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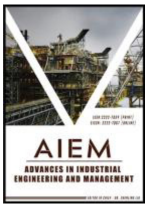

RESEARCH ARTICLE

CELLULOSE ACETATE MEMBRANE FOR CONTAMINANTS REMOVING AND DESALINATION

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ABSTRACT

Membrane separation technologies, such as nanofiltration (NF), reverse osmosis (RO), and forward osmosis (FO), have gained great appeal as a sustainable and energy-saving method for seawater desalination and water purification. After years of development, polyamide composite membranes have become the main membrane materials for the above-mentioned membrane separation technologies. Recently, the reuse and treatment of discarded membrane components, as well as the pollution problem of polyamide composite membranes, have enabled some early membranes to regain certain application prospects. The most representative separation membrane is cellulose acetate (CA) membrane, which using a widely available and biodegradable environmentally friendly material, holds promising application prospects in water purification. Unlike aromatic polyamide composite membranes, CA-based membranes do not require complex detoxification processes after disposal, making them a sustainable alternative for water treatment applications. In this review, the history and the history and development of CA membrane are traced, the influence of Phase Inversion Parameters on CA Membrane Fabrication, and its potential applications are evaluated.

KEYWORDS

Cellulose acetate, Membrane, Contaminants, Desalination

1. INTRODUCTION

Membrane materials, serving as the cornerstone of membrane separation technology, directly determine the separation efficiency and practical applicability of the technology. Currently, membranes are categorized based on the size of target substances into microfiltration (MF), ultrafiltration (UF), Nanofiltration (NF), and reverse osmosis (RO) membranes. Among these, NF membranes feature a pore size of ~1 nm, enabling effective removal of pharmaceutically active compounds (PhACs) from drinking water while maintaining high water permeability—a unique advantage over other membrane types. At present, polyamide nanofiltration membranes fabricated via interfacial polymerization are widely adopted for end-user drinking water purification. However, the polyamide separation layer is prone to oxidative degradation by residual active chlorine in water, significantly compromising membrane performance (Wang et al., 2021; Liu et al., 2018; Lu et al., 2023; Banks et al., 2020). Additionally, decomposition of the polyamide layer can release harmful small organic molecules, leading to secondary contamination of drinking water. More critically, polyamide NF membranes primarily consist of non-eco-friendly materials such as polyester non-woven fabric, polyethersulfone, and polyamide. Once these membranes reach their service life, disposal of the waste poses another environmental challenge. Cellulose, a widely available and biodegradable environmentally friendly material, exhibits excellent chlorine resistance. Among cellulose derivatives, cellulose acetate (CA) stands out as the most representative. CA-based reverse osmosis membranes emerged as early as 1960 and remain in use today. Studies demonstrate that CA membranes can operate stably in high-concentration active chlorine solutions over extended periods (Thi Phuong Nga et al., 2017). Consequently, CA membranes retain significant application potential and research value for end-point drinking water purification.

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In the 1960s, scientists Loeb and Sourirajan pioneered the development of asymmetric cellulose acetate reverse osmosis (CA-RO) membranes. Shortly thereafter, Toyo Boseki of Japan became the first to industrialize CA-RO membranes for desalination, dominating the global CA membrane market with its products (Sidney and Srinivasa., 1963; Li et al., 2011; Ukai et al., 1980). CA separation membranes once served as the core of desalination technology and were extensively studied (Joshi and Rao, 1984; Vasarhelyi et al., 1987). Although asymmetric polyamide composite membranes later emerged as the dominant RO membrane technology due to superior separation performance, gradually displacing CA-RO membranes, CA-RO membranes still retain a niche market share in desalination owing to their advantages in antifouling resistance and renewability. Countries and regions such as Saudi Arabia and the Red Sea area continue to use CA-RO membranes for seawater desalination. Consequently, research on enhancing CA-RO membrane performance persists to this day. China's research on CA-RO membranes began relatively late. The Water Treatment Center at Tianjin Polytechnic University also developed low-pressure reverse osmosis CTA hollow fiber RO membranes for desalination (Hao et al., 1996), achieving salt rejection rates exceeding 85%. Despite nearly five decades of domestic CA-RO membrane development, China's efforts in understanding CA membrane formation mechanisms, optimizing raw materials, and advancing precision membrane fabrication equipment remain lagging behind international standards. The performance of domestically produced CA membranes often fails to meet domestic application requirements, resulting in China's continued reliance on imported CA-RO membranes.

2. Preparation of Cellulose Acetate Membrane

The phase inversion method is one of the primary techniques for fabricating cellulose-based separation membranes and has been extensively studied and applied (Sidney and Srinivasa, 1963; Van de Witte et al., 1996). The membrane preparation process involves the following key steps: Preparing a homogeneous polymer solution with a specific composition. Inducing mass exchange between the casting solution and a non-solvent (or solvent) from the surrounding environment via physical methods. This disrupts the thermodynamic stability of the casting solution, triggering liquid-liquid phase separation. Transitioning the system into a three-dimensional macromolecular network gel structure. Obtaining the polymer separation membrane after completing the phase separation process. In this process, the solvent system, temperature, evaporation duration and thermal treatment, et al., have play an important role in membrane formation. The structure of conventional phase conversion CA membrane is shown in Fig.1.

