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Review

Comprehensive review of nanofiltration membranes for efficient resource recovery from textile wastewater

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ABSTRACT

With the advancement of sustainable development goals, the potential for resource recovery from textile wastewater streams, such as the recovery of acids, alkalis, salts, dyes, and water, has become a prominent research topic in both industrial and environmental fields. Nanofiltration (NF) membranes utilize mechanisms such as size exclusion and charge repulsion to effectively recover dyes, salts (e.g., NaCl, Na_2SO_4), and heavy metals, which have shown exceptional effectiveness, making them a promising technology for resource recovery in textile wastewater treatment. This review offers a comprehensive analysis of the potential applications of NF membranes for this purpose. It begins by examining the characteristics of wastewater quality and treatment requirements, emphasizing the essential role of NF membranes in resource recovery. A review of the overall process flow diagram for textile wastewater treatment provides a broad understanding of designing NF membranes and selecting appropriate upstream and downstream processes. The review then explores various types of NF membranes suited to specific recovery applications. Loose nanofiltration membranes are particularly suitable for dye recovery, while dense NF membranes excel at the selective separation of NaCl and Na_2SO_4 and heavy metal ion recovery. Additionally, the integration of NF membranes with other technologies is analyzed, demonstrating how these combined approaches can enhance recovery efficiency and broaden the range of resources that can be recovered. This review also summarizes different fabrication methods for NF membranes, focusing on how these modifications regulate membrane structure to improve resource recovery performance from textile wastewater. Finally, future research directions are proposed. These efforts aim to highlight the broader application potential of NF membranes in textile wastewater resource recovery.

1. Introduction

Wastewater from the printing and dyeing industries constitute a significant portion of textile wastewater. Specifically, the processing of a ton of textiles can reach a water consumption as high as 100 to 200 tons of which 80 to 90 % is discharged as wastewater [1,2]. This wastewater primarily originates from pretreatment processes (such as desizing, scouring, bleaching, and mercerizing) and the dyeing and printing stages. These waste streams contain dyes, auxiliaries, refractory organic matter, inorganic salts, and heavy metals (see Fig. 1) [3]. This complex composition renders the wastewater highly viscous, intensely colored, and poorly biodegradable, posing severe threats to ecosystems and human health [4]. However, the abundant resources, including dyes, present in the wastewater offer significant recovery potential, particularly to meet the growing market demand, as the dye market is expected to grow at a compound annual growth rate of 5.3% [5,6]. Moreover, recovering heavy metals and salts (such as Na_2SO_4 and NaCl) from wastewater can alleviate resource shortages and reduce environmental burdens, thereby enhancing economic benefits [7,8]. To address the challenges of treating printing and dyeing wastewater, it is imperative to adopt efficient pretreatment and advanced treatment technologies (see Table 1) that simultaneously achieve pollution control and fully harness the resource utilization potential of these waste streams.

The primary objectives of the pretreatment of printing and dyeing

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wastewater streams are to remove large particulate matter, adjust pH levels, and reduce color, chemical oxygen demand (COD), and biochemical oxygen demand (BOD). Advanced treatment methods aim to further remove dissolved pollutants to ensure compliance with discharge standards [8]. Advanced treatment methods are diverse and include physicochemical techniques (such as adsorption, and membrane separation) [9–11], chemical methods (such as chemical precipitation, and electrochemical oxidation) [12–14], biological methods (such as biofilm, and activated sludge processes) [15], and thermal techniques (such as evaporation, and crystallization) [16]. Each advanced treatment technique has its advantages and limitations. For instance, adsorption is highly effective in removing organic pollutants from wastewater, but adsorbents tend to saturate quickly, requiring frequent replacement or regeneration, which increases operating costs and lacks the capabilities for effective pollutant recovery [17,18]. Chemical precipitation is highly effective at removing metal ions but has limited efficacy for the removal of organic pollutants. Furthermore, this method cannot achieve efficient recovery of resources [19]. Electrochemical oxidation can effectively degrade certain organic pollutants, but its high energy consumption and electrode wear result in elevated operational costs, with limited potential for resource recovery [19,20]. Biological treatment methods, while cost-effective and easy to operate, are sensitive to variations in pH, temperature, and inhibitory substances. Furthermore, they exhibit low removal rates between 20 and 50% for refractory dyes, such as azo, triphenylmethane, and anthraquinone dyes [21,22]. In comparison, membrane technology stands out as a separation technology due to its simplicity, adaptability, consistent treatment efficiency across various pollutant types and concentrations, and its ability to avoid secondary pollution. Additionally, membrane technology has excellent resource recovery potential, making it an ideal choice for the advanced treatment of textile wastewater [3].

