

Zwitterionic SBMA-based nanofiltration membranes: Synthesis techniques, antifouling mechanisms, and future perspectives

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ABSTRACT

Membrane separation technologies face persistent challenges in balancing high water permeability, effective solute rejection, and resistance to fouling. Against the backdrop of escalating global water scarcity, nanofiltration (NF) has become a robust and sustainable solution for water purification. In this context, sulfobetaine methacrylate (SBMA), a zwitterionic polymer distinguished by simultaneous cationic and anionic functional groups, has attracted substantial attention owing to its exceptional hydrophilicity and electroneutrality. These attributes promote the formation of dense hydration layers and introduce steric repulsion effects, thereby significantly mitigating the membrane fouling. This review provides a systematic overview of fouling phenomena and classifies them into four principal categories: organic, inorganic (scaling), colloidal, and biofouling-based on their distinctive mechanisms of interaction with membrane surfaces. A comprehensive examination of the chemistry, morphology, and integration strategies of SBMA is presented, detailing the surface coating, surface grafting, and physical blending approaches for both polymeric and thin-film composite membranes. Numerous examples underscore the transformative impact of zwitterionic functionalization on separation performance, with marked improvements in antifouling behavior, flux recovery, and solute rejection. Finally, we discuss the remaining challenges and potential opportunities for optimizing zwitterionic membrane systems to satisfy the urgent demands of global water treatment. By illuminating key structure-property-performance relationships and highlighting innovative material engineering pathways, this review aims to guide the next generation of SBMA-based membranes toward greater durability, efficiency, and sustainability in water and wastewater treatment applications.

1. Introduction

1.1. Global water crisis and the emergence of nanofiltration

The global water crisis is escalating and driven by population growth, urbanization, industrialization, and the exacerbating effects of climate change. Over two billion individuals currently live in areas experiencing water stress, with nearly 3.6 billion facing water scarcity for at least one month each year. Projections indicate that by 2050, this number could rise to between 4.8 and 5.7 billion, influenced by ongoing

demographic shifts and climate-related impacts [1].

The economic and social consequences of water shortages are profound, potentially reducing the Gross Domestic Product (GDP) by up to 6 % in the hardest-hit regions. Associated risks include increased public health threats, the spread of waterborne diseases, and exacerbated conflicts and migration driven by food insecurity and rising prices owing to drought conditions [2].

Seawater desalination has become a crucial response, particularly in regions rich in ocean resources. Although only 3 % of the Earth's water is fresh, advancements in desalination technology have significantly

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alleviated the pressure on freshwater supplies. As of 2019, over 15,906 desalination plants worldwide have produced approximately 95 million cubic meter of freshwater daily. However, this process also generates substantial brine byproducts, posing further environmental challenges [3].

NF membranes have emerged as a versatile technology for water treatment and resource recovery, striking a balance between moderate operating pressure and high separation efficiency. Polymer membrane-based purification technologies, specifically NF [4], have attracted attention as promising solutions. NF is distinguished by its intermediate molecular weight cut-off (MWCO), typically ranging from 200 to 2000 Da, which effectively positions it between reverse osmosis (RO) and ultrafiltration (UF) [5]. This configuration makes NF exceptionally suitable for selective solute rejection, partly because of its significant surface charge, which plays a crucial role in repelling the charged solutes. Since its development in the late 1970s, NF has been successfully applied in various sectors including drinking water production, municipal and industrial wastewater treatment [6,7], resource recovery, and material separation [8]. The materials used in NF membranes, such as cellulose acetate, polyamide, polyetherimides (PEI), polyimide (PI), polysulfone (PS), poly(ether) sulfone (PES), and polyamide (PA), as well as polyvinylidene fluoride (PVDF) and polyacrylonitrile (PAN), are tailored for specific separation processes to enhance both performance and durability. These materials can be fabricated in symmetric or asymmetric configurations; the latter are frequently employed in thin-film composites designed to meet the demanding operational conditions [9].

In terms of fundamental performance, NF membranes rely on three primary solute rejection mechanisms: steric (size) exclusion, Donnan (electrostatic) effects, and dielectric exclusion (Fig. 1). Steric exclusion, akin to microfiltration (MF) and UF, blocks molecules exceeding the effective radius of the pore [10–14]. As a result, macromolecules such as polysaccharides (e.g. glucose, sucrose, and raffinose), polyethylene glycol (PEG) [15], certain hormones [16], and phenolic compounds [17] are efficiently retained, while smaller solutes pass depending on the diffusion coefficients, hindered transport, and pore geometry. Donnan effects, meanwhile, arise from the membrane's net surface charge - derived from its polymer backbone or specific surface modifications - leading to a Donnan potential at the membrane-solution interface [18, 19]. This potential selectively repels counter-ions and partially retains co-ions to maintain electroneutrality, making NF adept at water softening (removal of divalent cations) and partial desalination. Dielectric exclusion, although discussed less frequently, further refines rejection

by exploiting differences in solvation energy when ions transition from the bulk solution into membrane pores. These three mechanisms work in tandem to confer NF membranes with moderate operating pressures and strong solute rejection capabilities while offering meaningful avenues for optimisation.

1.2. Challenges in membrane separation

Despite their advantages, NF membranes face significant challenges, primarily fouling and concentration polarization. Fouling, a critical impediment to NF efficiency, manifests as organic, inorganic, colloidal, and biofouling, leading to a decline in permeate flux and increased maintenance costs. Traditional fouling mitigation strategies include pretreatment of raw water, optimisation of operational conditions, and regular membrane cleaning; however, these can be inefficient and resource-intensive.

1.3. Zwitterionic polymers as a key strategy

Given the persistent challenges associated with membrane fouling, zwitterionic polymers have emerged as a promising solution to enhance the functionality of nanofiltration (NF) membranes. This growing interest is driven by their exceptional superhydrophilicity, electro-neutrality, and antifouling properties, which collectively offer an innovative approach to mitigating fouling. Zwitterionic polymers possess both cationic and anionic functional groups while maintaining an overall neutral charge. These polymers can be classified into two groups based on the location of the ions: polyampholytes and polybetaines (Fig. 2). Polybetaines, including sulfo-, carboxy-, and phosphobetaines, effectively repel foulants through the formation of hydration layers and steric repulsion.

Recent advancements in membrane technology have increasingly focused on incorporating polymeric additives and nanomaterials, particularly zwitterionic polymers, to overcome the limitations of conventional NF membranes. A clear indicator of this growing interest is the significant rise in annual publications on zwitterionic polymers and zwitterionic polymeric membranes (Fig. 3). Researchers have demonstrated that membranes incorporating zwitterionic polymers exhibit substantial improvements in fouling resistance, flux recovery, and operational longevity, highlighting the critical role of these materials in enhancing the performance of NF membranes.

Since the 1990s, phosphorylcholine (PC) head groups have been recognized as pioneering zwitterionic materials, particularly for anti-

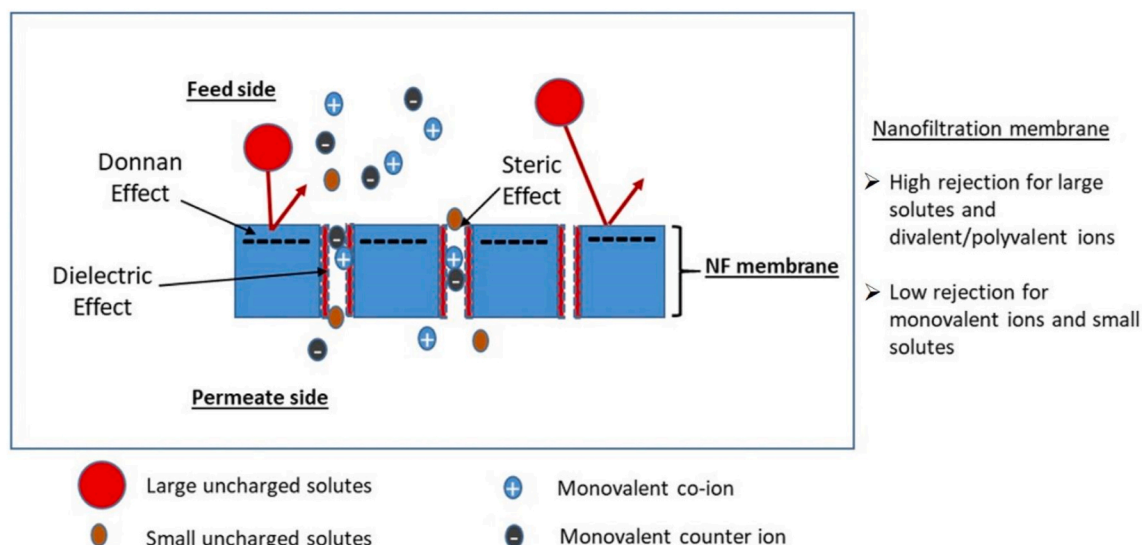


Fig. 1. Schematic illustration of NF membrane separation mechanism [20].

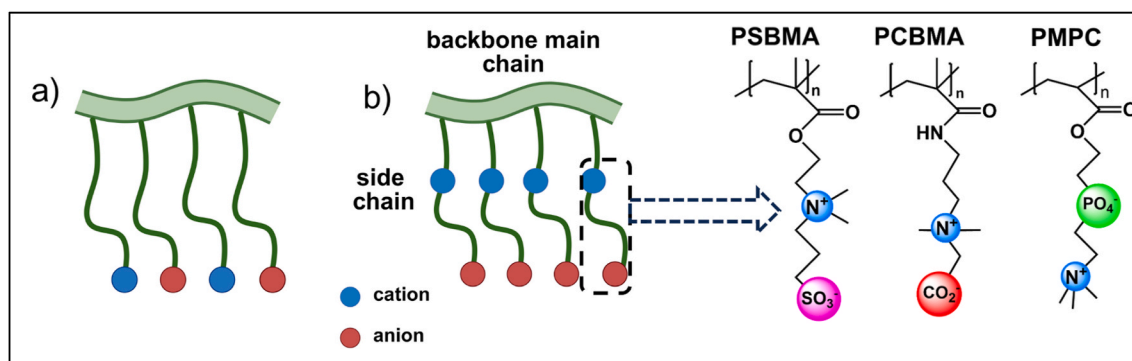


Fig. 2. Fundamental categorization of zwitterionic polymers into (a) polyampholyte and (b) betaine-like types, with representative examples.

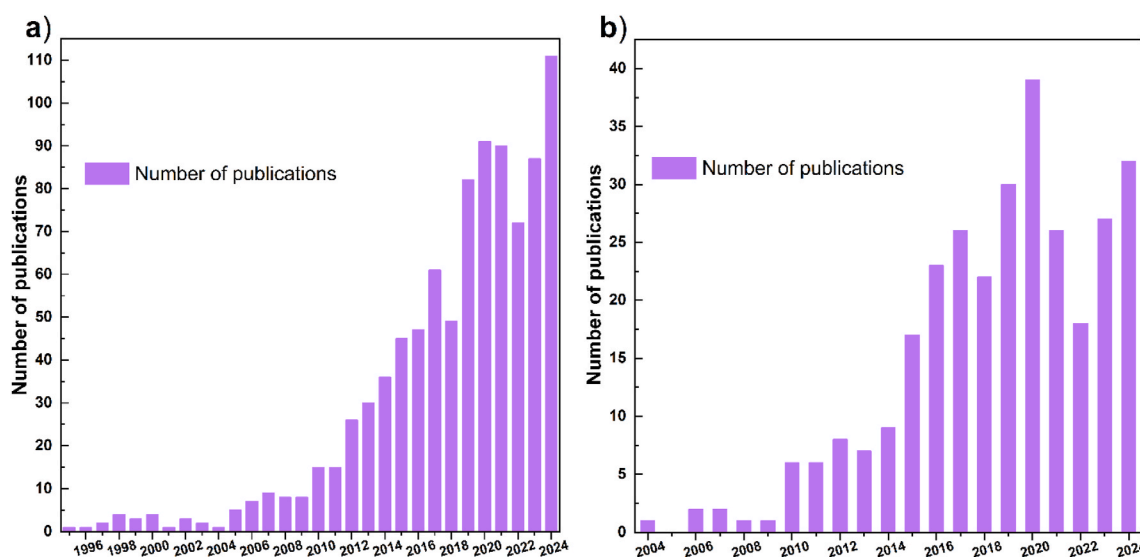


Fig. 3. Total annual publication on the topic of (a) SBMA since 1995; (b) SBMA-based NF membranes for the last 20 years. From Clarivate Web of Science, Dec 25, 2024.

biofouling applications. The unique properties of PC, such as its ability to mimic the structure of cell membranes, made it a popular choice for improving the fouling resistance of surfaces exposed to biological environments. However, despite its promising attributes, PC-based monomers, such as 2-methacryloyloxyethyl phosphorylcholine (MPC), are constrained by significant drawbacks. These include moisture sensitivity, low yield, and complex synthesis processes, which hinder their widespread use and scalability for industrial applications [21,22].

In response to these limitations, zwitterionic polymers have emerged as superior alternatives to PC materials. Among these, carboxybetaine (CB) and sulfobetaine (SB) have gained considerable attention due to their robust antifouling properties, ease of synthesis, and favorable chemical stability. These polymers are particularly valued for their biomimetic nature, closely resembling the properties of natural biological membranes. Sulfobetaine-based polymers, in particular, have been recognized for their biocompatibility, non-cytotoxicity, and the relative simplicity of their synthesis. The ability to easily incorporate sulfobetaine into various polymeric matrices, along with their excellent hydration properties, makes them an attractive choice for enhancing the fouling resistance of membranes in a range of applications, from water treatment to biomedical devices.

The growing interest in sulfobetaine-based polymers highlights their potential not only as antifouling agents but also as versatile materials that can be tailored for a variety of functionalized membrane applications. These materials offer a sustainable alternative to PC-based polymers, with the added benefit of simpler, more cost-effective production

methods, making them ideal candidates for large-scale industrial use.

Sulfobetaine (SB) has been extensively studied since its first synthesis of an SB analog in the 1950s, when Hart and Timmerman reported the synthesis of poly(4-vinylpyridine N-butyl sulfobetaine) [23]. SB, which was originally employed as a surfactant in petroleum exploration, has demonstrated ultralow fouling properties and has been adopted for a variety of biomedical and engineering applications [24]. Presently, SBMA is the most extensively researched sulfobetaine analog (Fig. 4), widely acknowledged for its efficacy as a non-fouling agent across diverse membrane technologies. SBMA enhances the membrane performance by effectively reducing the accumulation of organic and biological matter on the surface [25,26].