2.1 Influence of Phase Inversion Parameters on CA Membrane Fabrication

Effects of Solvent System. The first CA-RO membrane, developed by Matsuura and Sourirajan et al. (1971), Kimura and Souriraj (1968), and Pilon et al. (1971) utilized an acetone (solvent)/formamide (co-solvent) system, a formulation still widely adopted today. Acetone promotes dense membrane formation; increasing acetone content in the casting solution accelerates solvent evaporation, reduces surface pore size, and enhances solute rejection, albeit at the cost of reduced water permeability (Kesting and Menefee, 1969). Optimizing the acetone/formamide ratio remains a key strategy for balancing rejection and permeability in CA-RO membranes. Expanding beyond conventional solvents, Li et al. (2006) demonstrated that γ-butyrolactone (γ-GBL)/water systems exhibit delayed phase separation, while N-methyl-2-pyrrolidone (NMP)/water systems undergo instantaneous phase separation. By adjusting γ-GBL/NMP/water ratios, they achieved controlled evolution between sponge-like and finger-like pore structures, optimizing membrane performance. Similarly, Chung and Shieh (1998) employed NMP/tetrahydrofuran (THF) blends, modulating THF content (known to induce delayed phase inversion) to refine droplet-like pore dimensions. Liu et al. (2011) developed high-performance CA membranes using dioxane (DO)/acetone (AC) solvent systems. To address environmental concerns from organic waste in immersion precipitation phase inversion, Xing et al. (2016, 2011) pioneered ionic liquids (ILs) as green solvents. ILs disrupt CA molecular chain interactions through strong ionic forces, yielding homogeneous casting solutions with enhanced film-forming properties. Their recyclability minimizes ecological impact and operational costs. However, pure IL-based solutions suffer from excessive viscosity, compromising membrane structural stability. Kim et al. (Kim et al., 2016) resolved this by blending ILs with acetone, achieving reduced viscosity and improved mechanical strength. Falca et al. (2019) fabricated CA-NF membranes with tunable morphologies using three structurally distinct ILs (Fig.2), demonstrating solvent-driven pore architecture customization.

Effects of Casting Solution Temperature and Evaporation Duration. As early as the inception of CA membranes, S. Sourirajan pioneered investigations into the impacts of casting solution temperature and evaporation duration on membrane properties (Pageau and Sourirajan, 1972; Kunst and Sourirajan, 1970). Their studies revealed that increasing the temperature of the Loeb-Sourirajan-type CA-RO membrane casting solution reduces intermolecular aggregation of polymer chains. During film formation, polymer-rich phases tend to generate smaller non-solvent droplets, which evolve into surface micropores through structural reorganization, thereby enhancing water permeability. Concurrently, prolonging the solvent evaporation duration was found to promote the coalescence of small pores into larger ones within the membrane matrix. However, excessive evaporation may induce surface densification via partial pore collapse, ultimately forming a low-flux dense layer. To quantitatively analyze evaporation effects on CA phase inversion, Hao and Wang (2002). developed a diffusion model

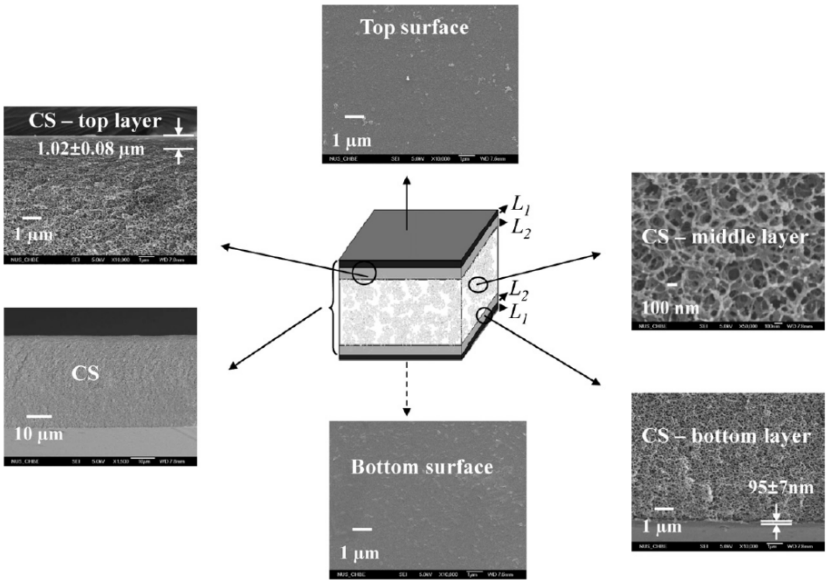

Figure 1: Structure of conventional phase conversion CA membrane (Zhang et al., 2010)

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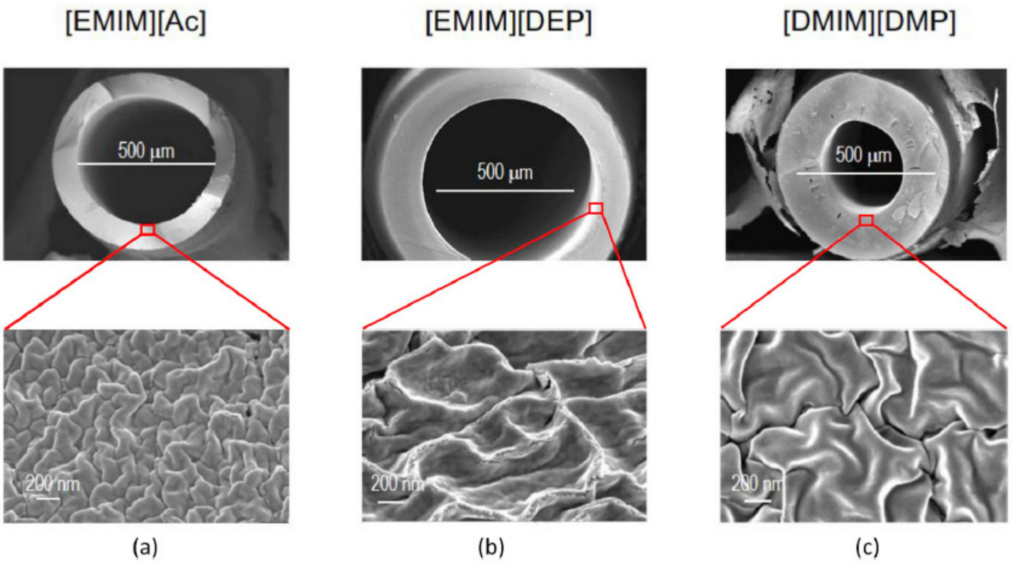