Nanofiltration (NF) membranes, with their charge repulsion and size sieving characteristics, have shown significant potential in resource recovery from textile wastewater. Dense NF membranes, with a molecular weight cutoff (MWCO) below 500 Da, are suitable for the separation of multivalent salts from monovalent salts and the recovery of metal ions [23,24]. In contrast, loose nanofiltration (LNF) membranes, with larger pore sizes (MWCO higher than 500 Da), offer higher fluxes at lower pressures and are particularly advantageous for separating dye/salt mixtures, making them uniquely suited for dye recovery [25,26]. The research related to LNF membranes has been systematically summarized in several reviews. For instance, Guo et al. [27] reviewed the applications of LNF membranes in the purification of oligosaccharides, and the separation of polyphenols, pigments, and dye/salt. Feng et al. [28] investigated the use of LNF membranes for dye/salt separations and compared the separation performance with candidate materials such as nanomaterials, two-dimensional materials, and ionic liquids. Jin et al. [29] summarized the applications of LNF membranes in dye/salt separations, exploring their separation mechanisms, membrane preparation methods, and antifouling strategies. These studies emphasize that dye wastewater represents both an environmental challenge and a valuable resource with significant recovery potential. Notably, existing reviews generally focus on the single application of LNF membranes for dye/salt separations, while there is only limited research providing a systematic overview of dense NF membranes and their potential for resource recovery from textile wastewater, although dense NF membranes perform