This review investigates the characteristics of prevalently utilized sulfobetaine methacrylate and its copolymers and emphasizes their role in overcoming the inherent constraints of traditional membrane technologies. The discussion centers on the synthesis techniques for these materials and their integral contributions to the advancement of nano-filtration membranes.

2. Fundamental aspects of fouling

2.1. Classification of fouling in membrane processes

Understanding fouling mechanisms in membrane systems necessitates a detailed exploration of the structure–property relationships that govern nonfouling behavior [27]. Ostuni et al. identified four key

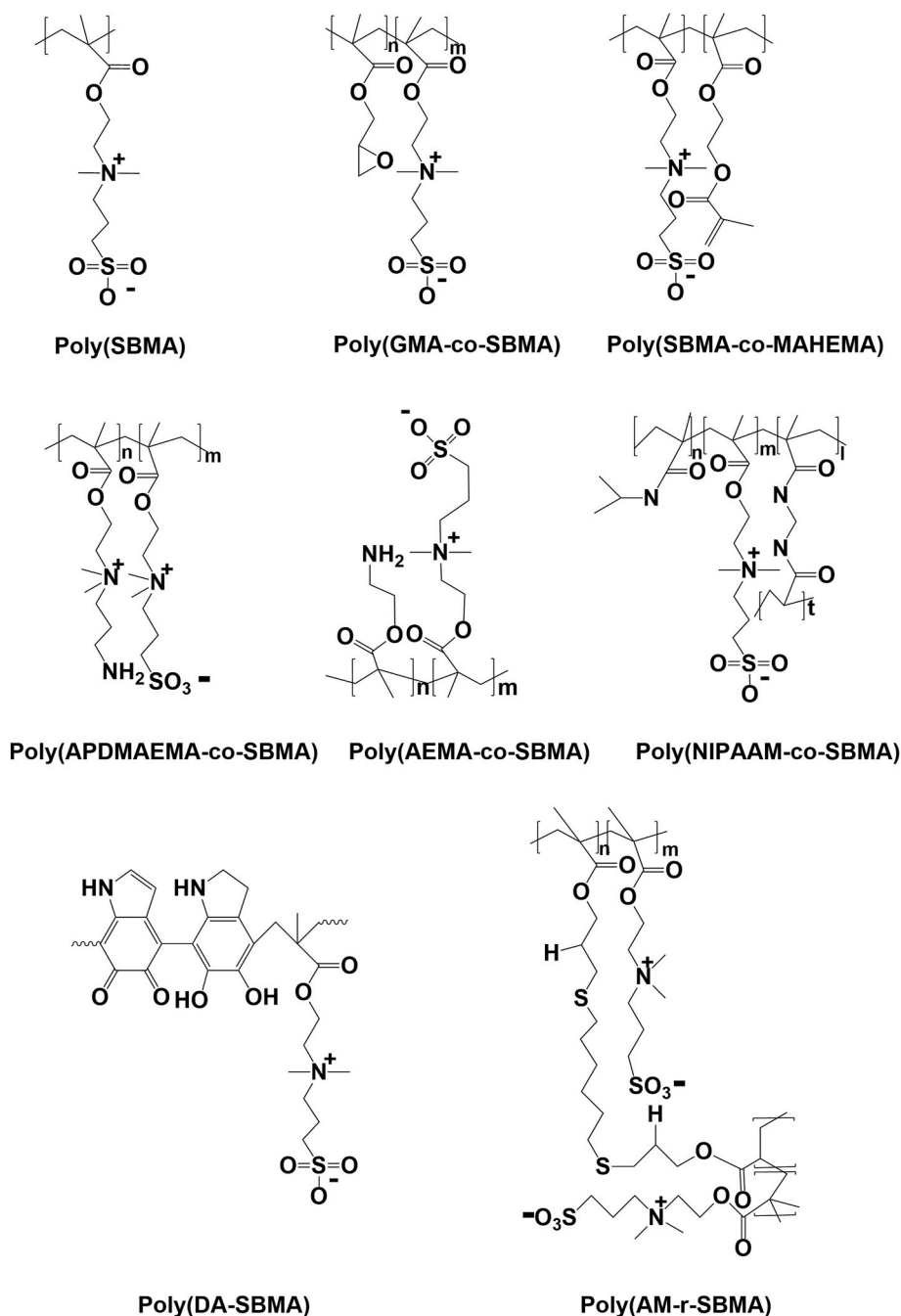


Fig. 4. Chemical structures of SBMA and its copolymers.

properties commonly associated with non-fouling materials: hydrophilicity, electrical neutrality, the presence of hydrogen-bond acceptors, and the absence of hydrogen-bond donors [28]. Although these properties are well recognized, notable exceptions exist, such as hydroxyl-rich materials that demonstrate excellent nonfouling characteristics.

A quintessential example of a non-fouling material is polyethylene glycol (PEG), a neutral and hydrophilic polymer. PEG's non-fouling properties of PEG are primarily attributed to two mechanisms.

- Osmotic Repulsion: Resistance to the release of bound and free water molecules from the polymer coil.
- Elastic Network Resistance (entropy repulsion): Resistance to compression owing to the polymer's intrinsic tendency to maintain an expanded conformation.

The repeating unit of PEG ($-\text{C}-\text{O}-\text{C}-$) binds water molecules via hydrogen bonding, creating a robust hydration layer that enhances its resistance to fouling. Unlike PEG, zwitterionic materials achieve non-fouling behavior through electrostatically induced hydration (ionic solvation), forming stable hydration layers even on rigid surfaces [29–31]. This hydration is driven by balanced charge distributions and minimized dipole moments, which are essential for their antifouling performance. Additionally, researchers have found that SB can bind more tightly and in greater quantities to water molecules—approximately 7–8 water molecules per SB unit than hydrophilic PEG, which binds only one water molecule per ethylene glycol unit. This property allows SB to permit more mobility of unbound water molecules in the first hydration layer, making it more effective than PEG-based materials in preventing fouling [32–34].

Recent advancements have also emphasized the antipolyelectrolyte

effect (APE) in zwitterionic materials, which further enhances hydration and improves the nonfouling efficiency in saline environments. Extensive experimental and computational studies have validated the critical role of strong surface hydration in mitigating protein adsorption and fouling [35].

Despite these advances, fouling remains a pervasive challenge in membrane systems, adversely affecting the water flux, operational pressures, and membrane longevity.

Fouling is generally classified into four types: organic, inorganic (scaling), colloidal, and biofouling (Fig. 5). Each type is governed by distinct mechanisms, as detailed below [36,37]:

2.1.1. Organic fouling

Natural Organic Matter (NOM) is universally recognized as the primary contributor to membrane fouling in nanofiltration (NF) systems, significantly impairing membrane performance and operational longevity [38–40]. Fouling initiated by NOM involves several interconnected mechanisms. Initially, NOM components adhere to the membrane surface, triggering electrostatic interactions that alter the membrane surface charge and hydrophilicity. This modification facilitates the further adsorption of NOM and other foulants, leading to a progressive flux decline [41]. Additionally, small NOM molecules can cause pore blockage and engage in hydrophobic interactions with the membrane, further reducing the permeability and enhancing fouling. A critical aspect of NOM-induced fouling is the formation of a filter cake layer driven by NOM functional groups, such as carboxyl groups, which are complex with metal ions. This complexation promotes the accumulation of a dense, restrictive layer on the membrane surface, particularly under concentration polarization conditions, resulting in irreversible fouling and sustained flux decline [42]. Biopolymers, including polysaccharides and proteins, are significant constituents of NOM that exacerbate irreversible fouling in NF membranes [43,44]. Their hydrophilic nature and adhesive properties facilitate the aggregation of both organic and inorganic molecules, forming a dense gel layer that obstructs water channels. The hydroxyl groups in polysaccharides enhance hydrogen bonding with membrane polymers, further promoting fouling. However, some studies suggest that biopolymers can also induce a size-exclusion effect, preventing the deposition of low-molecular-weight substances and forming a protective functional layer that mitigates pore clogging and maintains higher flux rates [45]. Humic substances such as humic acid (HA) and fulvic acid (FA) are the major components of NOM that intensify membrane fouling

through distinct mechanisms [46]. HA, a polyelectrolyte with polar functional groups ($-\text{COOH}$ and $-\text{OH}$), strongly complexes with metal ions, leading to pore blockage and filter cake formation [47].

In aqueous environments, biopolymers such as sodium alginate and bovine serum albumin (BSA) interact with humic substances through electrostatic and hydrophobic interactions, forming complex pollutant mixtures that significantly enhance fouling [48,49].

2.1.2. Inorganic fouling (scaling)

Inorganic fouling, also known as scaling, results from the precipitation of mineral salts such as calcium carbonate (CaCO_3), calcium sulfate (CaSO_4), magnesium sulfate (MgSO_4), barium sulfate (BaSO_4), and silica (SiO_2). These salts crystallize when their concentrations exceed their solubility limits, particularly near the membrane surface. Factors such as supersaturation, temperature fluctuations, and transmembrane pressure accelerate the scaling. For example, silica scaling is a common issue, with its solubility threshold being approximately 120 mg L^{-1} . Exceeding this limit leads to polymerization and the formation of gel-like deposits that degrade membrane performance. Mitigation strategies include chemical dosing with antiscalants, temperature control, and membrane surface modification to reduce scaling tendencies [50–52].

2.1.3. Colloidal fouling

Colloidal fouling is characterized by the accumulation of fine colloidal particles such as silica, metal oxides, clay minerals, salt precipitates, and suspended matter on the surface of nanofiltration (NF) membranes. These colloids typically range in size from 1 nm to $1 \mu\text{m}$, as documented in various studies [53,54]. A pivotal study by Boussou et al. explored the impact of colloidal size and charge on the fouling behavior of NF membranes using four different colloidal solutions composed of silica and aluminum particles. The results demonstrated that hydrophobic membranes are particularly prone to colloidal fouling, as evidenced by the development of a dense cake layer that uniformly covers the entire membrane surface. This dense layer significantly impairs membrane performance by obstructing water flow and reducing permeability. Furthermore, the characteristics of colloids play a crucial role in the fouling dynamics. The study found that larger and negatively charged colloids resulted in the least membrane fouling, suggesting that both the size and surface charge are key factors in mitigating fouling effects. Additionally, an increase in ionic strength exacerbates membrane fouling, especially in membranes with smaller pore sizes. This indicates that higher ionic concentrations facilitate the deposition and

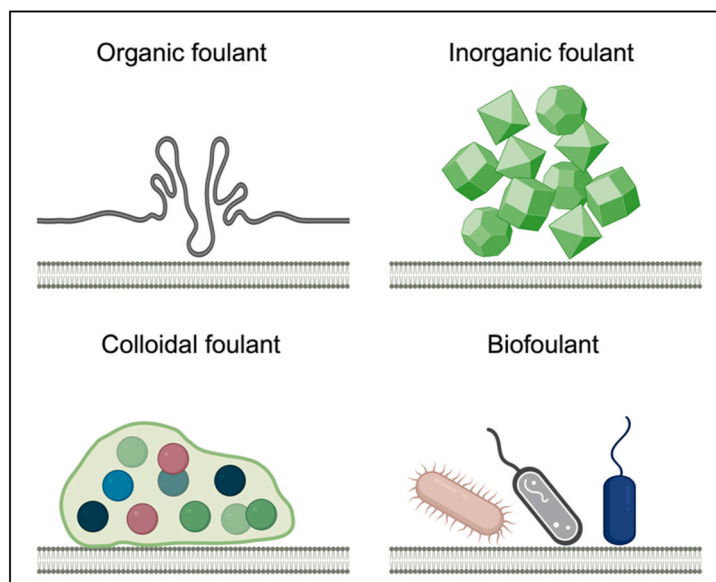


Fig. 5. Types of membrane fouling in water treatment.

aggregation of colloidal particles, thereby intensifying the fouling process [55].

2.1.4. Biofouling

Biofouling refers to the contamination of NF membranes by microorganisms, such as bacteria, algae, and viruses, along with their extracellular polymeric substances (EPS) [56–58]. This process can occur rapidly, typically within 24–48 h [59–61]. Even when 99.9 % of microorganisms are removed, residual cells can proliferate by utilizing biodegradable compounds in the feed water, leading to persistent fouling [62]. As biofilms develop and increase in coverage and thickness, they significantly reduce the permeate flux and, in severe cases, can cause complete blockage of membrane channels. Biofouling is considered one of the least understood and challenging types of fouling in real-world applications [63,64]. The consequences of biofouling include elevated membrane resistance, decreased permeate production, increased energy consumption, impeded tangential flow, inhibited convective transfer near the membrane surface, concentration polarization, potential microbial degradation of membrane materials, and reduced membrane lifespan owing to the need for frequent chemical cleaning. The biofilm formation process can be divided into four stages: initial reversible adhesion of microorganisms to the membrane surface, irreversible attachment facilitated by EPS production, biofilm maturation, and eventual biofilm dispersion. Understanding these stages is crucial for developing effective strategies to mitigate biofouling, thereby enhancing the membrane performance and durability in practical applications.

In response to these challenges, the development of zwitterionic polymers, especially Sulfobetaine Methacrylate (SBMA), offers a promising approach for fouling mitigation. The inherent properties of zwitterionic polymers, such as their high hydration and antifouling behavior, make them ideal candidates for membrane applications. Specifically, the switchable antifouling properties of SBMA-based polymers, which can dynamically alter their conformation in response to changes in ionic conditions, provide a powerful strategy for addressing fouling. Additionally, the surface hydration behavior of SBMA enhances its resistance to both organic and biofouling by preventing non-specific interactions with the foulants. The solutions discussed in Sections 2.2 and 2.3 offer innovative pathways for the design of next-generation membranes that maintain high performance even under challenging filtration conditions.

2.2. Switchable fouling- antifouling via salt-responsive zwitterionic brushes

Recent investigations have highlighted the remarkable “switchable” nature of zwitterionic polymer brushes, particularly those derived from SBMA, which can toggle between fouling (bio-adhesive) and antifouling states under varying ionic conditions [65,66]. This unique phenomenon, commonly referred to as the “anti-polyelectrolyte effect” (Fig. 6) arises when the introduction of salt solutions disrupts the inter- and intrachain electrostatic interactions that maintain the polymer brushes in a collapsed conformation, thereby prompting them to expand into a more open architecture. In pure water, SBMA-based brushes typically adopt a relatively dense configuration held together by strong ionic associations within or between the monomer units. However, once these brushes encounter high salt concentrations, the infiltrating counterions effectively dismantle the polymer’s internal dipole-dipole linkages. As a result, the chains extend, significantly intensifying polymer-water interactions and increasing the hydrophilicity and viscosity of the brush, thereby reducing its propensity to adsorb proteins or bacteria. The extent of brush expansion varies depending on the particular ions present; highly polarizable anions such as Br^- or ClO_4^- disrupt the zwitterionic network more effectively than less polarizable species, producing a stronger antifouling response [67].