Figure 2: Cross-sections SEM images of CA membrane prepared using different ionic liquids as solvents (Falca et al., 2019)

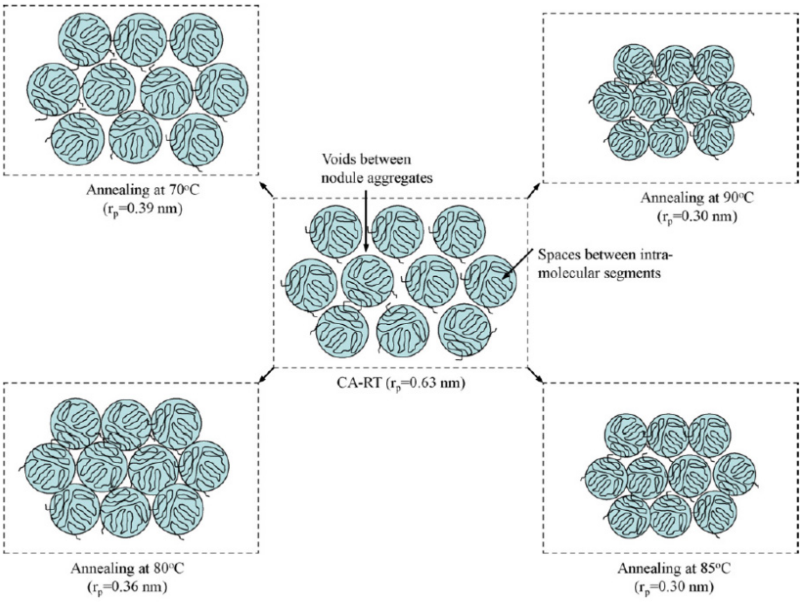

Figure 3: Temperature-dependent pore size reduction in CA-NF membranes (Su et al., 2010a)

for the evaporation step, incorporating: a mobile gas-film interface, correlations for mutual diffusion coefficients, and time-dependent mass transfer coefficients. This model rigorously describes how casting solution composition, membrane thickness, surface area, and vapor-phase composition collectively govern evaporation rates. Experimental validation confirmed its reliability, providing robust quantitative insights for optimizing evaporation protocols in membrane fabrication.

Effects of Thermal Treatment. Thermal treatment. is a conventional method for regulating the separation properties of cellulose acetate (CA) membranes. Chan et al. (1984) and Depinho (1988) demonstrated that thermal annealing effectively modulates membrane pore size distribution. By correlating pore size distribution with separation performance, they established an optimized force-pore model for predictive pore structure analysis. Su et al., (2010a) investigated temperature-dependent pore size variations in CA-NF hollow fiber membranes. After thermal treatment at 70, 80, 85, and 90°C, the membrane pore size decreased from 0.63 nm to 0.39, 0.36, 0.3, and 0.3 nm, respectively (Fig.3). This confirmed that heat-induced shrinkage reduces pore dimensions by compressing voids between nodular aggregates and intramolecular chain segments. Khulbe et al. (2001) employed electron spin resonance (ESR) to analyze CA-RO membrane surface porosity. Membranes treated at 90°C exhibited flow channels (or “network pores”) akin to dense membranes, while those treated below 90°C retained larger “aggregate pores” between polymer clusters. Arneri et al. (1980) observed that thermal treatment expands crystalline regions while reducing amorphous domains in CA membranes. This process slightly diminishes the free volume of the selective layer, enhancing salt rejection but reducing water permeability. Han and Bhattacharyya (1995) reported improved pressure resistance in thermally treated CA membranes, attributed to pore size reduction and increased polymer chain alignment (crystallinity). Recently, Lu et al., (2019) reported a critical discovery: the water permeation pathways in membranes are predominantly governed by pore channels formed within amorphous regions. By reducing crystal size, the proportion of amorphous regions can be enhanced without inducing over-compaction, thereby achieving improved membrane rejection rates while maintaining high permeation flux.

2.2 Functional Modification of Cellulose Membrane

Conventional cellulose acetate (CA) materials often fail to meet practical requirements for chemical stability, mechanical strength, and fouling resistance. While both chemical modification and polymer blending are common strategies to enhance membrane performance and diversify product types, the limited availability of chemically graftable groups in CA restricts its optimization via chemical routes. In contrast, blending modification—owing to its operational simplicity and avoidance of

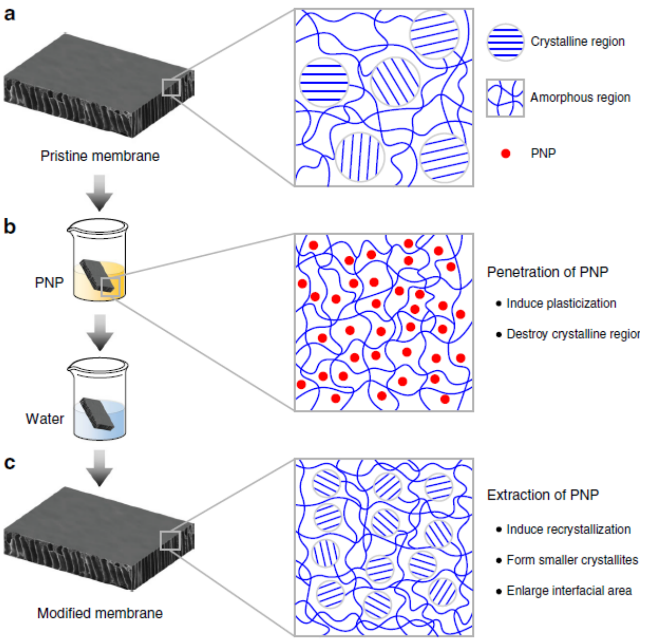

Figure 4: Optimizing separation performance by regulating CA crystallinity (Lu et al., 2019)

