membrane containing the optimum Ag loading exhibited superior CO₂ permeability and improved CO₂/N₂ and CO₂/O₂ selectivities, whereas excessive nanoparticle loading caused partial agglomeration and a slight decline in separation efficiency. Overall, the results demonstrate that Ag nanoparticle incorporation is an effective strategy for tailoring the gas separation performance of sustainable sodium alginate membranes, highlighting their potential for environmentally friendly and energy-efficient gas separation applications. Further investigations on long-term stability, mixed-gas permeation, and scale-up fabrication are recommended to facilitate industrial implementation.

DECLARATIONS

Conflict of Interests: The authors assert that there are no financial interests, personal relationships, or other conflicting interests that may have affected the work delineated in this manuscript. The study was conducted solely for

academic and scientific objectives, devoid of any commercial or financial engagement.

Use of AI and AI-Assisted Technologies: The authors used AI-assisted tools only for language improvement and grammar checking. All scientific content, interpretation, and conclusions remain the responsibility of the authors.

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Data Availability: The data used in this study are available from the corresponding author upon reasonable request.

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Figure

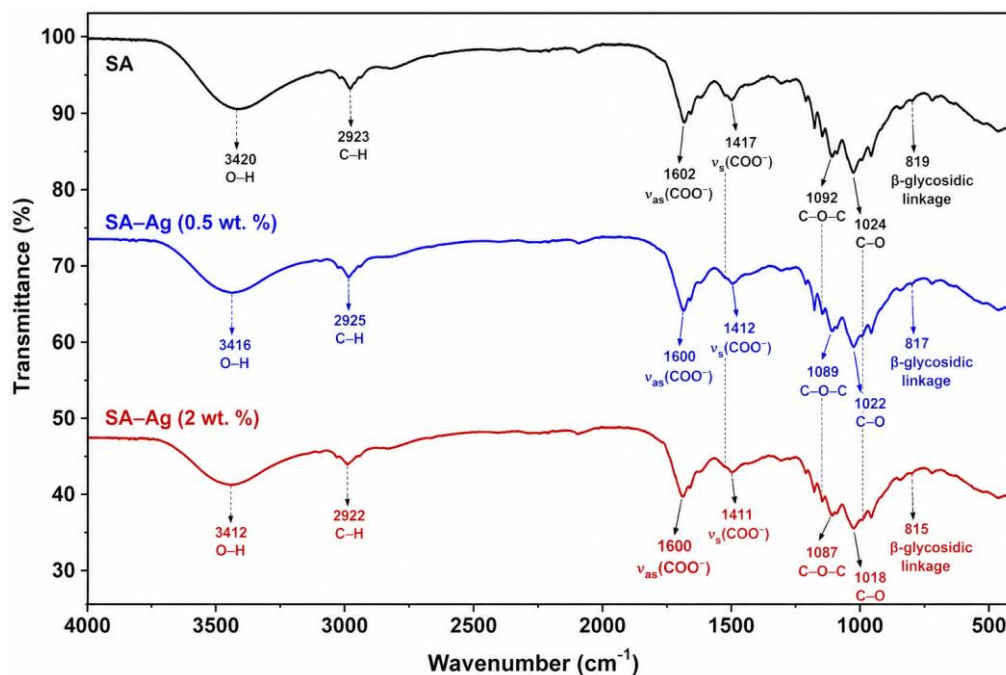


Fig. 1: The FTIR spectra of pristine sodium alginate (SA), SA-Ag (0.5 wt. %), and SA-Ag (2 wt. %) nanocomposite membranes.

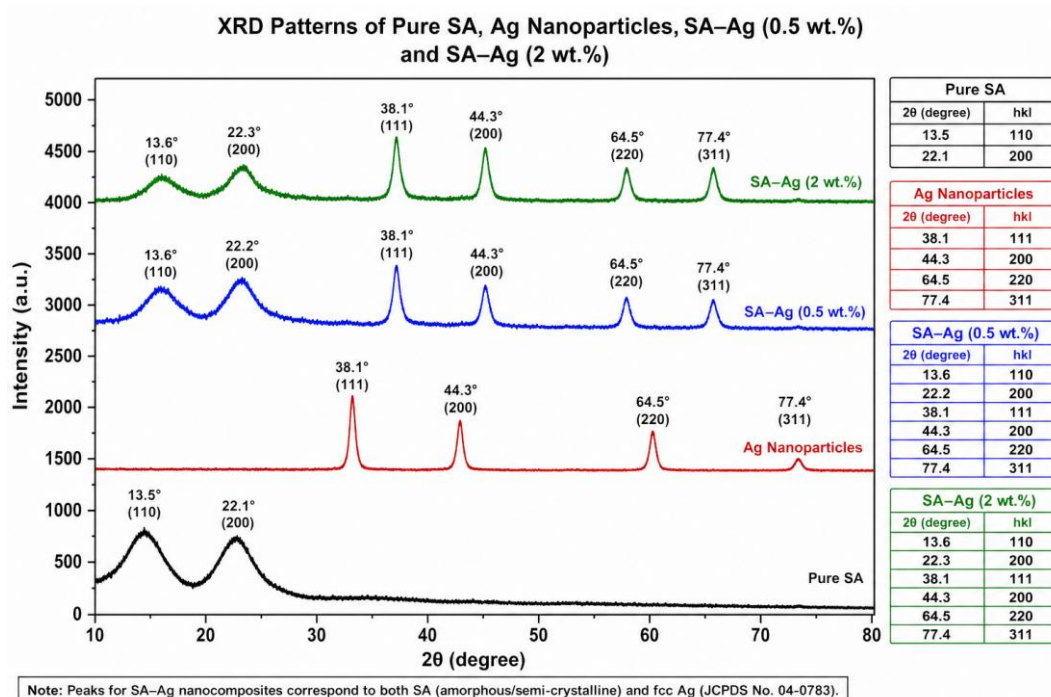


Fig. 2: The X-ray diffraction (XRD) patterns of pristine sodium alginate (SA), silver nanoparticles (AgNPs), and SA-Ag nanocomposite membranes containing 0.5 wt.% and 2 wt.% AgNPs.