Techniques such as atomic force microscopy (AFM) corroborate this

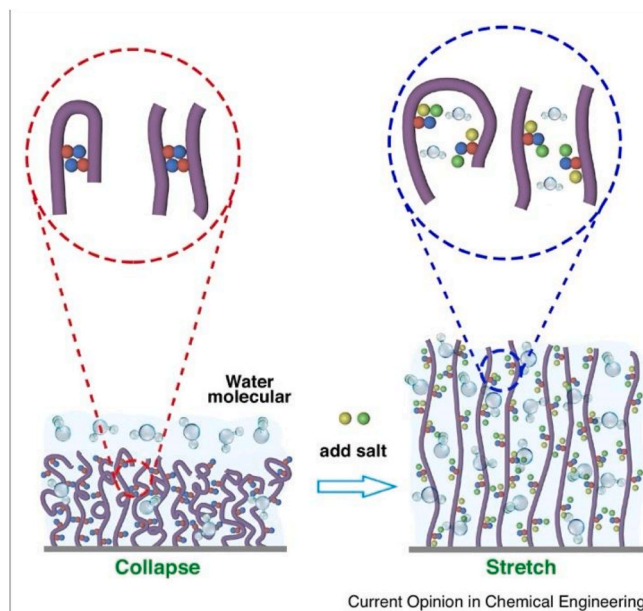


Fig. 6. Mechanism of anti-polyelectrolyte effect of zwitterionic polymer brushes [69–71].

enhanced brush thickness under salt conditions, whereas quartz crystal microbalance (QCM) and surface plasmon resonance (SPR) measurements confirm the release of proteins previously bound to the brush surface in pure water. Leveraging this salt-responsive behavior opens the door to designing “smart” surfaces that cyclically transition between fouling (bio-adhesive) and antifouling. For example, polymers such as SBMA can selectively capture proteins in mild buffer solutions (e.g., PBS) and subsequently release them into high-ionic-strength media (e.g., 1.0 M NaCl), a process that can be repeated over multiple cycles without significant loss of performance. These shifts in brush conformation also align with the changes in contact angles, highlighting the pivotal role of surface hydration in modulating the antifouling properties [68]. By exploiting this switchable functionality, SBMA-based zwitterionic brushes provide an innovative strategy for the development of advanced membranes and coatings with on-demand control over protein or bacterial attachment, offering considerable promise for applications ranging from protein purification to biomedical device design.

2.3. Surface hydration behavior of zwitterionic polymers

Zwitterionic polymers, known for their exceptional hydrophilicity, exhibit significant interactions with water molecules, as evidenced by the marked reduction in water contact angles on various surfaces. On polyurethane (PU) surfaces modified with SBMA brushes, the static water contact angle decreases dramatically from 90° to nearly 20° , indicating successful hydrophilization [72]. This transformation was further illustrated by acrylic resin discs grafted with thick, cross-linked poly(sulfobetaine methacrylamidopropyl) (polySBMAAP), where the water contact angle reached a minimum value of 6.7° at 15 % zwitterionic monomer content, approaching superhydrophilic conditions [73]. Similarly, the water contact angle on the titanium alloy plates grafted with poly[SBMA-co-(methacryloyloxymethyl phosphonic acid)] decreased from 59.6° to between 12° and 15° [74]. In cases where the surface was grafted with poly[SBMA-b-(methacryloyloxymethyl diethyl phosphonate)], the water droplets disappeared immediately, indicating extreme superhydrophilicity. Porous polypropylene membranes with densely tethered SBMA exhibited a minimum water contact angle of 17.4° , which was significantly lower than that of untreated membranes

(106°) [75].

Beyond surface wetting, zwitterionic polymers, such as poly(carboxybetaine acrylamide) (pCBAA) and SBMA, are characterized by their robust hydration layers driven by electrostatic interactions with water molecules. Sum-frequency generation (SFG) vibrational spectroscopy studies revealed intense O–H stretching signals below 3200 cm^{-1} , indicative of a dense, hydrogen-bonded hydration layer. The hydration behavior of these polymers varies with pH; for instance, pCBAA shows strong hydration under neutral and alkaline conditions, but decreases significantly under acidic conditions, correlating with increased protein adsorption. In contrast, SBMA maintained consistent hydration across a broad pH range (pH 5–9), contributing to its low bacterial attachment and enhanced versatility in fluctuating pH environments. The resilience of zwitterionic polymers against protein-induced disruptions is a testament to their superior hydration properties. SFG studies have demonstrated that proteins such as bovine serum albumin (BSA), fibrinogen, and lysozyme cannot disrupt the hydration layer on SBMA surfaces even in protein-rich environments, unlike PEG, which exhibits reversible hydration disruption upon protein interaction [76–81]. This robustness underlines the efficacy of zwitterionic polymers in maintaining antifouling performance under challenging conditions, including marine environments, where their hydration layers discourage adhesion by marine organisms. Zwitterionic polymers also perform effectively in high-ionic-strength environments, such as seawater, where they demonstrate remarkable resilience despite potential reductions in hydration owing to the ionic screening of surface charges. This attribute underscores the broad utility of zwitterionic materials for diverse industrial and environmental applications.

3. Fundamental principles of applications

The common membrane characterization for water treatment, including permeation flux determination, was conducted according to the following equation:

$$J = \frac{V}{A \times \Delta t} \quad (1)$$

where A is the effective surface area of the membrane (cm^2), V is the volume of permeate water (L), and Δt is the time required to permeate a fixed volume of water (h), respectively. The flux decline ratio (FDR) was determined using the following equation:

$$FDR = \frac{J_0 - J_t}{J_0} \times 100\% \quad (2)$$

where J_0 is the initial water flux, and J_t is the real-time permeate flux. The flux recovery ratio (FRR) is determined using the following equation:

$$FRR = \frac{J_r}{J_0} \times 100\% \quad (3)$$

where J_r is the water flux determined after the flux recovery stage.

Examine salt removal performance of zwitterionic polymer membranes using apparatuses with an ionic conductometer.

The rejection is calculated as

$$R(\%) = \left(1 - \frac{C_p}{C_f}\right) \times 100\% \quad (4)$$

where C_p and C_f are the salt and dye concentrations in the feed and the permeate, respectively.

The evaluation of ion rejection in a mixed-salt solution involves the use of simulated seawater as the feed solution. The rejection of ions in both the mixed and single salt solutions was determined using Eq. (2). A conductivity meter was used to measure the concentration of the single salt solution.

The cation concentrations (Ca^{2+} , Mg^{2+} , and Na^{+}) were measured using an inductively coupled plasma emission spectrometer, while the anion concentrations (SO_4^{2-} , Cl^{-}) were determined using atomic absorption spectroscopy. Multiple tests were conducted for each membrane to ensure reliability, and the data were calculated to obtain averages and standard deviations. This study also examined the selectivity of the Na_2SO_4 solution over CaCl_2 and the mixture containing SO_4^{2-} , expressed as per the provided equation.

$$S = \frac{R_A}{R_B} \quad (5)$$

where R_A represents the rejection of Na_2SO_4 or SO_4^{2-} and R_B represents the rejection of CaCl_2 or Ca^{2+} .

4. Synthesis and fabrication strategies

The monomer N-(3-sulfopropyl)-N-methacroyloxyethyl-N, N-dimethylammonium betaine, commonly known as SBMA, is widely available and has been rigorously studied since its polymerization was first described in 1986 [82]. The polymerization of SBMA (Fig. 7a) typically proceeds via radical polymerization, yielding a physically cross-linked gel network [83]. This foundational process imparts significant mechanical stability and structural integrity to the resulting polymers, rendering SBMA a versatile component for various membrane fabrication techniques. In contemporary applications, the inherent versatility of SBMA has been prominently demonstrated through its integration into membrane systems or its modification with diverse functional groups to synthesize copolymers. This adaptability facilitates the precise customization of membrane properties, thereby effectively addressing specific industrial and environmental challenges. Building upon this foundational knowledge, the current research predominantly employs three principal synthesis methodologies for the fabrication of zwitterionic NF membranes, as illustrated in Fig. 7b surface grafting, physical blending, and surface coating. Among these, surface-initiated atom transfer radical polymerization (SI-ATRP) is the most extensively utilized technique owing to its superior control over polymer chain growth, graft density, and uniformity of the functional layer. The following sections delineate these synthesis methods, emphasising their mechanisms, advantages, and application-specific optimisation.

4.1. Surface-initiated atom transfer radical polymerization (SI-ATRP)

Atom-transfer radical polymerization (ATRP) is essential for effective synthesis of antifouling membranes that require specific solvents and catalysts [84]. In conventional bulk and non-aqueous ATRP settings, catalyst systems commonly involve binuclear Cu(I) complexes with bridging halide ligands. By contrast, aqueous systems preferentially use monocationic $[\text{Cu}(\text{Bpy})_2]^+$ complexes with halide counterions. Chiang et al. developed an innovative approach to address these complexities in practical applications by grafting brush-like zwitterionic SBMA onto the surface of PVDF membranes [85]. This procedure involved ozone activation of the PVDF substrate and thermally induced polymerization of the initiator 2-(2-bromoisobutyryloxy)ethyl acrylate (BIEA), which preceded the ATRP-driven copolymerization of the SBMA macromonomer [86]. Expanding upon this foundation, the SI-ATRP method offers precise control over the molecular weight and graft density of polymers by adjusting monomer concentrations and reaction durations. It also facilitates the chemical customization of copolymer chains through modulation of the comonomer ratios during copolymerization. Using this technique, layers of poly(methacryloyloxyethyl phosphorylcholine) (polyMPC) and SBMA were synthesized on the surfaces of porous silica microspheres used as the stationary phases. Choi et al. further extended the application of SI-ATRP by grafting silica nanoparticles with crosslinked polyMPC shells, employing molybdenum hexacarbonyl ($\text{Mo}(\text{CO})_6$) as a catalyst, and initiating trichloroacetyl

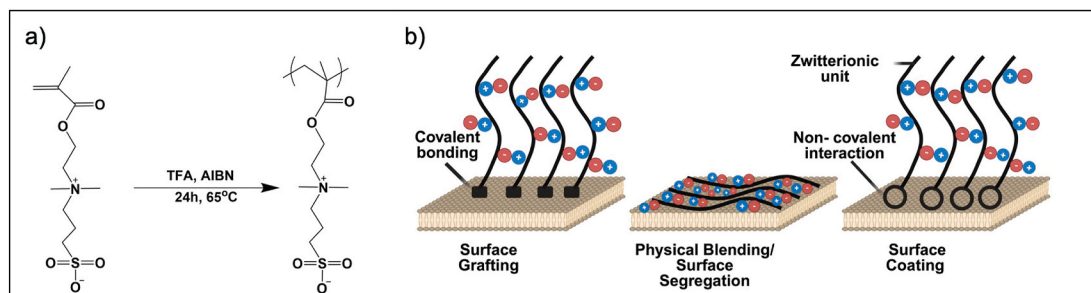


Fig. 7. (a) Reaction Scheme of SBMA Polymerization; (b) Modification methods for the zwitterionic NF membrane.

groups [87]. Moreover, SBMA and poly(sulfobetaine methacrylamidopropyl) (polySBMAAP) brushes were engineered onto gold surfaces pretreated with mercaptoundecyl bromoisobutyrate initiators, resulting in polymer layers approximately 20 nm thick, highlighting the precision of the method [88,89]. Further applications include the meticulous grafting of well-controlled SBMA brushes onto chloromethylated PES membranes, where the grafting yield is precisely regulated by the reaction time. Yue et al. synthesized zwitterionic SBMA and grafted it onto chloromethylated PES membranes via SI-ATRP [90]. Davenport et al. prepared membranes for grafting by immobilizing bromoisobutyryl bromide (BIBB) with dopamine hydrochloride, followed by the ATRP-based synthesis of SBMA brushes [91]. Guo et al. proposed a highly efficient strategy to fabricate SBMA-zwitterionic TFC membranes using different initiators, specifically 2-bromopropionyl bromide (BpBr) and BIBB, illustrating diverse approaches to membrane enhancement via SI-ATRP [92].

4.2. Surface grafting polymerization

Surface grafting has emerged as a prominent method for enhancing the antifouling properties of membranes used for water treatment. This technique entails covalent attachment of polymer chains directly onto the membrane surface, establishing durability through chemical bonding. Various polymerization methods, including redox polymerization, free-radical polymerization, and ultraviolet (UV) irradiation, have been employed to achieve effective integration.

For instance, one-step distillation-precipitation polymerization utilizes pre-fixed unsaturated carbon double bonds on the surface to initiate polymerization of SBMA in aqueous solutions. Similarly, methacrylate groups anchored on the gold electrode surfaces were activated under UV light to react with carboxybetaine monomers, resulting in a zwitterionic-grafted gold surface [93].

To overcome traditional challenges such as the degradation of zwitterionic polymer chains, physisorbed free-radical polymerization (FRP) has been developed [94]. This innovative approach uses azobis (isobutyronitrile) (AIBN) as an initiator, enhancing the covalent bonding of zwitterions such as SBMA to both the surface and inner structure of the membrane. This method facilitates the synthesis of zwitterions via the reactions between 2-(dimethylamino)ethyl methacrylate (DMAEMA) and β -propiolactone.

Expanding upon these innovations, Shahkaramipour et al. successfully co-deposited dopamine with zwitterions such as SBMA and sulfobetaine amine (SBAm) onto PES membranes, significantly improving their antifouling properties [95–97]. Moreover, the incorporation of porous materials, such as Zeolitic Imidazolate Frameworks (ZIF-7 and ZIF-8), results in advanced membrane functionality. Researchers such as S. Mohammad Nejad and Zhengis et al. utilized these frameworks to develop advanced nanofiltration membranes by initially functionalizing substrates with a co-deposited layer of SBMA zwitterion [98,99]. This method ensures the stable anchoring of metal-organic framework (MOF) nanocrystals on the membrane surface, thus enhancing both selectivity

and functionality.

Additionally, zwitterionic polymer brushes were grafted onto the surfaces of PVDF membranes through physisorbed free-radical grafting polymerization in a heterogeneous reaction system. The hydrophobicity of PVDF membranes aids the adsorption of AIBN, facilitating radical reactions that may terminate, initiate polymerization in solution, or abstract hydrogen from the PVDF backbone. The macroradicals formed on the PVDF backbone then reacted with SBMA monomers in solution to form grafted polymer chains, enabling polymerization directly from both the surface and inside of the membrane [100].