complex chemical reactions—is widely regarded as the most efficient and practical approach to improve CA membrane performance. This method involves liquid-phase blending of two or more polymers/ additives, where intermolecular penetration and diffusion form a stable multicomponent system. By leveraging the intrinsic advantages of each component and their intermolecular interactions, the phase inversion process can be precisely regulated to optimize membrane properties such as pore structure, thickness, and separation efficiency. Additionally, blending can impart functionalities like antibacterial activity to the membrane.

Doping of functional materials. The physical and chemical properties of cellulose acetate (CA) membranes can be optimized by incorporating inorganic nanomaterials, leading to significant improvements in separation performance. Ahmad Rahimpour et al. blended boehmite nanoparticles into CTA-CA casting solutions(Zirehpour et al., 2015). Due to hydrogen bonding between hydroxyl groups on the nanoparticle surface and cellulose chains, the nanoparticles achieved uniform dispersion, resulting in a 140% increase in water permeability of the fabricated membranes. Zoheir Dabaghian enhanced forward osmosis (FO) membrane performance by adding carboxylated/aminated porous carbon nanofibers to CTA casting solutions, achieving a 2-fold improvement in water flux (Dabaghian et al., 2016). Zhang et al. (2017) synthesized MCM-48 nanoparticles and incorporated them into CTA casting solutions. The resulting CA-FO membranes exhibited elevated permeability, attributed to nanoparticle-induced modulation of phase inversion parameters and increased membrane porosity. Wang et al. developed Al_2O_3/CA and ZnO/CA mixed-matrix membranes, achieving flux enhancements of 96.5% and 111.1%, respectively, through nanomaterial integration (Wang et al., 2009; Ali et al., 2011). Similarly, Ilker Akin and Ersoz (2016) introduced aminated ZnO into casting solutions, which not only improved separation efficiency but also enhanced the membrane's optical transparency.

The molecular chain entanglement and other interactions between organic polymers and cellulose acetate (CA) are superior to those of inorganic particles, exerting a more significant influence on the phase inversion and membrane formation process of CA. QIN et al. (2003) and Saljoughi and Mohammadi (2009) investigated the effects of polyvinylpyrrolidone (PVP) on the morphology, permeability, and thermal stability of CA-UF membranes. They found that increasing PVP content enlarged the surface pores of membranes. Rajesh et al., (2011) fabricated polyamide-imide (PNI)-doped PNI/CA-UF membranes, demonstrating that amide-imide groups on the blended membrane surface could better interact with water molecules, thereby reducing permeation resistance. Similarly, Vijayalakshmi et al. (2008) developed polycarbonate (PC/CA) blended matrix membranes exhibiting excellent mechanical strength and heavy metal adsorption capacity. Sajitha and Mohan. (2003) and Sivakumar et al. (1998) prepared high-flux UF

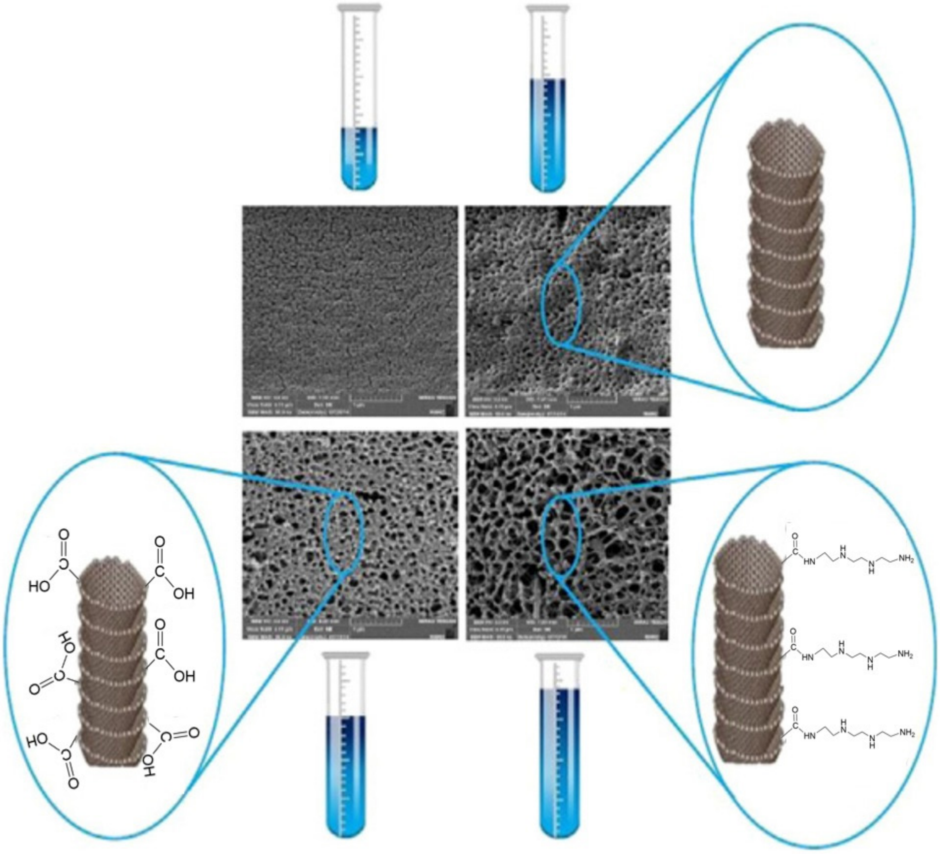

Figure 5: Highly porous carbon nanofiber (CNF)/cellulosic membranes (Dabaghian et al., 2016)