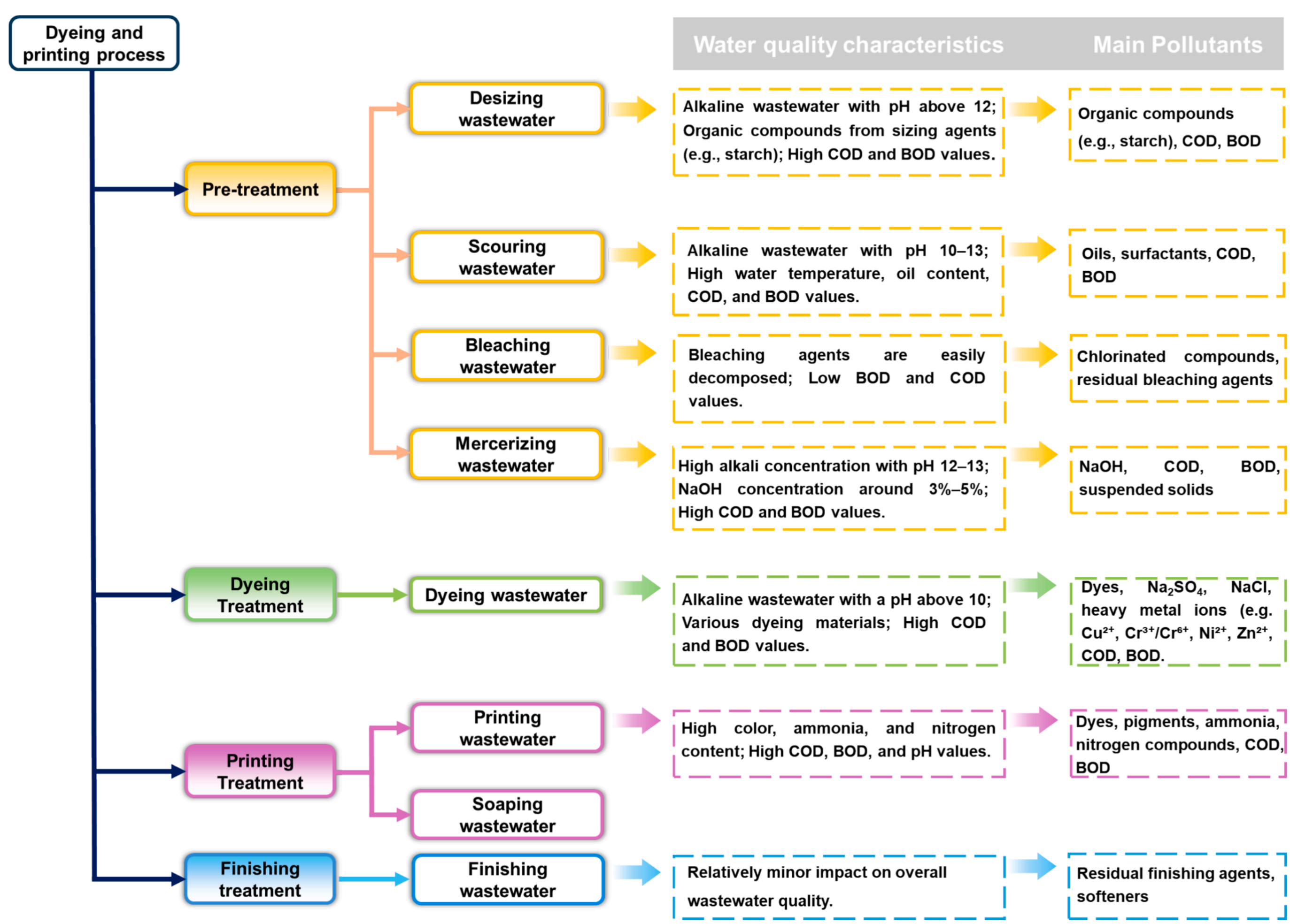

Fig. 1. Water quality characteristics and main pollutants in textile processing wastewater.

Table 1
Overview of pretreatment and advanced treatment technologies [2,8,30,31].

Category	Treatment technology	Function/advantages and disadvantages
Pre-treatment	**Physical methods**	Remove large particles from wastewater, reduce color and suspended solids, and improve the biodegradability of the wastewater.
	Chemical methods	Use agents such as coagulants and flocculants to remove pollutants (such as color, COD, and some dissolved substances), adjust pH, and precipitate heavy metals.
	Biological methods	Employ microorganisms to biodegrade organic substances, reducing the COD of wastewater.
Advanced treatment	**Adsorption**	**Advantages:** High adsorption efficiency and adaptability to various pollutants; simple operation capable of removing multiple pollutants. **Disadvantages:** High cost due to complex adsorbent regeneration; limited adsorption capacity requiring regular replacement of adsorbents.
	Membrane separation	**Advantages:** High treatment efficiency and suitability for various pollutants; no secondary pollution. **Disadvantages:** Membrane fouling is a major issue, requiring regular cleaning or replacement, which increases costs; high initial investment, and membrane material costs.
	Electrochemical oxidation	**Advantages:** Treat both organic and inorganic pollutants simultaneously; environmentally friendly, no secondary pollution. **Disadvantages:** High electrode material costs and difficult maintenance; treatment efficiency is greatly affected by current density and electrode material.
	Chemical precipitation	**Advantages:** Fast reaction rate and simple operation; suitable for large-scale industrial applications. **Disadvantages:** Require chemical agents, increasing operating costs; produce a large amount of sludge that needs further treatment.
	Biofilm technology	**Advantages:** Efficient in removing organic pollutants and reducing secondary pollution; stable operation with simple maintenance. **Disadvantages:** Sensitive to environmental changes, with effectiveness greatly affected by factors such as temperature and pH; longer reaction time and lower treatment efficiency.
	Activated sludge process	**Advantages:** Mature technology with good treatment effect; treat a wide range of organic pollutants. **Disadvantages:** Poor removal of recalcitrant organic substances (such as dyes); requires periodic sludge removal, increasing treatment costs.
	Evaporation crystallization	**Advantages:** Recover usable salts, achieving resource recycling. **Disadvantages:** Require higher salt concentrations; and high energy consumption, especially during the evaporation process.

well in selective separation of NaCl/Na_2SO_4, and heavy metals recovery. Moreover, there is a gap in reviews exploring pilot studies on integrating NF membranes (including both LNF and dense NF membranes) with other treatment technologies for the complete process of resource recovery from textile wastewater.