4.3. Physical blending/surface segregation

Physical blending and surface segregation are increasingly being recognized as effective modification methods within the interdisciplinary realm of membrane technology. These techniques, which are celebrated for their simplicity, versatility, and cost efficiency, have catalyzed the development of pioneering membranes. Innovations include conductive polymers that boast self-cleaning properties through electro-oxidation reactions and smart pH-responsive membranes that offer reversible molecular sieving capabilities for effective pollutant removal. This approach is in contrast to surface coating and grafting, which, while effective, can be time-intensive and often requires harsh chemical environments. In the physical blending process, a variety of polymers are used as additives during membrane casting, a technique often described as surface segregation. During phase inversion, amphiphilic copolymers, created from a blend of hydrophilic zwitterions and a hydrophobic membrane matrix, naturally arrange themselves at the water/membrane interface. Hydrophilic components, which possess a lower chemical potential, migrate more slowly than their hydrophobic counterparts in the casting solution prior to precipitation. This results in the enrichment of hydrophilic side chains at the membrane surface, endowing the membrane with substantial antifouling properties, whereas the hydrophobic segments remain embedded within the membrane matrix. Prior to the blending process, certain polymers are chemically modified through substitution reactions or various polymerization techniques to introduce the functional groups necessary for the synthesis of zwitterionic membranes. This strategic modification not only enhances the functionality of the membranes, but also aligns with the goal of creating advanced filtration systems that are both effective and environmentally friendly.

Expanding on these developments, Zhang et al. synthesized a novel copolymer by polymerizing 2-aminoethyl methacrylate (AEMA) and SBMA, which was then employed as an effective grafting agent to enhance both the filtration and antifouling properties of the TFC-NF membranes [101]. In this design, the zwitterionic SBMA segments act as antifouling polymer brushes because of their pronounced hydrophilicity and electroneutral character, whereas the primary amine groups in poly(AEMA) serve as reactive anchors. These amines form covalent bonds with residual acyl chloride functionalities on the nascent polyamide surface, ensuring the robust integration of the zwitterionic chains.

Xiang et al. synthesized SBMA and cross-linked it in situ with PES [102]. Unlike traditional methods, they used water-phase suspension polymerization, which involved dilution with deionized water to synthesize a novel copolymer, poly((2-dimethylaminoethyl methacrylate)-acrylonitrile) (PAN-DMAEMA). This copolymer was then reacted with 1,3-propanesultone to generate a zwitterionic N, N-dimethyl-N-methacryloxyethyl-N-(3-sulfopropyl) (DMMSA) functional group. The resulting DMMSA copolymer was blended with dimethyl sulfoxide (DMSO) to prepare solutions suitable for membrane casting. The zwitterionic monomer PEI-g-SBMA was synthesized via Michael addition reaction prior to interfacial polymerization for the formation of NF membranes [103]. Zhu et al. utilized reverse atom transfer radical polymerization (ATRP) to graft SBMA onto graphene oxide (GO) surfaces, further integrating it into the production of PES nanofiltration membranes [104].

Guo et al. advanced this field by integrating zwitterionic nanogels into PES-NF membranes via interfacial polymerization. In this approach, various zwitterionic monomers, including SBMA, were copolymerized with allylamine hydrochloride (AH) to form nanogels of zwitterionic polymers [105]. These nanogels were then incorporated into the interfacial polymerization process used to fabricate the TFC- NF membranes.

4.4. Surface coating

Surface coating methods for membrane modification. One of the most convenient strategies for altering membrane surfaces involves surface coating, wherein a “blanket” of material envelops the membrane through hydrophobic interactions or electrostatic attraction. Although this approach can reduce the permeability, it often yields improved selectivity and enhanced antifouling properties. The stability of any such coating depends on two primary factors: (1) the strength and nature of the interactions between the membrane surface and the zwitterionic (or otherwise functional) units, and (2) the polar interactions between these functional units and the surrounding medium. In these so-called “coating” techniques, antifouling layers are typically formed in-situ on the membrane surface. When inorganic nanomaterials are utilized, a pretreatment phase is frequently required to promote the adsorption of precursor species, ensuring adequate coverage and adhesion. In contrast, polymeric coatings can be achieved via methods such as self-assembled monolayers (SAMs), which leverage specific molecular interactions to create a uniform coating, and initiated chemical vapor deposition (iCVD), in which polymer films are deposited and polymerized directly on the membrane under controlled vacuum conditions.

Building upon these advancements, Xia et al. introduced an innovative surface-coating technique by synthesizing an SBMA-DA zwitterionic copolymer through a Michael addition reaction and subsequently coating it onto PVDF membranes [106].

Jia et al. introduced zwitterionic SBMA onto the surface of ethylene vinyl alcohol copolymer (EVOH) nanofibrous membranes (NFMs) using a straightforward spray-coating process followed by plasma treatment [107].

Samuel J. et al. laid the groundwork by polymerizing cross-linkable allyl methacrylate (AMA) with the zwitterionic SBMA using activator regenerated electron transfer atom transfer radical polymerization (ARGET-ATRP). The abundant allyl groups in the copolymer facilitated easy cross-linking via UV-initiated photopolymerization. Consequently, their membranes exhibited exceptional ion selectivity and fouling resistance, with tunable pore sizes as small as 0.9 nm [108].

Polymer self-assembly is increasingly recognized as an effective approach for fabricating antifouling membranes with controlled pore sizes, enabling enhanced selectivity without sacrificing the permeability [109–111]. Bengani et al. introduced an innovative TFC membrane, in which a selective layer was formed through the self-assembly of zwitterionic amphiphilic copolymers. In this study, SBMA was reacted with three hydrophobic polymers, 2,2,2-trifluoroethyl methacrylate (TFEMA), methyl methacrylate (MMA), and acrylonitrile (AN), to create

zwitterionic copolymers [112]. The rigid hydrophobic components in these copolymers prevented swelling of the zwitterionic nanochannels, which could otherwise impair the separation performance of the membrane.

5. Zwitterionic SBMA based membrane for nanofiltration

NF membranes effectively separate solutes through mechanisms such as steric hindrance and the Donnan effect, which are particularly significant for the rejection of charged ions. In addition to these mechanisms, size exclusion plays a crucial role in the removal of uncharged species, and this process is influenced by differences in molecular size and diffusion rates. Owing to these separation capabilities, NF membranes have wide-ranging applications in areas such as drinking water purification, wastewater reclamation, industrial chemical separation, and the desalination of brackish water. The primary advantage of NF in water treatment is its ability to efficiently remove hardness and particulate contaminants from water.

Table 1 provides an overview of the separation efficiency and anti-fouling characteristics of zwitterionic membranes used in nanofiltration. The modified zwitterionic membranes exhibited superior antifouling performance, which can be attributed to their enhanced hydrophilicity and smoother surface topography compared with the pristine membranes. Additionally, the negative charge on most zwitterionic membrane surfaces results in increased repulsive interactions with negatively charged particles, further contributing to their improved antifouling properties.

Zhang et al. successfully synthesized a copolymer comprising beta-cyclodextrin, 2-(dimethylamino)ethyl methacrylate (DMAEMA), and SBMA via interfacial polymerization to fabricate self-healing NF membranes. DMAEMA was incorporated as a guest molecule to enhance the self-healing capability and overall durability of the membranes. At a transmembrane pressure of 1 bar, the resulting membranes exhibited high rejection rates for dye molecules and a 12 % rejection rate for NaCl. In addition, they achieved a permeate flux of 24.39 L/m²·h·bar [113]. In parallel, researchers synthesized a membrane through a one-step polymerization of SBMA, DMAEMA, and cyclodextrin (β-CD). Subsequently, the membrane was successfully fabricated via interfacial polymerization using the constructed β-CD-DX-S as the only aqueous phase monomer. The resulting membrane exhibited a pure water permeability as high as 24.39 L/m²·h at an operating pressure of 1.0 bar. Furthermore, the membrane demonstrated excellent dye rejection (>97 %) while maintaining low salt rejection, with NaCl retention below 12 %.

Extending this research, Ma et al. constructed a high-flux PEI-g-SBMA membrane featuring excellent organic contaminant rejection, but relatively modest salt rejection. Such elevated antifouling efficacy can be ascribed to the electroneutral surface of the membrane and its inherently low surface energy, which minimizes foulant adsorption. Furthermore, integrating zwitterions with nanomaterials has proven to be an effective strategy for enhancing the membrane antifouling properties [103].

Zhu et al. synthesized a graphene oxide-SBMA (GO-PSBMA) composite membrane that doubled the pure water flux of its pristine counterpart to approximately 71.7 L/m²·h, which was attributed to the higher porosity and hydrophilicity conferred by the reduced compactness and density of the membrane skin layer [104]. This zwitterionic membrane exhibited low FDR, high FRR, and superior mechanical strength owing to its intercalated structure. Similarly, Guo et al. developed a zwitterionic NF membrane utilizing SBMA, yielding strong fouling resistance while achieving high rejection of Na₂SO₄ and raffinose with lower NaCl rejection at a permeability of 16.8 L/m²·h·bar. Additionally, the influence of SI-ATRP duration has been shown to impact water permeability and Na₂SO₄ rejection in zwitterionic polyamide membranes. These membranes effectively separated monovalent salts and neutral organics, concentrating raffinose five-fold with minimal increases in NaCl concentration over 30 h. Another study

Table 1
Separation performane and antifouling properties of zwitterionic SBMA-Based NF membranes.

Membrane Support	Zwitterion Modification	Monomer Preparation/Surface Modification Method	Test Conditions (°C/bar)	Contact Angle(deg)	Surface Charge (mV)	Flux(L/ m ² ·h·bar)	Rejection (%)	FRR (%) and FDR (%) /Antifouling Properties	Ref.
PVDF	SBMA-AA	Surface coating		13–9	–49 ~ –55	12	3.5 wt% NaCl	118 %	[119]
PES	SBMA-AH, CBMA-AH, META-AH	IP	RT	20.2, 39.1, 41.6		20.6	Na ₂ SO ₄ : ~98–100 % MgSO ₄ : ~90–98 % MgCl ₂ : ~40–60 % NaCl: ~10–25 %		[120]
PVDF	SBMA	NIPS/IP	30 °C	83	pH = 6, –15.4, ~ –18.9,			FRR:13.6 % BSA Luria-Bertani medium and E. coli bacteria	[121]
PSF	SBMA-AA	NIPS	RT/2 bar	68	pH = 7, –34, –38	144		FRR: BSA-46.5 %, HA-63 %	[122]
PS	SBMA	IIFRP/IP	RT/8 psi			12.2		FRR: Myoglobin: 92 %	[123]
PES	SiO ₂ -SBMA	RATRP/casting		72.3		36.8	Na ₂ SO ₄ : 11.4		[124]
PSF	PA-Brs-SBMA	SI-ATRP	RT	27–28.8	pH = 7, –30	10.7	Na ₂ SO ₄ : 98.6 NaCl: 35.2	FRR: HA-97.46-98.46 FDR: 6.08–4.01	[125]
PVDF	SBMA	UV-assisted surface grafting	RT	35–45	pH = 7, –10, –20				[126]
CA	DA-SBMA	Wet-phase inversion	RT/1.5 bar	115, 120, 125	–35, –40, –45			FRR: 67.59 % 84.17 %	[127]
PA-TFM	SBMA	SI-ATRP/	RT	18.4	pH = 7, –25.5	7.6	Na ₂ SO ₄ :99.1, MgSO ₄ :98.3, MgCl ₂ :97.9, NaCl:80.2	HA-FRR:92.1 % FDR: 60.5 %	[128]
PVDF	(S-EGMA-SBAA)	VIPS	/1.5 atm	110, 115, 120, 130			E. coli: 89.6	FRR: 73 %	[129]
PP	EVOH-SBMA	Melt phase-separation/Spray coating/Plasma grafting	0.2 MPa	50.4	ph = 7 –50			FRR: BSA-95.65–78.26 %	[130]
HPAN	SBMA, PDA	CuSO ₄ /H ₂ O ₂ triggered co-deposition/casting	4 bar	38, 28.5, 24,5		13.2	Na ₂ SO ₄ :46.2 %, MgSO ₄ :12.3 %, NaCl:8.4 %, MgCl ₂ :1.9 %,		[131]
PES	ZIF-7-SBMA-PDA	NIPS/coating and surface functionalization	1.5 bar	51.43	pH = 7 –33	28		FRR: HA-60 % E. coli –48 % Congo Red-59 %	[132]
PA-TFC	P(SBMA-MAHEMA)	CP/surface-selective hydrogel coating	15 bar		pH = 7 –15		NaCl: 39.3 % Na ₂ SO ₄ : 89.9 %	FRR: BSA-95-100 % Myo-93-97 %	[133]
PAN	PEI-SBMA	Michael addition reaction./IP/grafting	6 bar	30	pH = 7 +2	8.6	Na ₂ SO ₄ : 99.5 % MgCl ₂ : 80.14 % NaCl: 64.55 %		[134]
PSF	SBMA-AEMA	grafting	RT/5 bar	26, 12.7, 39.5	pH = 7 –20 –10 –15	15.6, 27.5, 32.9	Na ₂ SO ₄ : 95–97 % MgSO ₄ : 93–95 % MgCl ₂ : 55–65 % NaCl: 28–32 %	BSA-FRR: 84–97 % FDR: 68–90 %	[135]
PAN	PEI-SBMA	coating	2 bar	37, 39, 40, 43	pH = 7 –15 –12	118.5	NaCl: 6 %	BSA-FRR: 99.9 %	[136]
PSF	P(DA-SBMA)	casting/IP	6 bar	30.23, 22,47, 20,82, 18,48, 14,79	–36.87		Na ₂ SO ₄ :98 %, MgSO ₄ :95 %, MgCl ₂ :54 %, NaCl:42 %	BSA-FRR: 99.53 %	[137]
PVDF	PSBMA-GO	phase inversion	0.1 MPa	72,3, 57,3, 68,6		18, 31, 39.5		FRR: BSA-68, 83, 90 % HA-78, 86, 90 % SA-82, 84, 87 %	[138]
TFC RO	SBMA-AEMA	Covalent codeposition	RT/15 bar	30, 22, 8, 5	pH = 7 –24	4.4, 4.2, 4, 3.4	Na ₂ SO ₄ : 99.5 %		[139]
NF90 VNF1	PDA-SBMA	ARGET-ATRP/grafting	6.89 bar	46.7–33.2 28.4–23.7	pH = 7 –27.3 –28.8		Na ₂ SO ₄ :98,98.5 % MgSO ₄ :91, 92 % MgCl ₂ : 88, 91.5 % NaCl:19, 74 %		[140]

(continued on next page)

Table 1 (continued)