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membranes with low hydraulic resistance by blending carboxylated polysulfone (CPSU) with CA. Sivakumar et al. (1998) blended bacterial cellulose with cellulose diacetate (CA) and cellulose triacetate (CTA) to create UF membranes outperforming single-component cellulose membranes. Analogously, Zhou and Chen (1999) fabricated CA/CTA asymmetric nanofiltration membranes, where the introduction of high-crystallinity CTA could partially compensate for the performance limitations of CA materials. Additionally, cellulose nanocrystals (CNC) possess nanoscale dimensions, excellent mechanical properties, and abundant surface hydroxyl groups with strong hydrophilicity. Their incorporation into separation membranes can induce comprehensive improvements in mechanical properties, surface hydrophilicity, permeability, selectivity, and antifouling performance (Lv et al., 2018). Lv et al. (2017) demonstrated that CNC addition could accelerate CA phase inversion rate, resulting in membranes with denser/smoother surfaces, increased porosity, and enlarged average pore size. Meanwhile, the abundant hydroxyl groups in CNC significantly enhanced membrane antifouling properties.

Improvement in Antifouling Performance. Currently, biofouling remains a critical issue limiting the widespread application of cellulose acetate (CA) membranes. The evolution of bacterial contamination on membrane surfaces mainly involves four stages Fig.7): (a) Initial reversible bacterial attachment on the membrane surface; (b) Irreversible biological adsorption or bioadhesion of bacteria on the surface; (c) Bacterial proliferation and diffusion leading to gradual maturation of biofilms; (d) Redispersion of bacteria into the aqueous environment. Antibacterial modification of CA membranes is primarily achieved by incorporating antimicrobial materials. Chou et al. (2005) added $AgNO_3$ as a non-solvent into the CA casting solution and fabricated Ag nanoparticle-coated antibacterial CA membranes via direct immersion precipitation phase inversion. Similarly, Perera et al. (2014) immersed CA membranes in $AgNO_3$ solution followed by $NaBH_4$ reduction to form Ag nanoparticles on the membrane surface. Results showed that the bacterial count on the modified membrane surface decreased by four orders of magnitude. Natural antibacterial materials have also been explored to enhance the antimicrobial properties of CA membranes. Waheed et al. (2014) prepared CA/chitosan (CS) membranes using a two-step liquid-liquid phase inversion method with chitosan as the antibacterial agent. The resulting membranes exhibited significantly improved antibacterial performance, along with enhanced salt rejection and permeation flux. Liu et al. (2010) modified CS/CA membranes with heparin, quaternary ammonium salts, or Ag—all known for their antibacterial effects. The study revealed that the relationship between membrane hydrophilicity and biofouling resistance was not straightforward. Preventing bacterial adhesion on the membrane surface proved more effective than bactericidal action, highlighting that constructing anti-adhesive surfaces is key to improving membrane biofouling resistance.

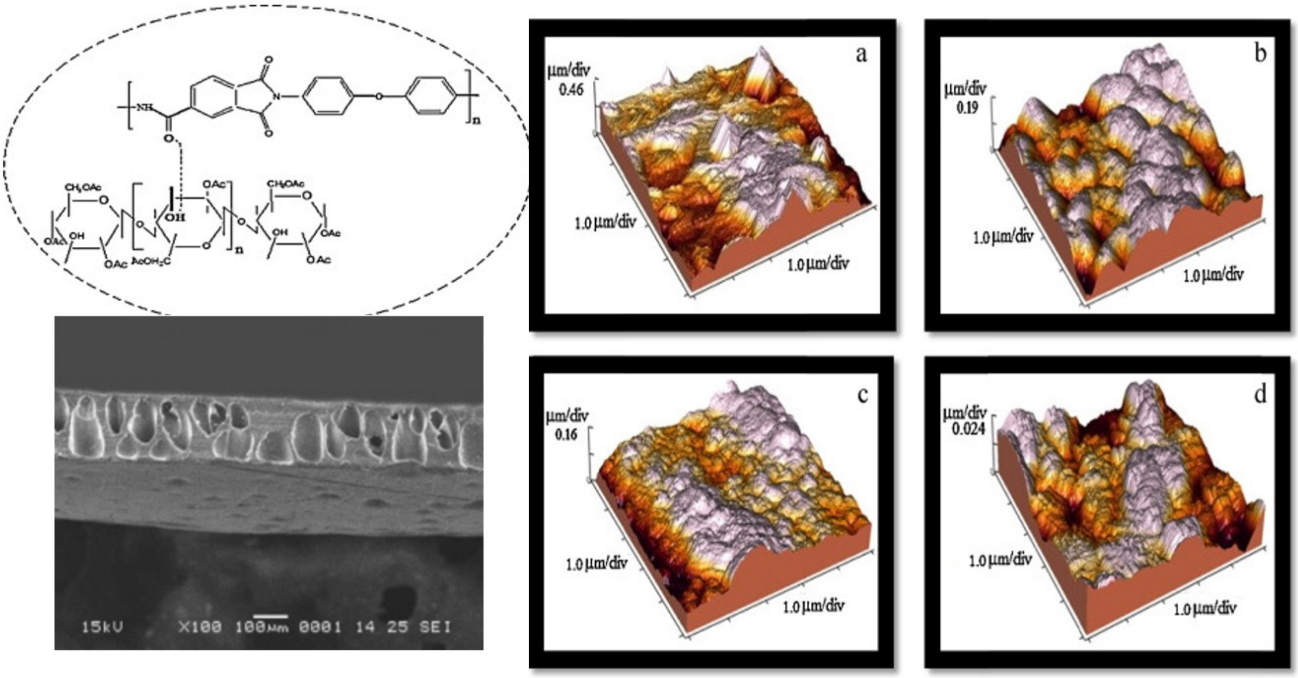

Figure 6: Poly (amide-imide) incorporated cellulose acetate membrane (Rajesh et al., 2011)