This review provides a comprehensive understanding of the textile wastewater treatment process and valuable insights for designing NF membranes or aligning them with suitable upstream and downstream processes. First, this review introduces the characteristics of printing and dyeing wastewater and the potential of NF membranes in resource recovery. Next, the role of NF membranes in textile wastewater resource recovery systems is presented through a clear depiction of the treatment flowchart. Then, the application of both LNF and dense NF membranes in resource recovery (of salts, dyes, heavy metals, and water) is discussed and the synergistic effects of integrating NF membranes with various technologies for resource recovery are examined. This section highlights the key performance requirements for NF membranes to achieve efficient resource recovery and guides membrane fabrication methods to meet these needs. Furthermore, different membrane fabrication methods are explored, including substrate modification, interfacial polymerization (IP) methods, surface modification, and post-treatment techniques, to precisely control membrane structure for effective separation and resource recovery. Finally, future research directions are proposed within the field of NF membrane technology to achieve more efficient resource recovery.

2. Role of NF membranes in resource recovery of textile wastewater

Textile wastewater treatment is typically divided into three main stages: primary treatment, secondary treatment, and tertiary treatment (as shown in Fig. 2**a**) [32]. In the primary treatment stage, large particulate matter and solids in the wastewater are removed primarily through physical methods, such as grilles, screens, and sedimentation tanks, to reduce the load in subsequent treatment stages [28,33]. Secondary treatment primarily uses biological processes to significantly reduce organic pollutants in wastewater, such as BOD and COD. Biological treatment methods include activated sludge, biofilm, and anaerobic–aerobic combined processes, with appropriate combinations chosen based on the characteristics of the wastewater [34]. Tertiary treatment aims to further remove dissolved pollutants and salts to meet the required effluent standards. However, tertiary treatment often requires the integration of pretreatment methods such as membrane separation technologies (ultrafiltration (UF) or microfiltration (MF)) to prevent subsequent membrane fouling due to the adsorption of organic pollutants or microbial contamination. NF membrane and reverse osmosis (RO) serve distinct roles in advanced wastewater treatment. NF excels in solute separation, such as salts, dyes, heavy metals, and water reuse, making it pivotal for resource recovery. Conversely, RO primarily functions to concentrate solutions [35].

Assuming that the effluent contains dyes, NaCl, Na_2SO_4, and heavy metals after ultrafiltration, a deep resource recovery process integrating LNF membranes, NF membranes, and RO membranes is shown in Fig. 2**b**. First, the wastewater passes through an LNF membrane, where dyes are recovered and mixed salts (NaCl and Na_2SO_4) and heavy metals can pass through. The permeate then flows to an NF membrane, where the heavy metals are recovered and the mixed salts can permeate. The permeate containing mixed salts proceeds to the next NF membrane, which selectively separates NaCl and Na_2SO_4. Finally, the NaCl permeate is sent to an RO membrane, where clean water is recovered for reuse, and concentrated NaCl is recovered for industrial applications. This integrated process efficiently recovers valuable resources such as dyes, heavy metals, and salts, while promoting water conservation in the textile industry.

3. Applications of NF membranes in resource recovery from dyeing wastewater

NF membranes (including LNF and dense NF membranes), due to their size exclusion, electrostatic repulsion, and dielectric effects, play a crucial role in resource recovery from textile wastewater, particularly in