Membrane Support	Zwitterion Modification	Monomer Preparation/Surface Modification Method	Test Conditions (°C/bar)	Contact Angle(deg)	Surface Charge (mV)	Flux(L/ m ² ·h·bar)	Rejection (%)	FRR (%) and FDR (%) /Antifouling Properties	Ref.
PES	SBMA	Dry-jet wet spinning/IP	12 bar			8.6	NaCl: 98.5 %	BSA-FRR: 85 %	[141]
PS	PS-SBMA	NIPS	0.1 MPa	75 68				BSA FRR: 90–91 %	[142]
PSF	SBMA	IP + SI-ATRP	RT/6	23	−40	13.5	Na ₂ SO ₄ : NSA, 98.1	FRR: 95.5 for HA	[143]
TFC	PSBMA	ARGET-ATRP grafting	RT	23 31	pH = 7 −57, 60	3.55		H ₂ O-FRR: 96.5 %	[144]
PES	DMAEMA, SBMA, f β-CD	IP	2.5 bar	40, 35, 26,	18, 24, 15.5, 19		NaCl: 12 %	FRR: SA- 73, HA- 90 %	[145]
PES	SBMA	NIPS/corona air plasma treatment	2 bar	39.5, 37, 35				FRR: H ₂ O- 87.5 and 93.7 %	[146]
PAN	p(BMA-PEGMA-SBMA)	VIPS/IP	RT	40–17					[147]
PVDF	SBMA-S	VIPS/casting	RT/1 atm	12					[148]
PVDF	PS-PEGMA-PSBMA	FRP/casting/VIPS	37 °C	95				Fibrinogen-FRR: 91 %	[149]
PA	SBMA	SI-ATRP/coating	RT/15.6 bar	34.9			Na ₂ SO ₄ : 100 %		[150]
PEI	PAPDMAEMA-PSBMA	ATRP/IP	2 bar	50 40 20	pH = 7 −26 −20 4	38 105 135	NaCl:3–5 % MgCl ₂ :4–5 % MgSO ₄ : 0.5–2 % Brilliant Blue R:98–99.5 % Congo Red:53–97 %		[151]
PES	GO-SBMA	ARGET-ATRP/IP	20 °C/13.6 bar	62 51 59	pH = 6.4 −13 −8.7 −6	2.2	NaCl:73.6–90 % MgCl ₂ : 82.3–92.8 %	BSA FRR: 95 % FDR: 50 % for 12 h	

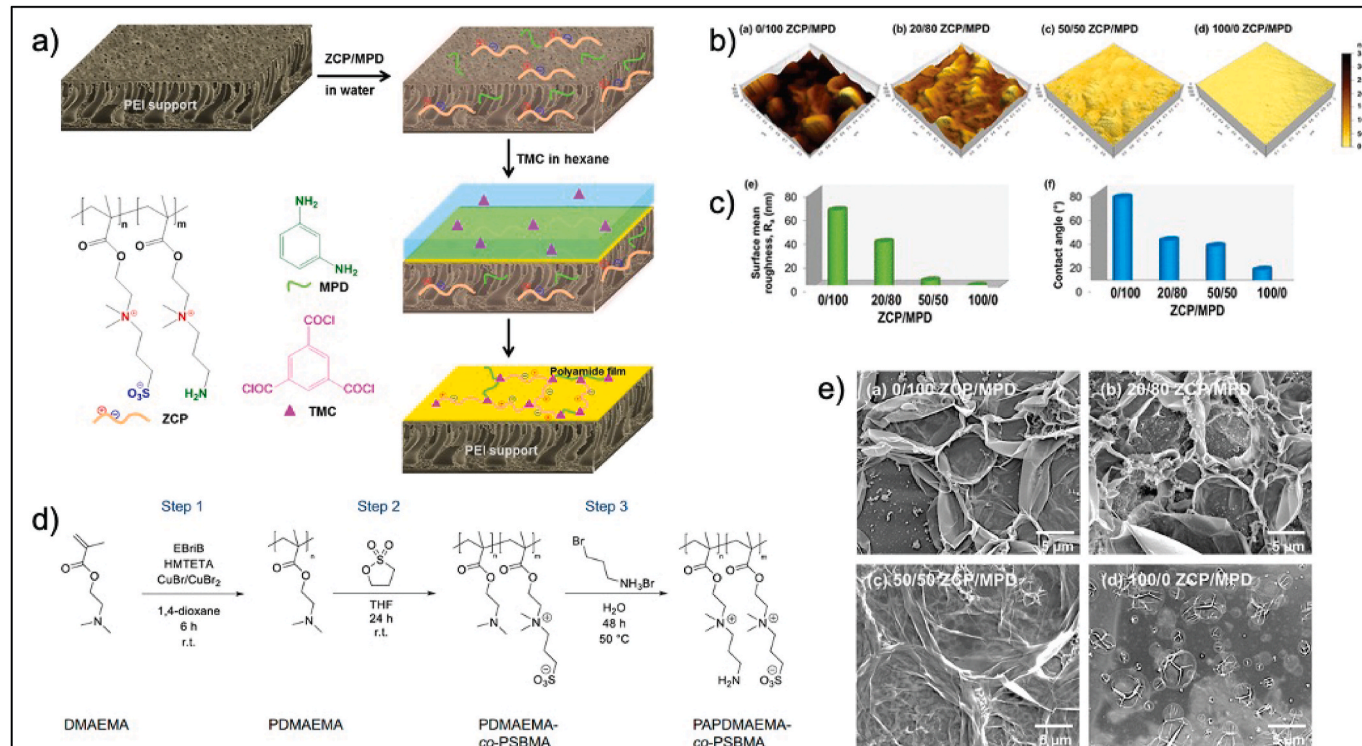


Fig. 8. (a) Schematic illustration of the fabrication of polyamide membranes by the interfacial polymerization reaction of amines (zwitterionic copolymer, and m-phenylenediamine, MPD) and trimesoyl chloride (TMC); (b) AFM topographic images of polyamide membranes prepared with amine solutions containing different ZCP/MPD ratios; (c) surface mean roughness, and contact angle of polyamide membranes prepared with amine solutions containing different ZCP/MPD ratios; (d) Overview of the zwitterionic copolymer synthesis; (e) Field Emission Scanning Electron Microscopy (FESEM) images of the surfaces of free-standing films obtained using various ratios of copolymer and MPD (ZCP/MPD) [114].

demonstrated that a moderate SBMA graft length and low graft density are beneficial for achieving enhanced water flux, whereas longer graft lengths or higher graft densities provide optimal antifouling performance.

In nanofiltration membranes, the separation of dyes and salts is crucial; however, in industrial wastewater, the challenge extends to the removal of heavy metals and dyes from the effluent. In this context, SBMA-based polymers have shown significant promise as antifouling agents and for heavy metal removal. The zwitterionic moieties in SBMA have garnered considerable interest for ion removal because of their unique advantages: they combine the properties of both inorganic and organic materials, offering structural flexibility and the ability to electrostatically interact with ionic pollutants. The presence of charges on the pendant side chains allows these materials to effectively remove ionic contaminants, including heavy metals and dyes [115].

For instance, Prabhakar et al. synthesized $\text{H}_2\text{N-MIL-53(Fe)}$ via a metal displacement reaction, which was then modified into MIL-53(Fe)-SBMA brushes using atom ATRP reaction. The amine groups of $\text{NH}_2\text{-MIL-53(Fe)}$ facilitated the connection between the MOF and the polymeric SBMA brushes, which were subsequently coated onto PVDF surfaces. To evaluate the performance of these modified membranes, a feed solution was prepared containing 100 ppm of reactive black-5 (RB-5) and sunset yellow (SY) dyes, alongside 500 ppm of heavy metals such as $\text{Cd(NO}_3)_2$, $\text{Pb(NO}_3)_2$, HgCl_2 , and NaAsO_4 in deionized water.

The membranes demonstrated excellent rejection efficiencies for heavy metal ions, achieving 97.33 % for Pb^{2+} , 95.19 % for Hg^{2+} , 82.06 % for As^{3+} , and 78.47 % for Cd^{2+} . Additionally, 96.23 % and 94.04 % rejections were observed for the RB-5 and SY dyes, respectively. These results emphasize the substantial potential of SBMA-modified membranes for removing both heavy metals and dyes from wastewater, highlighting their antifouling capabilities and selective separation properties [116].

By utilizing the well-studied zwitterionic polymer SBMA, researchers successfully fabricated a PAPDMAEMA-co-SBMA membrane via interfacial polymerization, as illustrated in Fig. 8a and b. Increasing the concentration of zwitterionic moieties resulted in a smoother membrane surface. Furthermore, the copolymer structure, characterized by longer segments between the reactive groups, promotes the formation of a looser polyamide layer (Fig. 8b–e). This structural modification significantly influenced water permeation, driven by the enhanced hydrophilicity of the membrane, as shown in Fig. 8c. The resulting membrane demonstrated an impressive pure water permeability of $135 \text{ L/m}^2 \text{ h bar}$, while maintaining excellent dye rejection capabilities, achieving a 97 % rejection rate for Brilliant Blue R.

In addition to the aforementioned studies, Chaabane et al. synthesized zwitterionic graphene oxide for the adsorption of Co (II) and Ni (II) from water, demonstrating its effectiveness in removing metal ions from wastewater systems [117]. Similarly, Ibrahim et al. fabricated thin-film composite membranes incorporating polymeric zwitterionic nanoparticles for the removal of Pb^{2+} and Cd^{2+} from contaminated water, further demonstrating their role in heavy metal remediation [118]. These studies further demonstrate how SBMA-based zwitterionic polymers can be leveraged for both antifouling and heavy metal removal, making them promising solutions for wastewater treatment applications.

6. Summary and outlook

Zwitterionic membranes exhibit exceptional potential for mitigating various types of fouling, making them highly suitable for chemical separation applications in numerous industries. Extensive research has shown that zwitterionic membranes significantly reduce protein adsorption, classifying them as effective against non-migratory foulants. Additionally, certain zwitterionic membranes inherently possess antibacterial properties, enabling them to counteract proliferative foulants and efficiently manage oil-water emulsions. The antifouling efficacy of

these membranes is primarily governed by two mechanisms: steric repulsion and hydration layer formation. Steric repulsion reduces the entropy associated with protein adsorption, making the process energetically unfavourable. The hydration layer, formed through robust electrostatic interactions between zwitterions and water molecules, serves as an effective barrier against foulant attachment. In the context of salt/dye separation mechanisms, such as those employed in nanofiltration membranes, zwitterionic polymers have been shown to enhance the rejection capacity. Functionalization of the zwitterionic backbone can further improve the switchability of the membranes, making them long-term reusable and capable of easily removing foulants and waste materials.

Among the various synthesis methodologies, surface grafting, physical blending, and surface coating are predominantly utilized, each presenting distinct advantages and challenges. Surface grafting establishes strong chemical bonds; however, it involves multiple steps, complicating the accurate quantification of the final SBMA content within the membrane. Physical blending, characterised by surface segregation with less than 1 wt% zwitterionic polymer in solution, offers time efficiency and ensures uniform distribution of additives. In contrast, surface coating is a straightforward and rapid process but may suffer from durability issues and reduced permeability, although it allows for higher concentrations of SBMA or its copolymers than interfacial polymerization.

Future advancements in zwitterionic membrane technology require a deeper understanding of and precise control over the interactions between zwitterionic polymers, membrane matrices, and solvents. Strategies to reduce fabrication costs and enhance scalability are essential for the widespread adoption of zwitterionic membranes in various fields. Long-term stability studies are crucial for validating the durability of antifouling properties under extended operational conditions. To further enhance antibiofouling capabilities, maintaining the surface charge and incorporating nanoparticles can be explored to introduce biocide release mechanisms. Hybrid inorganic-organic techniques offer promising avenues to fine-tune the mechanical stability, thermal resilience, and structural flexibility of membranes. Additionally, adopting green synthetic approaches using environmentally benign solvents can minimise solvent waste and align membrane development with sustainable practices in the long run.

Ultimately, the development of advanced zwitterionic membranes for wastewater treatment focuses on optimizing permeate flux, salt rejection, antifouling performance, and overall membrane robustness. This review aims to provide materials scientists with a comprehensive and insightful perspective on pioneering studies involving zwitterionic SBMA polymers, fostering innovations that contribute to the sustainable development of membrane technology.

CRedit authorship contribution statement

Arshyn Zhengis: Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Arailym Yergesheva:** Writing – original draft, Investigation, Data curation. **Yenglik Amrenova:** Writing – original draft, Resources, Methodology, Data curation. **Munziya Abutalip:** Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **Nurxat Nuraje:** Writing – review & editing, Writing – original draft, Validation, Supervision, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