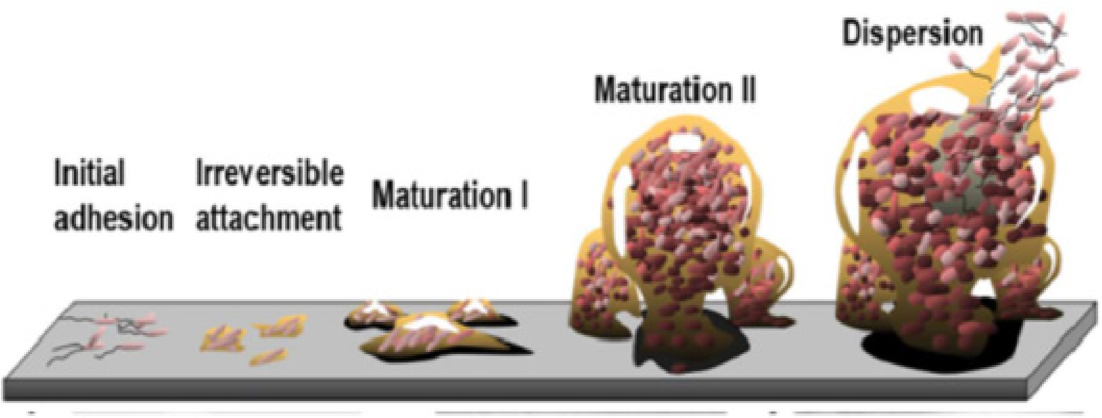

Figure 7: Evolution of biofouling on membrane surface (Zhu et al., 2018)

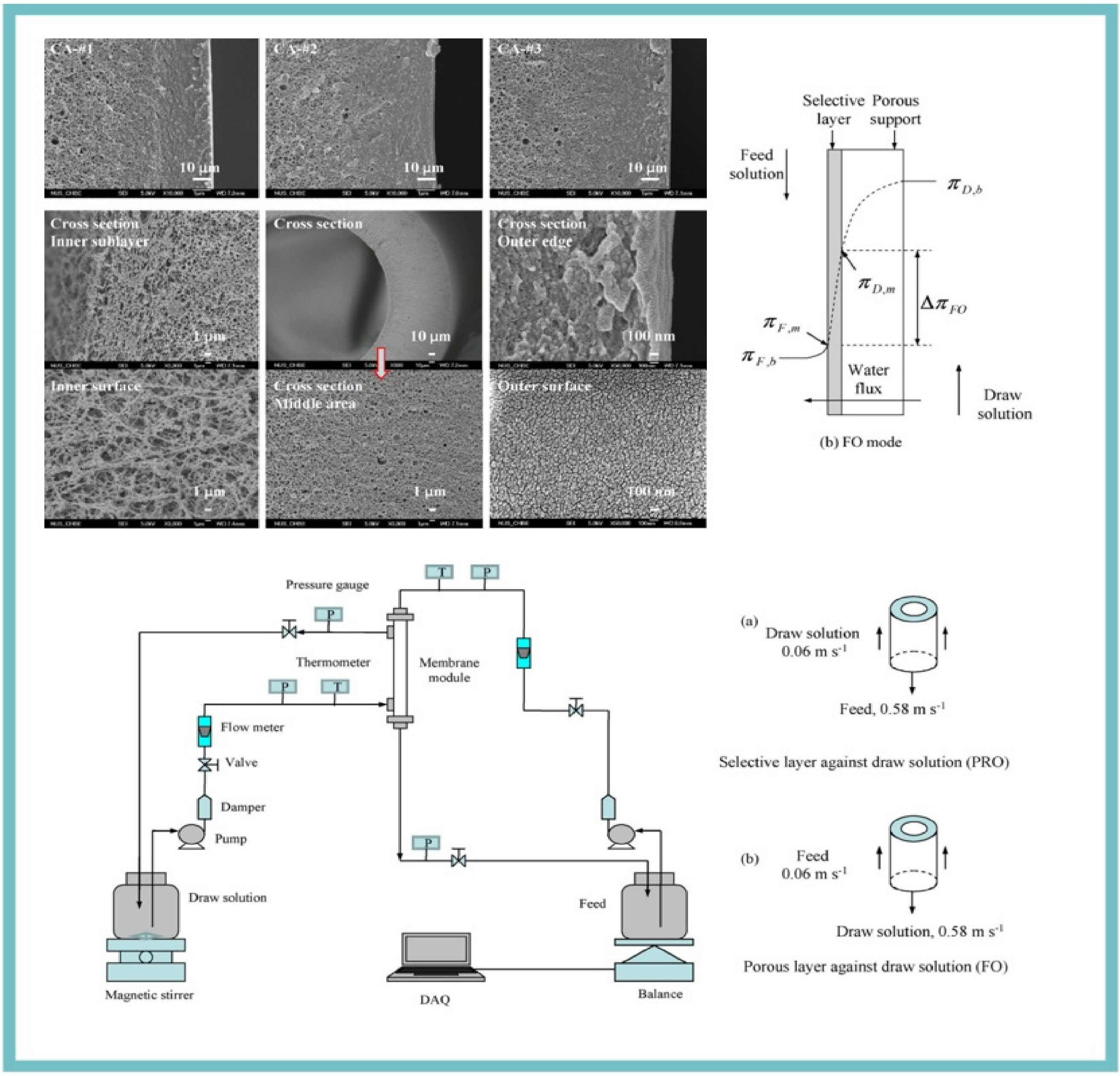

Figure 8: Morphology of the CA hollow fiber membranes, the FO mode in FO processes and schematic diagram of the experimental set-up for forward osmosis (Su et al., 2010b)