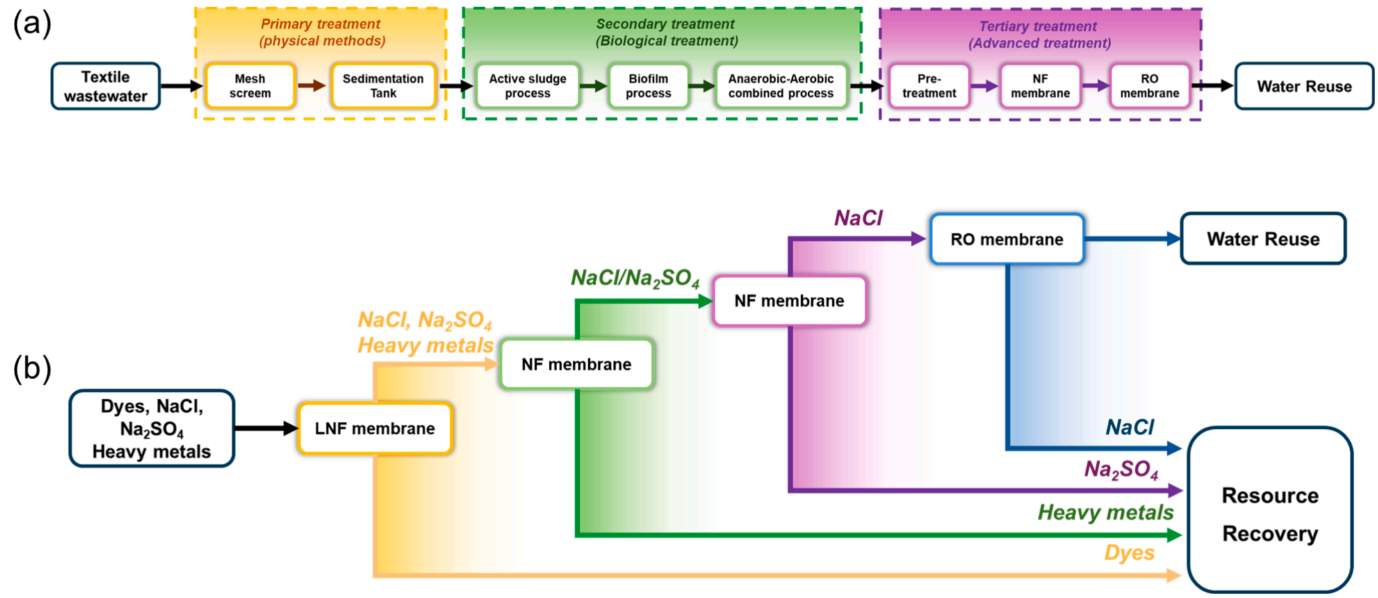

Fig. 2. Flowchart for (a) the typical treatment train of textile wastewater; and (b) an integrated, membrane-based treatment train for deep resource recovery from textile wastewater.

dye recovery, $NaCl/Na_2SO_4$ separation, heavy metals recovery, and integrated treatment processes (Fig. 3) [36]. Therefore, systematically studying and gaining an in-depth understanding of the application of NF membranes in these areas is of great significance, providing valuable guidance for optimizing resource recovery and water reuse technologies.

3.1. *Dye recovery*

The fixation efficiency of many dyes on fibers (*i.e.*, dye uptake rate) is relatively low, typically ranging from 50 to 70%. Dyes that are not adsorbed or fixed on fibers are directly discharged into the wastewater. Additionally, dye molecules possess complex aromatic structures, which

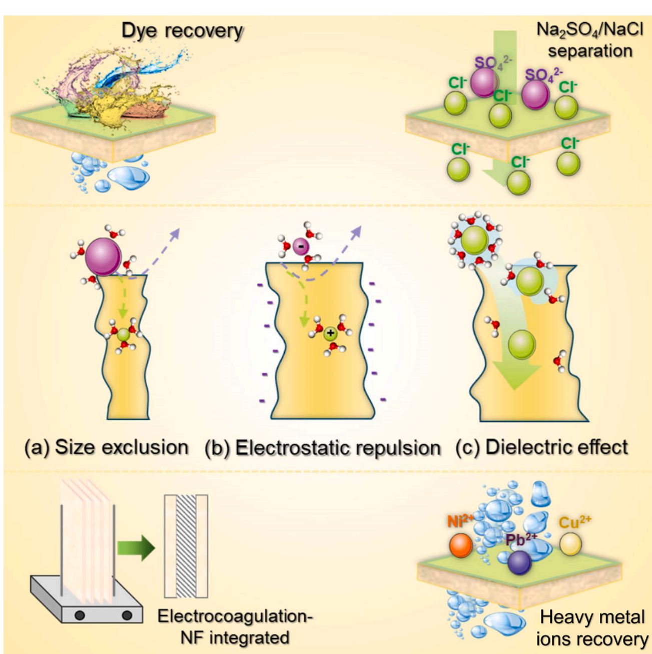

Fig. 3. Applications of NF membranes and their separation mechanisms: (a) size exclusion, (b) electrostatic repulsion, and (c) dielectric effect for resource recovery from textile wastewater.