- [1] World Health Organization Drinking Water. <https://www.who.int/news-room/fact-sheets/detail/drinking-water>. (Accessed 10 September 2020).
- [2] The World Bank, High and Dry: Climate Change, Water, and the Economy, International Bank for Reconstruction and Development/The World Bank, Washington, DC, 2016.
- [3] E. Jones, M. Qadir, M.T.H. van Vliet, V. Smakhtin, S. Kang, The state of desalination and brine production: a global outlook, *Sci. Total Environ.* 657 (Mar. 2019) 1343–1356, <https://doi.org/10.1016/j.scitotenv.2018.12.076>.
- [4] K. Wang, et al., Tailored design of nanofiltration membranes for water treatment based on synthesis–property–performance relationships, *Chem. Soc. Rev.* 51 (2) (2022) 672–719, <https://doi.org/10.1039/D0CS01599G>.
- [5] Y. Zhao, T. Tong, X. Wang, S. Lin, E.M. Reid, Y. Chen, Differentiating solutes with precise nanofiltration for next generation environmental separations: a review, *Environ. Sci. Technol.* 55 (3) (Feb. 2021) 1359–1376, <https://doi.org/10.1021/acs.est.0c04593>.
- [6] C. Zhao, et al., Polyamide membranes with nanoscale ordered structures for fast permeation and highly selective ion-ion separation, *Nat. Commun.* 14 (1) (Feb. 2023) 1112, <https://doi.org/10.1038/s41467-023-36848-8>.
- [7] Y. Zhang, et al., Ice-confined synthesis of highly ionized 3D-quasylayered polyamide nanofiltration membranes, *Science* (1979) 382 (6667) (Oct. 2023) 202–206, <https://doi.org/10.1126/science.adf9531>.
- [8] H. Zhang, Q. He, J. Luo, Y. Wan, S.B. Darling, Sharpening nanofiltration: strategies for enhanced membrane selectivity, *ACS Appl. Mater. Interfaces* 12 (36) (Sep. 2020) 39948–39966, <https://doi.org/10.1021/acsami.0c11136>.
- [9] J.M. Gohil, P. Ray, A review on semi-aromatic polyamide TFC membranes prepared by interfacial polymerization: potential for water treatment and desalination, *Sep. Purif. Technol.* 181 (Jun. 2017) 159–182, <https://doi.org/10.1016/j.seppur.2017.03.020>.
- [10] Y.H. Teow, J.Y. Sum, K.C. Ho, A.W. Mohammad, Principles of nanofiltration membrane processes, in: *Osmosis Engineering*, Elsevier, 2021, pp. 53–95, <https://doi.org/10.1016/B978-0-12-821016-1.00014-0>.
- [11] D.L. Oatley-Radcliffe, S.R. Williams, M.S. Barrow, P.M. Williams, Critical appraisal of current nanofiltration modelling strategies for seawater desalination and further insights on dielectric exclusion, *Desalination* 343 (Jun. 2014) 154–161, <https://doi.org/10.1016/j.desal.2013.10.001>.
- [12] W.R. Bowen, J.S. Welfoot, Modelling the performance of membrane nanofiltration—critical assessment and model development, *Chem. Eng. Sci.* 57 (7) (Apr. 2002) 1121–1137, [https://doi.org/10.1016/S0009-2509\(01\)00413-4](https://doi.org/10.1016/S0009-2509(01)00413-4).
- [13] J.E. Almazán, E.M. Romero-Dondiz, V.B. Rajal, E.F. Castro-Vidaurre, Nanofiltration of glucose: analysis of parameters and membrane characterization, *Chem. Eng. Res. Des.* 94 (Feb. 2015) 485–493, <https://doi.org/10.1016/j.cherd.2014.09.005>.
- [14] R. Epsztein, E. Shauly, N. Dizge, D.M. Warsinger, M. Elimelech, Role of ionic charge density in donnan exclusion of monovalent anions by nanofiltration, *Environ. Sci. Technol.* 52 (7) (Apr. 2018) 4108–4116, <https://doi.org/10.1021/acs.est.7b06400>.
- [15] C.T. Cleveland, T.F. Seacord, A.K. Zander, Standardized membrane pore size characterization by polyethylene glycol rejection, *J. Environ. Eng.* 128 (5) (May 2002) 399–407, [https://doi.org/10.1061/\(ASCE\)0733-9372\(2002\)128:5\(399\)](https://doi.org/10.1061/(ASCE)0733-9372(2002)128:5(399)).
- [16] L.D. Nghiem, A.I. Schäfer, M. Elimelech, Removal of natural hormones by nanofiltration membranes: measurement, modeling, and mechanisms, *Environ. Sci. Technol.* 38 (6) (Mar. 2004) 1888–1896, <https://doi.org/10.1021/es034952r>.
- [17] M.J. López-Muñoz, A. Sotto, J.M. Arsuaga, B. Van der Bruggen, Influence of membrane, solute and solution properties on the retention of phenolic compounds in aqueous solution by nanofiltration membranes, *Sep. Purif. Technol.* 66 (1) (Apr. 2009) 194–201, <https://doi.org/10.1016/j.seppur.2008.11.001>.
- [18] Y. Zhu, et al., Quercetin confers protection of murine sepsis by inducing macrophage M2 polarization via the TRPM2 dependent calcium influx and AMPK/ATF3 activation, *J. Funct. Foods* 56 (May 2019) 1–13, <https://doi.org/10.1016/j.jff.2019.03.001>.
- [19] D.L. Oatley, et al., Investigation of the dielectric properties of nanofiltration membranes, *Desalination* 315 (Apr. 2013) 100–106, <https://doi.org/10.1016/j.desal.2012.09.013>.
- [20] N.N.R. Ahmad, W.L. Ang, Y.H. Teow, A.W. Mohammad, N. Hilal, Nanofiltration membrane processes for water recycling, reuse and product recovery within various industries: a review, *J. Water Process Eng.* 45 (Feb. 2022) 102478, <https://doi.org/10.1016/j.jwpe.2021.102478>.
- [21] T. Umeda, T. Nakaya, M. Imoto, Polymeric phospholipid analogues, 14. The convenient preparation of a vinyl monomer containing a phospholipid analogue, *Makromol. Chem., Rapid Commun.* 3 (7) (Jul. 1982) 457–459, <https://doi.org/10.1002/marc.1982.030030701>.
- [22] K. Uchida, et al., Biomedical engineering. Relationship between blood compatibility and nontrombogenic polymer surfaces, *Kagaku Kogaku Ronbunshu* 24 (2) (1998) 217–221, <https://doi.org/10.1252/kakoronbunshu.24.217>.
- [23] R. Hart, D. Timmerman, New polyampholytes: the polysulfobetaines, *J. Polym. Sci.* 28 (118) (Apr. 1958) 638–640, <https://doi.org/10.1002/pol.1958.1202811820>.
- [24] Z. Zhang, S. Chen, Y. Chang, S. Jiang, Surface grafted sulfobetaine polymers via atom transfer radical polymerization as superlow fouling coatings, *J. Phys. Chem. B* 110 (22) (Jun. 2006) 10799–10804, <https://doi.org/10.1021/jp057266i>.
- [25] N. Cheng, A.A. Brown, O. Azzaroni, W.T.S. Huck, Thickness-dependent properties of polyzwitterionic brushes, *Macromolecules* 41 (17) (Sep. 2008) 6317–6321, <https://doi.org/10.1021/ma800625y>.
- [26] O. Azzaroni, A.A. Brown, W.T.S. Huck, UCST wetting transitions of polyzwitterionic brushes driven by self-association, *Angew. Chem. Int. Ed.* 45 (11) (Mar. 2006) 1770–1774, <https://doi.org/10.1002/anie.200503264>.
- [27] Tiraferri, A. Membrane-Based Water Treatment to Increase Water Supply; h t t p : / / w w w . c o l l o i d . c h / g r o u p / p a g e / p d f s / MembraneBasedWaterTreatment1.pdf (accessed November 28, 2020).".
- [28] E. Ostuni, R.G. Chapman, R.E. Holmlin, S. Takayama, G.M. Whitesides, A survey of structure–property relationships of surfaces that resist the adsorption of protein, *Langmuir* 17 (18) (Sep. 2001) 5605–5620, <https://doi.org/10.1021/la010384m>.
- [29] Q. Shao, S. Jiang, Molecular understanding and design of zwitterionic materials, *Adv. Mater.* 27 (1) (Jan. 2015) 15–26, <https://doi.org/10.1002/adma.201404059>.
- [30] B. Cao, Q. Tang, G. Cheng, Recent advances of zwitterionic carboxybetaine materials and their derivatives, *J. Biomater. Sci. Polym. Ed.* 25 (14–15) (Oct. 2014) 1502–1513, <https://doi.org/10.1080/09205063.2014.927300>.
- [31] A.J. Keefe, S. Jiang, Poly(zwitterionic)protein conjugates offer increased stability without sacrificing binding affinity or bioactivity, *Nat. Chem.* 4 (1) (Jan. 2012) 59–63, <https://doi.org/10.1038/nchem.1213>.
- [32] P. Zhang, B.D. Ratner, A.S. Hoffman, S. Jiang, Nonfouling surfaces, in: *Biomaterials Science*, Elsevier, 2020, pp. 507–513, <https://doi.org/10.1016/B978-0-12-816137-1.00034-9>.
- [33] Q. Shao, S. Jiang, Molecular understanding and design of zwitterionic materials, *Adv. Mater.* 27 (1) (Jan. 2015) 15–26, <https://doi.org/10.1002/adma.201404059>.
- [34] B. Cao, Q. Tang, G. Cheng, Recent advances of zwitterionic carboxybetaine materials and their derivatives, *J. Biomater. Sci. Polym. Ed.* 25 (14–15) (Oct. 2014) 1502–1513, <https://doi.org/10.1080/09205063.2014.927300>.
- [35] W. Choi, et al., Reverse actuation of polyelectrolyte effect for *in vivo* antifouling, *ACS Nano* 15 (4) (Apr. 2021) 6811–6828, <https://doi.org/10.1021/acsnano.0c10431>.
- [36] A. Al-Amoudi, P. Williams, S. Mandale, R.W. Lovitt, Cleaning results of new and fouled nanofiltration membrane characterized by zeta potential and permeability, *Sep. Purif. Technol.* 54 (2) (Apr. 2007) 234–240, <https://doi.org/10.1016/j.seppur.2006.09.014>.
- [37] C. Bartels, M. Wilf, W. Casey, J. Campbell, New generation of low fouling nanofiltration membranes, *Desalination* 221 (1–3) (Mar. 2008) 158–167, <https://doi.org/10.1016/j.desal.2007.01.074>.
- [38] L. Shan, H. Fan, H. Guo, S. Ji, G. Zhang, Natural organic matter fouling behaviors on superwetting nanofiltration membranes, *Water Res.* 93 (Apr. 2016) 121–132, <https://doi.org/10.1016/j.watres.2016.01.054>.
- [39] Z. Su, T. Liu, X. Li, N. Graham, W. Yu, Beneficial impacts of natural biopolymers during surface water purification by membrane nanofiltration, *Water Res.* 201 (Aug. 2021) 117330, <https://doi.org/10.1016/j.watres.2021.117330>.
- [40] N. Lee, G. Amy, J.-P. Croué, H. Buisson, Identification and understanding of fouling in low-pressure membrane (MF/UF) filtration by natural organic matter (NOM), *Water Res.* 38 (20) (Dec. 2004) 4511–4523, <https://doi.org/10.1016/j.watres.2004.08.013>.
- [41] Y. Wang, Y. Deng, L. Yao, X. Yang, Colloid-bound radicals formed in NOM-enhanced Fe(III)/peroxymonosulfate process accelerate the degradation of trace organic contaminants in water, *Water Res.* 248 (Jan. 2024) 120880, <https://doi.org/10.1016/j.watres.2023.120880>.
- [42] S. Zhao, et al., Engineering antifouling reverse osmosis membranes: a review, *Desalination* 499 (Feb. 2021) 114857, <https://doi.org/10.1016/j.desal.2020.114857>.
- [43] K. Kimura, N. Ando, Maximizing biopolymer removal by coagulation for mitigation of fouling in the following membrane process, *Sep. Purif. Technol.* 163 (May 2016) 8–14, <https://doi.org/10.1016/j.seppur.2016.02.013>.
- [44] X. Zheng, M.T. Khan, X. Cao, J.-P. Croué, Importance of origin and characteristics of biopolymers in reversible and irreversible fouling of ultrafiltration membranes, *Sci. Total Environ.* 784 (Aug. 2021) 147157, <https://doi.org/10.1016/j.scitotenv.2021.147157>.