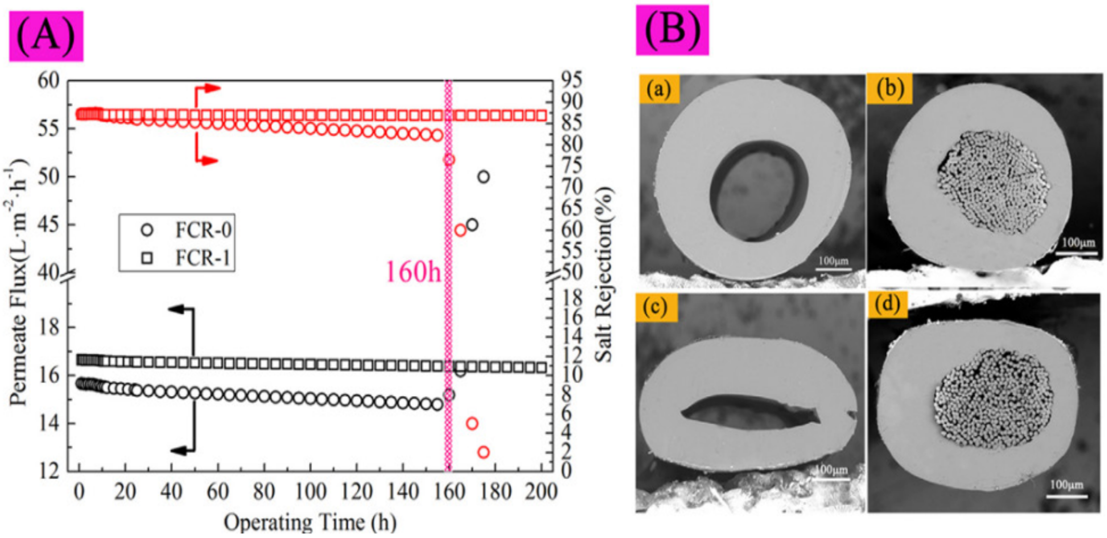

Figure 9: The membrane produced has good structural stability and can operate under high pressure (Chen et al., 2019)

3. POTENTIAL APPLICATIONS

3.1 CA Membranes in Forward Osmosis (FO) Desalination

Kravath and Davis (1975) demonstrated that a high-concentration glucose solution could generate osmotic pressure for transmembrane water transport. Based on this principle, they successfully used CA forward osmosis membranes to extract pure water from seawater, yielding a glucose solution suitable for drinking. This discovery holds potential for emergency water supply in lifeboats. Similarly, Kessler and Moody. (1976) combined theoretical calculations with experimental validation to confirm that five types of CA membranes exhibited excellent FO-driven pure water extraction, with the diluted solutions meeting potable standards. To further investigate water diffusion across membranes, Wallace et al. (2008) developed a thermodynamic benchmark for evaluating the suitability of emergency water purification systems in treating small volumes of brackish water. This framework integrated thermodynamic relationships with membrane transport models to better characterize non-ideal solution behavior and nonlinear flow dynamics. Their work validated the feasibility of continuous water purification systems based on this principle, potentially spurring interest in CA-FO membrane-based purification technologies. Su et al. (2010b) pioneered the application of CA hollow fiber membranes in FO desalination. Through a two-step thermal treatment process, the researchers reduced membrane pore size from 0.63 nm to 0.3 nm. The optimized membrane achieved a pure water flux of 7.3 L m^{-2} h^{-1} under 285.3 bar osmotic pressure, with a $MgCl_2$ permeation rate of 0.53 g m^{-2} h^{-1}. Sui Zhang et al. systematically regulated CA-FO membrane structures by optimizing casting solution formulations and substrate types. Advanced characterization techniques, including field-emission scanning electron microscopy (FE-SEM) and positron annihilation lifetime spectroscopy, were employed to elucidate membrane formation mechanisms. These findings provide critical insights for enhancing separation performance and mitigating internal concentration polarization in CA-FO membranes.

3.2 CA Membranes in RO/NF Desalination

Haddad (2004) fabricated a CA nanofiltration (NF) membrane via the phase inversion method for brackish water desalination. C.A. Smolders developed a CA reverse osmosis (RO) membrane using a two-step process, achieving a salt rejection rate of up to 99%. Idris et al. (2002) systematically optimized the preparation of CA-RO membranes through Taguchi methods (fractional factorial design), investigating the relationships between waste liquid ratio coefficients, permeability, and dry-wet spinning processes to produce desalination-specific RO membranes. Lin et al. (1997) enhanced conventional low-pressure CA membranes by adjusting the solid content concentration in the casting solution, creating a high-pressure-resistant (5 MPa) RO membrane with superior salt rejection. To improve the mechanical strength and pressure tolerance of CA-RO membranes, Fan et al. (2015) and Chen et al. (2019) introduced a novel twisted fiber bundle as a support layer with enhanced fiber bonding, increasing tensile strength from 9.8 MPa to 96.8 MPa. Toyobo Co., Ltd., a leading manufacturer of CA-RO membranes, dominates markets in challenging water environments, holding 50% and 82% market shares in the Middle East and regions like Saudi Arabia and the Red Sea, respectively. For instance, the world's largest desalination plant, Ras Al Khair, utilizes Toyobo's RO modules to produce 345,000 cubic meters of freshwater daily, accounting for 34.5% of its total 1 million cubic meters/day output. The "Hollowsep" series features a bidirectional open-ended (B.O.E) structure, enabling high packing density that doubles processing efficiency. This design not only reduces membrane fouling rates per unit area but also minimizes the number of ancillary components and required footprint.