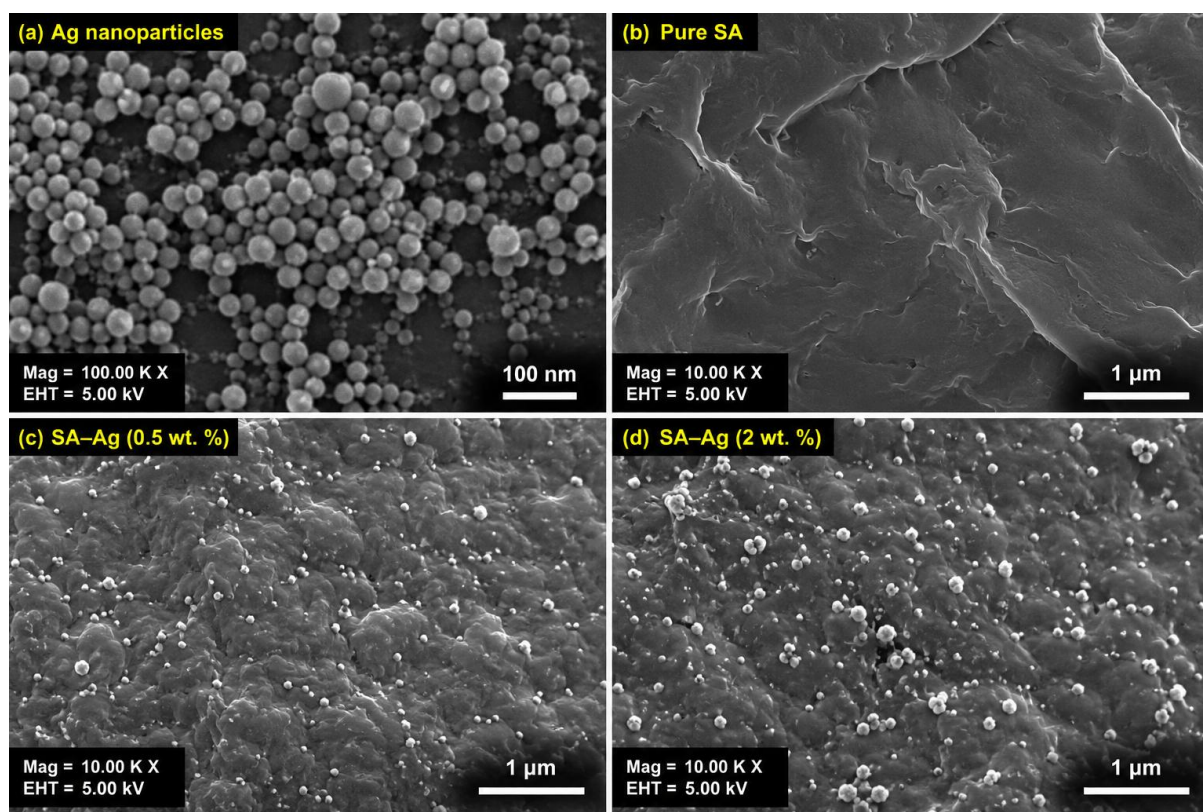


Fig. 3: FESEM Morphological Analysis of Silver Nanoparticles and Sodium Alginate–Silver Nanoparticle Nanocomposite Membranes.

Tables

Sample Code	Sodium Alginate (Wt. %)	AgNP (Wt. %)
SA-0	5	0
SA-1	5	0.5
SA-2	5	1
SA-3	5	1.5
SA-4	5	2

Table 1: Different concentrations of Ag nanoparticles.

Membrane Sample	O₂ Permeability (Barrer)	N₂ Permeability (Barrer)	CO₂ Permeability (Barrer)
Pure SA	4.0	1.2	25.0
SA–Ag (0.5 wt.%)	5.5	1.5	32.0
SA–Ag (1.0 wt.%)	6.8	1.8	40.0
SA–Ag (1.5 wt.%)	7.2	2.0	45.0
SA–Ag (2.0 wt.%)	7.0	2.1	47.0

Table 2: Single Gas Permeability of SA and SA–Ag Nanocomposite Membranes.

Membrane Sample	CO₂/N₂ Selectivity	CO₂/O₂ Selectivity	O₂/N₂ Selectivity
Pure SA	20.83	6.25	3.33
SA–Ag (0.5 wt.%)	21.33	5.82	3.67
SA–Ag (1.0 wt.%)	22.22	5.88	3.78
SA–Ag (1.5 wt.%)	22.50	6.25	3.60
SA–Ag (2.0 wt.%)	22.38	6.71	3.33

Table 3: Selectivity Data.