- [45] Z. Su, et al., Discovery of welcome biopolymers in surface water: improvements in drinking water production, *Environ. Sci. Technol.* 55 (3) (Feb. 2021) 2076–2086, <https://doi.org/10.1021/acs.est.0c05758>.
- [46] W. Chen, C. Qian, W.-L. Hong, J.-X. Cheng, H.-Q. Yu, Evolution of membrane fouling revealed by label-free vibrational spectroscopic imaging, *Environ. Sci. Technol.* 51 (17) (Sep. 2017) 9580–9587, <https://doi.org/10.1021/acs.est.7b02775>.
- [47] L. Tian, et al., Insights into the properties of surface waters and their associated nanofiltration membrane fouling: the importance of biopolymers and high molecular weight humics, *Chem. Eng. J.* 451 (Jan. 2023) 138682, <https://doi.org/10.1016/j.cej.2022.138682>.
- [48] L. Wang, W. Zhang, H. Chu, B. Dong, Forward osmosis filtration for removal of organic foulants: effects of combined tannic and alginic acids, *Water Res.* 91 (Mar. 2016) 251–263, <https://doi.org/10.1016/j.watres.2016.01.018>.
- [49] Y.-F. Guan, C. Qian, W. Chen, B.-C. Huang, Y.-J. Wang, H.-Q. Yu, Interaction between humic acid and protein in membrane fouling process: a spectroscopic insight, *Water Res.* 145 (Nov. 2018) 146–152, <https://doi.org/10.1016/j.watres.2018.08.019>.
- [50] A.S. Al-Amoudi, Factors affecting natural organic matter (NOM) and scaling fouling in NF membranes: a review, *Desalination* 259 (1–3) (Sep. 2010) 1–10, <https://doi.org/10.1016/j.desal.2010.04.003>.
- [51] W. Liu, et al., Effects of UV/Fe(II)/sulfite pre-treatment on NOM-enhanced Ca²⁺ scaling during nanofiltration treatment: fouling mitigation, mechanisms, and correlation analysis of membrane resistance, *Water Res.* 223 (Sep. 2022) 119025, <https://doi.org/10.1016/j.watres.2022.119025>.
- [52] H.-B. Yu, et al., Nanofiltration membrane fouling and control caused by residual aluminum in feed water, *Water Air Soil Pollut.* 233 (1) (Jan. 2022) 1, <https://doi.org/10.1007/s11270-021-05470-z>.
- [53] W. Stumm, Aquatic colloids as chemical reactants: surface structure and reactivity, in: *Colloids in the Aquatic Environment*, Elsevier, 1993, pp. 1–18, <https://doi.org/10.1016/B978-1-85861-038-2.50004-8>.
- [54] J. Buffle, G.G. Leppard, Characterization of aquatic colloids and macromolecules. 1. Structure and behavior of colloidal material, *Environ. Sci. Technol.* 29 (9) (Sep. 1995) 2169–2175, <https://doi.org/10.1021/es00009a004>.
- [55] K. Boussu, et al., Influence of membrane and colloid characteristics on fouling of nanofiltration membranes, *J. Membr. Sci.* 289 (1–2) (Feb. 2007) 220–230, <https://doi.org/10.1016/j.memsci.2006.12.001>.
- [56] H.-C. Flemming, Reverse osmosis membrane biofouling, *Exp. Therm. Fluid Sci.* 14 (4) (May 1997) 382–391, [https://doi.org/10.1016/S0894-1777\(96\)00140-9](https://doi.org/10.1016/S0894-1777(96)00140-9).
- [57] S. Anand, D. Singh, M. Avadhanula, S. Marka, Development and control of bacterial biofilms on dairy processing membranes, *Compr. Rev. Food Sci. Food Saf.* 13 (1) (Jan. 2014) 18–33, <https://doi.org/10.1111/1541-4337.12048>.
- [58] H.F. Ridgway, A. Kelly, C. Justice, B.H. Olson, Microbial fouling of reverse-osmosis membranes used in advanced wastewater treatment technology: Chemical, bacteriological, and ultrastructural analyses, *Appl. Environ. Microbiol.* 45 (3) (Mar. 1983) 1066–1084, <https://doi.org/10.1128/aem.45.3.1066-1084.1983>.
- [59] Y. Baek, J. Yu, S.-H. Kim, S. Lee, J. Yoon, Effect of surface properties of reverse osmosis membranes on biofouling occurrence under filtration conditions, *J. Membr. Sci.* 382 (1–2) (Oct. 2011) 91–99, <https://doi.org/10.1016/j.memsci.2011.07.049>.
- [60] M. Herzberg, M. Elimelech, Biofouling of reverse osmosis membranes: role of biofilm-enhanced osmotic pressure, *J. Membr. Sci.* 295 (1–2) (May 2007) 11–20, <https://doi.org/10.1016/j.memsci.2007.02.024>.
- [61] C.V. Manalo, M. Ohno, T. Okuda, S. Nakai, W. Nishijima, Rapid novel test for the determination of biofouling potential on reverse osmosis membranes, *Water Sci. Technol.* 73 (12) (Jun. 2016) 2978–2985, <https://doi.org/10.2166/wst.2016.159>.
- [62] H. Ivnitsky, et al., Characterization of membrane biofouling in nanofiltration processes of wastewater treatment, *Desalination* 185 (1–3) (Nov. 2005) 255–268, <https://doi.org/10.1016/j.desal.2005.03.081>.
- [63] O. Habimana, A.J.C. Semão, E. Casey, The role of cell-surface interactions in bacterial initial adhesion and consequent biofilm formation on nanofiltration/reverse osmosis membranes, *J. Membr. Sci.* 454 (Mar. 2014) 82–96, <https://doi.org/10.1016/j.memsci.2013.11.043>.
- [64] J.S. Vrouwenvelder, et al., Quantitative biofouling diagnosis in full scale nanofiltration and reverse osmosis installations, *Water Res.* 42 (19) (Dec. 2008) 4856–4868, <https://doi.org/10.1016/j.watres.2008.09.002>.
- [65] L. Mi, S. Jiang, Integrated antimicrobial and nonfouling Zwitterionic polymers, *Angew. Chem. Int. Ed.* 53 (7) (Feb. 2014) 1746–1754, <https://doi.org/10.1002/anie.201304060>.
- [66] Y.-H. Zhao, K.-H. Wee, R. Bai, A novel electrolyte-responsive membrane with tunable permeation selectivity for protein purification, *ACS Appl. Mater. Interfaces* 2 (1) (Jan. 2010) 203–211, <https://doi.org/10.1021/am900654d>.
- [67] J. Klein, Polymers in living systems: from biological lubrication to tissue engineering and biomedical devices, *Polym. Adv. Technol.* 23 (4) (Apr. 2012) 729–735, <https://doi.org/10.1002/pat.3038>.
- [68] T. Wang, X. Wang, Y. Long, G. Liu, G. Zhang, Ion-Specific conformational behavior of polyzwitterionic brushes: exploiting it for protein adsorption/desorption control, *Langmuir* 29 (22) (Jun. 2013) 6588–6596, <https://doi.org/10.1021/la401069y>.
- [69] S. Xiao, et al., Salt-responsive zwitterionic polymer brushes with anti-polyelectrolyte property, *Curr. Opin. Chem. Eng.* 19 (Mar. 2018) 86–93, <https://doi.org/10.1016/j.coche.2017.12.008>.
- [70] J. Yang, et al., Salt-responsive zwitterionic polymer brushes with tunable friction and antifouling properties, *Langmuir* 31 (33) (Aug. 2015) 9125–9133, <https://doi.org/10.1021/acs.langmuir.5b02119>.
- [71] T. Wang, X. Wang, Y. Long, G. Liu, G. Zhang, Ion-specific conformational behavior of polyzwitterionic brushes: exploiting it for protein adsorption/desorption control, *Langmuir* 29 (22) (Jun. 2013) 6588–6596, <https://doi.org/10.1021/la401069y>.
- [72] H.J. Kwon, et al., Zwitterionic sulfobetaine polymer-immobilized surface by simple tyrosinase-mediated grafting for enhanced antifouling property, *Acta Biomater.* 61 (Oct. 2017) 169–179, <https://doi.org/10.1016/j.actbio.2017.08.007>.
- [73] M. Hirasawa, C. Tsutsumi-Arai, K. Takakusaki, T. Oya, K. Fukei, N. Wakabayashi, Superhydrophilic co-polymer coatings on denture surfaces reduce *Candida albicans* adhesion—An in vitro study, *Arch. Oral Biol.* 87 (Mar. 2018) 143–150, <https://doi.org/10.1016/j.archoralbio.2017.12.024>.
- [74] T. Huang, H. Liu, P. Liu, P. Li, L. Li, J. Shen, Zwitterionic copolymers bearing phosphonate or phosphonic motifs as novel metal-anchorable anti-fouling coatings, *J. Mater. Chem. B* 5 (27) (2017) 5380–5389, <https://doi.org/10.1039/C7TB01017F>.
- [75] Y.-H. Zhao, K.-H. Wee, R. Bai, Highly hydrophilic and low-protein-fouling polypropylene membrane prepared by surface modification with sulfobetaine-based zwitterionic polymer through a combined surface polymerization method, *J. Membr. Sci.* 362 (1–2) (Oct. 2010) 326–333, <https://doi.org/10.1016/j.memsci.2010.06.037>.
- [76] C. Leng, S. Sun, K. Zhang, S. Jiang, Z. Chen, Molecular level studies on interfacial hydration of zwitterionic and other antifouling polymers in situ, *Acta Biomater.* 40 (Aug. 2016) 6–15, <https://doi.org/10.1016/j.actbio.2016.02.030>.
- [77] C. Leng, et al., In situ probing of the surface hydration of zwitterionic polymer brushes: structural and environmental effects, *J. Phys. Chem. C* 118 (29) (Jul. 2014) 15840–15845, <https://doi.org/10.1021/jp504293r>.
- [78] C. Leng, et al., Probing the surface hydration of nonfouling zwitterionic and PEG materials in contact with proteins, *ACS Appl. Mater. Interfaces* 7 (30) (Aug. 2015) 16881–16888, <https://doi.org/10.1021/acsami.5b05627>.
- [79] C. Leng, H.-C. Hung, O.A. Sieggreen, Y. Li, S. Jiang, Z. Chen, Probing the surface hydration of nonfouling zwitterionic and poly(ethylene glycol) materials with isotopic dilution spectroscopy, *J. Phys. Chem. C* 119 (16) (Apr. 2015) 8775–8780, <https://doi.org/10.1021/acs.jpcc.5b01649>.
- [80] X. Han, C. Leng, Q. Shao, S. Jiang, Z. Chen, Absolute orientations of water molecules at Zwitterionic Polymer interfaces and interfacial dynamics after salt exposure, *Langmuir* 35 (5) (Feb. 2019) 1327–1334, <https://doi.org/10.1021/acs.langmuir.8b01515>.
- [81] H. Huang, et al., Strong surface hydration and salt resistant mechanism of a new nonfouling zwitterionic polymer based on protein stabilizer TMAO, *J. Am. Chem. Soc.* 143 (40) (Oct. 2021) 16786–16795, <https://doi.org/10.1021/jacs.1c08280>.
- [82] A.B. Lowe, C.L. McCormick, Synthesis and solution properties of Zwitterionic polymers, *Chem. Rev.* 102 (11) (Nov. 2002) 4177–4190, <https://doi.org/10.1021/cr020371t>.
- [83] A. Clark, et al., Glass-forming ability of polyzwitterions, *Macromolecules* 54 (21) (Nov. 2021) 10126–10134, <https://doi.org/10.1021/acs.macromol.1c01393>.
- [84] Y. Amrenova, A. Zhengis, A. Yergesheva, M. Abutalip, N. Nuraje, Preparation of Zwitterionic sulfobetaines and study of their thermal properties and nanostructured self-assembling features, *Nanomaterials* 15 (1) (Jan. 2025) 58, <https://doi.org/10.3390/nano15010058>.
- [85] K. Matyjaszewski, J. Xia, Atom transfer radical polymerization, *Chem. Rev.* 101 (9) (Sep. 2001) 2921–2990, <https://doi.org/10.1021/cr940534g>.
- [86] Y.-C. Chiang, Y. Chang, A. Higuchi, W.-Y. Chen, R.-C. Ruaan, Sulfobetaine-grafted poly(vinylidene fluoride) ultrafiltration membranes exhibit excellent antifouling property, *J. Membr. Sci.* 339 (1–2) (Sep. 2009) 151–159, <https://doi.org/10.1016/j.memsci.2009.04.044>.
- [87] S.K. Choi, H.A. Son, H.T. Kim, J.W. Kim, Nanofluid enhanced oil recovery using hydrophobically associative zwitterionic polymer-coated silica nanoparticles, *Energy Fuel* 31 (8) (Aug. 2017) 7777–7782, <https://doi.org/10.1021/acs.energyfuels.7b00455>.
- [88] T. Wang, X. Wang, Y. Long, G. Liu, G. Zhang, Ion-specific conformational behavior of polyzwitterionic brushes: exploiting it for protein adsorption/desorption control, *Langmuir* 29 (22) (Jun. 2013) 6588–6596, <https://doi.org/10.1021/la401069y>.
- [89] W.K. Cho, B. Kong, I.S. Choi, Highly efficient non-biofouling coating of zwitterionic polymers: poly((3-(methacryloylamino)propyl)-dimethyl(3-sulfopropyl)ammonium hydroxide), *Langmuir* 23 (10) (May 2007) 5678–5682, <https://doi.org/10.1021/la063737w>.
- [90] W.-W. Yue, H.-J. Li, T. Xiang, H. Qin, S.-D. Sun, C.-S. Zhao, Grafting of zwitterion from polysulfone membrane via surface-initiated ATRP with enhanced antifouling property and biocompatibility, *J. Membr. Sci.* 446 (Nov. 2013) 79–91, <https://doi.org/10.1016/j.memsci.2013.06.029>.
- [91] D.M. Davenport, J. Lee, M. Elimelech, Efficacy of antifouling modification of ultrafiltration membranes by grafting zwitterionic polymer brushes, *Sep. Purif. Technol.* 189 (Dec. 2017) 389–398, <https://doi.org/10.1016/j.seppur.2017.08.034>.
- [92] Y.-S. Guo, Y.-F. Mi, Y.-L. Ji, Q.-F. An, C.-J. Gao, One-step surface grafting method for preparing zwitterionic nanofiltration membrane via in situ introduction of initiator in interfacial polymerization, *ACS Appl. Polym. Mater.* 1 (5) (May 2019) 1022–1033, <https://doi.org/10.1021/acscpm.9b00059>.
- [93] X. Luo, M. Xu, C. Freeman, T. James, J.J. Davis, Ultrasensitive label free electrical detection of insulin in neat blood serum, *Anal. Chem.* 85 (8) (Apr. 2013) 4129–4134, <https://doi.org/10.1021/ac4002657>.