3.3 Conventional Organic Pollutant Separation

Early studies on separation membranes for organic wastewater primarily focused on polyamide membranes, offering foundational insights for CA membranes in removing organic Emerging Contaminants. Van der Bruggen et al., (1999) evaluated four nanofiltration (NF) membranes—NF70 (Dow/FilmTec), NTR 7450 (Nitto Denko), UTC-20 (Toray Ind.), and Zirfon® (VITO)—with varying pore sizes for separating Emerging Contaminantss of different molecular dimensions. Their results demonstrated a strong correlation between separation efficiency, membrane pore size, and molecular size, a conclusion further supported by Ozaki and Li (2002). Kiso et al. (2001a) confirmed that NF membranes exhibit high retention rates for small organic molecules like aromatic compounds and phthalates, while highlighting the significant influence of solute hydrophobicity on rejection performance. Subsequent studies proposed the octanol-water partition coefficient (Kow), a measure of hydrophobicity, as a key predictor of pollutant separation efficiency (Kiso et al., 2001a; Kiso et al., 2001b; kimura et al.,2003). Additionally, Van der Bruggen et al. (Van der Bruggen et al., 1998) found that molecular polarity inversely affects retention rates, with highly polar molecules showing reduced rejection. Matsuura and Sourirajan (1972; 1973; 1973; 1971) extensively investigated CA-RO membranes for separating organic wastewater components (e.g., sugars, phenols, hydrocarbons, alcohols), revealing their promising potential in wastewater purification and resource recovery. Choi et al. (2007) validated the long-term stability of CA-NF membranes, achieving stable salt rejection rates of 40–60% and COD retention rates of 70–90% over 80 days. Dubey et al. (2005) developed chitosan (CS)/CA blend membranes via phase inversion for pervaporation, effectively separating ethanol-water mixtures. He et al. (2009) applied CA-NF membranes to separate dye molecules (730–1003 Da), achieving over 99% dye retention. However, parameters like dye solubility and concentration were shown to influence separation performance.

3.4 Emerging Contaminants Removal

Emerging contaminants in aquatic environments include pharmaceutically active compounds (PhACs), endocrine-disrupting chemicals (EDCs), pharmaceuticals and personal care products (PPCPs), persistent organic pollutants (POPs), microcystins, novel flame retardants, antibiotic resistance genes, and microplastics. Early technologies for Emerging Contaminants removal, such as biological filtration and activated carbon, showed limited efficacy due to the ultra-low concentrations (ng/L level) of these contaminants in water (Stumpf et al., 1999; Schafer et al.,2003). RO/NF membrane separation has demonstrated advantages in Emerging Contaminants removal (Van der Bruggen et al., 1998; Kiso et al., 2000). While most studies focus on polyamide (PA) membranes, research on cellulose acetate (CA) membranes remains limited (Ghaemi et al., 2012; Lajimi et al.,2011; Rana et al.,2012). Notably, Yuksel et al., (2013) compared the bisphenol A (BPA) removal efficiency of NF90, NF270, XLE BWRO, BW30, and CE BWRO (cellulose triacetate, CTA) membranes, revealing that CE BWRO achieved only 40% BPA rejection, whereas PA membranes reached 98%. Kimura et al. (2004) evaluated the retention performance of PA-NF and CA-NF membranes for various Emerging Contaminantss (Table 1-1). PA-NF membranes outperformed CA-NF membranes, likely due to their smaller molecular weight cutoffs (MWCOs) and tighter pore sizes. This aligns with Van der Bruggen's conclusion that pollutant retention by RO/NF membranes primarily depends on pore size. However, CA-NF membranes exhibited superior rejection of sulfamethoxazole (SMX), attributed to SMX's higher hydrophilicity (log Kow = 0.89). These findings suggest that hydrophilic CA-NF membranes are more suitable for separating hydrophilic compounds. Recent efforts have focused on enhancing the surface charge of CA membranes to improve their removal efficiency for charged pollutants (Narbaitz et al., 2013).

4. CONCLUSION

Cellulose, a widely available and biodegradable environmentally friendly material, exhibits excellent chlorine resistance as a membrane material. Among cellulose derivatives, cellulose acetate stands out as the most representative. CA-based reverse osmosis membranes first emerged as early as 1960 and have remained in use to this day. Thus, CA membranes continue to demonstrate significant application prospects and research value in the field of end-point drinking water purification.

In summary, the solution phase inversion method is particularly suitable for fabricating separation membranes tailored to diverse application requirements, owing to its advantages such as simplicity of operation, process flexibility, and multiparameter adjustability. The membrane formation via solution phase inversion primarily involves two stages:

phase separation and solidification. As discussed above, the effects of fabrication conditions on membrane structure and separation performance have been systematically outlined, providing insights for enhancing membrane separation performance through conventional processing techniques. To further improve the desalination performance of CA membrane, blended boehmite nanoparticles and adding carboxylated/aminated porous carbon nanofibers methods were also applied and achieved positive results. Addressing the demands for membrane reuse and regeneration, CA membranes not only maintain their applications in traditional NF and RO desalination but also show promising potential in FO desalination. Notably, CA membranes demonstrate distinct advantages in purifying emerging contaminants, positioning them for future policy-driven support and market competitiveness in drinking water security applications.

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