- [94] Q. Zhou, X.-P. Lei, J.-H. Li, B.-F. Yan, Q.-Q. Zhang, Antifouling, adsorption and reversible flux properties of zwitterionic grafted PVDF membrane prepared via physisorbed free radical polymerization, *Desalination* 337 (Mar. 2014) 6–15, <https://doi.org/10.1016/j.desal.2014.01.006>.
- [95] N. Shakhkaramipour, et al., Facile grafting of zwitterions onto the membrane surface to enhance antifouling properties for wastewater reuse, *Ind. Eng. Chem. Res.* 56 (32) (Aug. 2017) 9202–9212, <https://doi.org/10.1021/acs.iecr.7b02378>.
- [96] N. Shakhkaramipour, C.K. Lai, S.R. Venna, H. Sun, C. Cheng, H. Lin, Membrane surface modification using thiol-containing zwitterionic polymers via bioadhesive polydopamine, *Ind. Eng. Chem. Res.* 57 (6) (Feb. 2018) 2336–2345, <https://doi.org/10.1021/acs.iecr.7b05025>.
- [97] N. Shakhkaramipour, A. Jafari, T. Tran, C.M. Stafford, C. Cheng, H. Lin, Maximizing the grafting of zwitterions onto the surface of ultrafiltration membranes to improve antifouling properties, *J. Membr. Sci.* 601 (Mar. 2020) 117909, <https://doi.org/10.1016/j.memsci.2020.117909>.
- [98] S. Mohammad Nejad, et al., Loose nanofiltration membranes functionalized with in situ-synthesized metal organic framework for water treatment, *Mater. Today Chem.* 24 (Jun. 2022) 100909, <https://doi.org/10.1016/j.mtchem.2022.100909>.
- [99] A. Zhengis, et al., Structural studies and applications of sulfobetaine-based polybetaines at interfaces, *Eur. J. Chem.* (Feb. 2024), <https://doi.org/10.31489/2959-0663/1-24-3>.
- [100] M.-Z. Li, et al., Grafting zwitterionic brush on the surface of PVDF membrane using physisorbed free radical grafting technique, *J. Membr. Sci.* 405 (406) (Jul. 2012) 141–148, <https://doi.org/10.1016/j.memsci.2012.02.062>.
- [101] X. Zhang, et al., In situ chemical modification with Zwitterionic copolymers of nanofiltration membranes: cure for the trade-off between filtration and antifouling performance, *ACS Appl. Mater. Interfaces* 14 (25) (Jun. 2022) 28842–28853, <https://doi.org/10.1021/acami.2c05311>.
- [102] T. Xiang, C.-D. Luo, R. Wang, Z.-Y. Han, S.-D. Sun, C.-S. Zhao, Ionic-strength-sensitive polyethersulfone membrane with improved anti-fouling property modified by zwitterionic polymer via in situ cross-linked polymerization, *J. Membr. Sci.* 476 (Feb. 2015) 234–242, <https://doi.org/10.1016/j.memsci.2014.11.045>.
- [103] T. Ma, et al., Fabrication of electro-neutral nanofiltration membranes at neutral pH with antifouling surface via interfacial polymerization from a novel zwitterionic amine monomer, *J. Membr. Sci.* 503 (Apr. 2016) 101–109, <https://doi.org/10.1016/j.memsci.2015.12.038>.
- [104] J. Zhu, et al., Surface zwitterionic functionalized graphene oxide for a novel loose nanofiltration membrane, *J. Mater. Chem. A Mater.* 4 (5) (2016) 1980–1990, <https://doi.org/10.1039/C5TA08024J>.
- [105] L. Guo, Y. Zhu, L. Hou, D. Dong, A. Wang, Y. Yang, Enhancing the desalination performance of polyamide nanofiltration membranes via in-situ incorporation of zwitterionic nanohydrogel, *Desalination* 549 (Mar. 2023) 116355, <https://doi.org/10.1016/j.desal.2022.116355>.
- [106] D. Xia, H. Pan, C. Yang, Z. Chen, M. Liao, Q. Lin, One-step separation of oil-water emulsion with heavy metal ions by PVDF membrane modified with zwitterionic coating, *Colloids Surf. A Physicochem. Eng. Asp.* 701 (Nov. 2024) 134855, <https://doi.org/10.1016/j.colsurfa.2024.134855>.
- [107] X. Jia, et al., Facile plasma grafting of zwitterions onto nanofibrous membrane surface for improved antifouling properties and filtration performance, *Colloids Surf. A Physicochem. Eng. Asp.* 651 (Oct. 2022) 129752, <https://doi.org/10.1016/j.colsurfa.2022.129752>.
- [108] S.J. Lounder, A. Asatekin, Zwitterionic ion-selective membranes with tunable subnanometer pores and excellent fouling resistance, *Chem. Mater.* 33 (12) (Jun. 2021) 4408–4416, <https://doi.org/10.1021/acs.chemmater.1c00374>.
- [109] A. Asatekin, E.A. Olivetti, A.M. Mayes, Fouling resistant, high flux nanofiltration membranes from polyacrylonitrile-graft-poly(ethylene oxide), *J. Membr. Sci.* 332 (1–2) (Apr. 2009) 6–12, <https://doi.org/10.1016/j.memsci.2009.01.029>.
- [110] A. Asatekin, C. Vannucci, Self-assembled polymer nanostructures for liquid filtration membranes: a review, *Nanosci. Nanotechnol. Lett.* 7 (1) (Jan. 2015) 21–32, <https://doi.org/10.1166/nnl.2015.1930>.
- [111] A. Asatekin, A. Menniti, S. Kang, M. Elimelech, E. Morgenroth, A.M. Mayes, Antifouling nanofiltration membranes for membrane bioreactors from self-assembling graft copolymers, *J. Membr. Sci.* 285 (1–2) (Nov. 2006) 81–89, <https://doi.org/10.1016/j.memsci.2006.07.042>.
- [112] P. Bengani, Y. Kou, A. Asatekin, Zwitterionic copolymer self-assembly for fouling resistant, high flux membranes with size-based small molecule selectivity, *J. Membr. Sci.* 493 (Nov. 2015) 755–765, <https://doi.org/10.1016/j.memsci.2015.07.025>.
- [113] W. Zhang, et al., Preparation of self-healing and pH-responsive nanofiltration membranes with improved anti-fouling property for salt/dye separation, *Desalination* 586 (Oct. 2024) 117866, <https://doi.org/10.1016/j.desal.2024.117866>.
- [114] P.H.H. Duong, K. Daumann, P.-Y. Hong, M. Ulbricht, S.P. Nunes, Interfacial polymerization of zwitterionic building blocks for high-flux nanofiltration membranes, *Langmuir* 35 (5) (Feb. 2019) 1284–1293, <https://doi.org/10.1021/acs.langmuir.8b00960>.
- [115] J. Liu, Y. Ma, T. Xu, G. Shao, Preparation of zwitterionic hybrid polymer and its application for the removal of heavy metal ions from water, *J. Hazard. Mater.* 178 (1–3) (Jun. 2010) 1021–1029, <https://doi.org/10.1016/j.jhazmat.2010.02.041>.
- [116] N. Prabhakar, A.M. Isloor, R. Farnood, A. Fauzi Ismail, Fabrication and incorporation of MIL-53(Fe)-zwitterionic brushes into PVDF thin film composite membranes for enhancing heavy metal/dye rejection from aqueous body, *Sep. Purif. Technol.* 358 (Jun. 2025) 130348, <https://doi.org/10.1016/j.seppur.2024.130348>.
- [117] L. Chaabane, E. Beyou, M.H.V. Baouab, Preparation of a novel zwitterionic graphene oxide-based adsorbent to remove of heavy metal ions from water: modeling and comparative studies, *Adv. Powder Technol.* 32 (7) (Jul. 2021) 2502–2516, <https://doi.org/10.1016/j.apt.2021.05.011>.
- [118] J. Liu, Y. Ma, T. Xu, G. Shao, Preparation of zwitterionic hybrid polymer and its application for the removal of heavy metal ions from water, *J. Hazard. Mater.* 178 (1–3) (Jun. 2010) 1021–1029, <https://doi.org/10.1016/j.jhazmat.2010.02.041>.
- [119] Y.-H. Huang, M.-J. Wang, T.-S. Chung, Zwitterionic poly(sulfobetaine methacrylate-co-acrylic acid) assisted simultaneous anti-wetting and anti-fouling membranes for membrane distillation, *Desalination* 555 (Jun. 2023) 116527, <https://doi.org/10.1016/j.desal.2023.116527>.
- [120] L. Guo, Y. Zhu, L. Hou, D. Dong, A. Wang, Y. Yang, Enhancing the desalination performance of polyamide nanofiltration membranes via in-situ incorporation of zwitterionic nanohydrogel, *Desalination* 549 (Mar. 2023) 116355, <https://doi.org/10.1016/j.desal.2022.116355>.
- [121] S. Ren, G. Huang, Y. Yao, P. Zhang, Z. Zhang, Y. Wang, Integrating radical polymerization and non-solvent induced phase inversion strategy for functionalized ultrafiltration membrane fabrication, *Desalination* 573 (Mar. 2024) 117220, <https://doi.org/10.1016/j.desal.2023.117220>.
- [122] A. Hosseinzadeh, P.R. Ranjbar, A. Bozorg, pH-responsive P(AA-b-SBMA)-grafted magnetic GO high-performance ultrafiltration membrane with improved antifouling tendency and cleaning efficiency, *Desalination* 574 (Apr. 2024) 117299, <https://doi.org/10.1016/j.desal.2024.117299>.
- [123] A.O. Aguiar, H. Yi, A. Asatekin, Fouling-resistant membranes with zwitterion-containing ultra-thin hydrogel selective layers, *J. Membr. Sci.* 669 (Mar. 2023) 121253, <https://doi.org/10.1016/j.memsci.2022.121253>.
- [124] Y. Zhang, Q. Song, X. Liang, J. Wang, Y. Jiang, J. Liu, High-flux, high-selectivity loose nanofiltration membrane mixed with zwitterionic functionalized silica for dye/salt separation, *Appl. Surf. Sci.* 515 (Jun. 2020) 146005, <https://doi.org/10.1016/j.apsusc.2020.146005>.
- [125] Y.-S. Guo, et al., Construction of nonfouling nanofiltration membrane via introducing uniformly tunable zwitterionic layer, *J. Membr. Sci.* 583 (Aug. 2019) 152–162, <https://doi.org/10.1016/j.memsci.2019.04.055>.
- [126] L. Han, Y.Z. Tan, C. Xu, T. Xiao, T.A. Trinh, J.W. Chew, Zwitterionic grafting of sulfobetaine methacrylate (SBMA) on hydrophobic PVDF membranes for enhanced anti-fouling and anti-wetting in the membrane distillation of oil emulsions, *J. Membr. Sci.* 588 (Oct. 2019) 117196, <https://doi.org/10.1016/j.memsci.2019.117196>.
- [127] M.R. De Guzman, et al., Increased performance and antifouling of mixed-matrix membranes of cellulose acetate with hydrophilic nanoparticles of polydopamine-sulfobetaine methacrylate for oil-water separation, *J. Membr. Sci.* 620 (Feb. 2021) 118881, <https://doi.org/10.1016/j.memsci.2020.118881>.
- [128] J. Ding, et al., Surface modification of nanofiltration membranes with zwitterions to enhance antifouling properties during brackish water treatment: a new concept of a 'buffer layer', *J. Membr. Sci.* 637 (Nov. 2021) 119651, <https://doi.org/10.1016/j.memsci.2021.119651>.
- [129] A. Venault, R.-J. Zhou, T.A. Galeta, Y. Chang, Engineering sterilization-resistant and fouling-resistant porous membranes by the vapor-induced phase separation process using a sulfobetaine methacrylamide amphiphilic derivative, *J. Membr. Sci.* 658 (Sep. 2022) 120760, <https://doi.org/10.1016/j.memsci.2022.120760>.
- [130] X. Jia, et al., Facile plasma grafting of zwitterions onto nanofibrous membrane surface for improved antifouling properties and filtration performance, *Colloids Surf. A Physicochem. Eng. Asp.* 651 (Oct. 2022) 129752, <https://doi.org/10.1016/j.colsurfa.2022.129752>.
- [131] G. Li, et al., Improving the performance of loose nanofiltration membranes by polydopamine/zwitterionic polymer coating with hydroxyl radical activation, *Sep. Purif. Technol.* 238 (May 2020) 116412, <https://doi.org/10.1016/j.seppur.2019.116412>.
- [132] S. Mohammad Nejad, et al., Loose nanofiltration membranes functionalized with in situ-synthesized metal organic framework for water treatment, *Mater. Today Chem.* 24 (Jun. 2022) 100909, <https://doi.org/10.1016/j.mtchem.2022.100909>.
- [133] P. May, S. Laghmari, M. Ulbricht, Concentration polarization enabled reactive coating of nanofiltration membranes with Zwitterionic hydrogel, *Membranes* 11 (3) (Mar. 2021) 187, <https://doi.org/10.3390/membranes11030187>.
- [134] Y.-H. Chiao, et al., Zwitterion Co-Polymer PEI-SBMA nanofiltration membrane modified by fast second interfacial polymerization, *Polymers* 12 (2) (Jan. 2020) 269, <https://doi.org/10.3390/polym12020269>.
- [135] X. Zhang, et al., In situ chemical modification with Zwitterionic copolymers of nanofiltration membranes: cure for the trade-off between filtration and antifouling performance, *ACS Appl. Mater. Interfaces* 14 (25) (Jun. 2022) 28842–28853, <https://doi.org/10.1021/acami.2c05311>.
- [136] L. Zhao, et al., Tuning the microstructure of a zwitterion-functionalized polyethylenimine loose NF membrane for dye desalination, *Ind. Eng. Chem. Res.* 61 (5) (Feb. 2022) 2245–2256, <https://doi.org/10.1021/acs.iecr.1c04521>.
- [137] C.K.S. Haresco, M.B.M.Y. Ang, B.T. Doma, S.-H. Huang, K.-R. Lee, Performance enhancement of thin-film nanocomposite nanofiltration membranes via embedment of novel polydopamine-sulfobetaine methacrylate nanoparticles, *Sep. Purif. Technol.* 274 (Nov. 2021) 119022, <https://doi.org/10.1016/j.seppur.2021.119022>.
- [138] Z. Yang, et al., Antifouling capability of polyvinylidene fluoride ultrafiltration membranes prepared with poly sulfobetaine methacrylate-modified graphene oxide, *Colloids Surf. A Physicochem. Eng. Asp.* 686 (Apr. 2024) 133270, <https://doi.org/10.1016/j.colsurfa.2024.133270>.
- [139] X. Zhang, et al., Covalent codeposition modification of reverse osmosis membranes with Noria and zwitterionic copolymers for antifouling in reclaimed

- water production, *Desalination* 567 (Dec. 2023) 116973, <https://doi.org/10.1016/j.desal.2023.116973>.
- [140] M. Hu, et al., Facile preparation of antifouling nanofiltration membrane by grafting zwitterions for reuse of shale gas wastewater, *Sep. Purif. Technol.* 276 (Dec. 2021) 119310, <https://doi.org/10.1016/j.seppur.2021.119310>.
- [141] F. Li, C. Fang, W. Liu, L. Yang, B. Guo, S. Zhang, High recovery, energy efficient wastewater desalination, *J. Membr. Sci.* 631 (Aug. 2021) 119317, <https://doi.org/10.1016/j.memsci.2021.119317>.
- [142] C. Shen, B. Peng, Q. Meng, Hydrophilic modification of a PSU membrane with block copolymer of PS-b-SBMA, *Desalination Water Treat.* 252 (Mar. 2022) 42–49, <https://doi.org/10.5004/dwt.2022.28012>.
- [143] Y.-S. Guo, Y.-F. Mi, Y.-L. Ji, Q.-F. An, C.-J. Gao, One-step surface grafting method for preparing zwitterionic nanofiltration membrane via in situ introduction of initiator in interfacial polymerization, *ACS Appl. Polym. Mater.* 1 (5) (May 2019) 1022–1033, <https://doi.org/10.1021/acsapm.9b00059>.
- [144] C. Liu, R. Gao, X. Zhang, T. Tong, Q. He, J. Ma, Controlled architecture of multi-defense anti-fouling forward osmosis membrane for efficient shale gas wastewater treatment, *J. Membr. Sci.* 699 (Apr. 2024) 122625, <https://doi.org/10.1016/j.memsci.2024.122625>.
- [145] W. Zhang, et al., Preparation of self-healing and pH-responsive nanofiltration membranes with improved anti-fouling property for salt/dye separation, *Desalination* 586 (Oct. 2024) 117866, <https://doi.org/10.1016/j.desal.2024.117866>.
- [146] P. Salimi, A. Aroujalian, D. Iranshahi, Graft copolymerization of zwitterionic monomer on the polyethersulfone membrane surface by corona air plasma for separation of oily wastewater, *Sep. Purif. Technol.* 258 (Mar. 2021) 117939, <https://doi.org/10.1016/j.seppur.2020.117939>.
- [147] C.-C. Yeh, et al., Forward osmosis zwitterionic membranes for platelet concentration – evaluation of the feasibility of the concept, *Sep. Purif. Technol.* 354 (Feb. 2025) 129013, <https://doi.org/10.1016/j.seppur.2024.129013>.
- [148] A. Venault, et al., Surface zwitterionization of PVDF VIPS membranes for oil and water separation, *J. Membr. Sci.* 563 (Oct. 2018) 54–64, <https://doi.org/10.1016/j.memsci.2018.05.049>.
- [149] G.V. Dizon, A. Venault, Direct in-situ modification of PVDF membranes with a zwitterionic copolymer to form bi-continuous and fouling resistant membranes, *J. Membr. Sci.* 550 (Mar. 2018) 45–58, <https://doi.org/10.1016/j.memsci.2017.12.065>.
- [150] U. Hirsch, M. Ruehl, N. Teuscher, A. Heilmann, Antifouling coatings via plasma polymerization and atom transfer radical polymerization on thin film composite membranes for reverse osmosis, *Appl. Surf. Sci.* 436 (Apr. 2018) 207–216, <https://doi.org/10.1016/j.apsusc.2017.12.038>.
- [151] P.H.H. Duong, K. Daumann, P.-Y. Hong, M. Ulbricht, S.P. Nunes, Interfacial polymerization of zwitterionic building blocks for high-flux nanofiltration membranes, *Langmuir* 35 (5) (Feb. 2019) 1284–1293, <https://doi.org/10.1021/acs.langmuir.8b00960>.