confer high stability in water, allowing them to persist even under harsh conditions, such as high temperatures, oxidation, and biodegradation. This leads to significant accumulation and high residuals of dyes in wastewater [8]. The extensive discharge of dyes in wastewater can result in resource wastage and pose severe threats to aquatic ecosystems and the environment [26,32]. Transforming dyes in wastewater into reusable resources can reduce environmental pollution, lower the cost of dye production, and decrease dependence on new raw materials. Consequently, developing efficient and cost-effective dye recovery technologies, particularly those based on membrane separation, has become a focal point in the treatment of dye wastewater.

The separation mechanism of NF membranes is primarily based on size exclusion and electrostatic repulsion (Donnan effect). The size exclusion effect relies on the membrane pore size to screen dye molecules, while the electrostatic repulsion effect depends on the interactions between the membrane surface charge and the dye's charge [25]. For example, Yang et al. [37] developed negatively charged NF membranes using 4,4′-diaminodiphenylmethane and trimesoyl chloride (TMC), achieving 99% rejection of negatively charged dyes such as Congo Red (CR) and over 95% removal of Evans Blue. In contrast, positively charged dyes interact with negatively charged membranes through electrostatic attraction, forming a dense fouling layer that drastically reduces water flux and causes severe membrane fouling [38]. Dual-charged membranes, which combine positively and negatively charged layers, can address this issue by enhancing the rejection of both cationic and anionic dyes while mitigating membrane fouling. For instance, Chen et al. [39] fabricated a dually charged membrane by assembling ultrathin, positively charged polyethylenimine (PEI), and negatively charged poly(acrylic acid) nanofilms onto a commercial NF membrane (VM101) using dopamine as a bio-glue. The prepared membrane demonstrated high removal efficiencies for both cationic and anionic dyes, including CR (100%), Victoria Blue B (99.93%), Brilliant Green (99.91%), Basic Red 2 (99.82%), and Neutral Red (99.03%).

While high dye rejection is undoubtedly important, aligning with the goal of zero discharge, utilizing the characteristics of NF membranes to separate dyes from salts for resource recovery has become a prominent research focus. Therefore, the development of LNF membranes with high water permeability, excellent dye rejection, and precise salt permeation control has become a major focus, as summarized in Table 2. It is well known that dyes exist in aggregated forms in solution due to

Table 2
Overview of studies on the performance of LNF membranes for dye/salt separation.

Membranes	Fabrication method	MWCO (Da)	Separation performance				Ref
			Water permeance (L m^{-2}h^{-1} bar^{-1})	Dye rejection (%)	Salt rejection (%)	Mechanisms	
TAPB-TMC	Substrate modification/IP	8000	185.8	Congo Red (99.8%) Direct Red 23 (99.1%) Reactive Black 5 (98.1%)	Na_2SO_4 (22.4%) NaCl (12.4%)	Donnan effect / Size exclusion	[45]
QE-0.2/TMC-0.2	IP	5839	198.7	Congo Red (99.2%) Direct Red 23 (98.8%)	Na_2SO_4 (5.1%) NaCl (1.6%)	Donnan effect / Size exclusion	[36]
PAR	IP	7941	210	Direct Red 80 (99.5%) Direct Red 23 (99.3%) Congo Red (99.5%)	NaCl (10%)	Donnan effect / Size exclusion	[44]
PIP-COOH/TMC	IP	8205	59.8	Reactive Red (99.3%)	NaCl (5.4%)		[46]
EGCG-TMC	IP/heat treatment	6810	41.7	Congo Red (98.5%)	NaCl (7.4%)	Size exclusion/ Donnan effect	[40]
				Methylene Blue (93.4%) Evans Blue (94.8%)	Na_2SO_4 (37.3%)		
S-C-$T_{0.5}$	Surface crosslinking	3198	51.6	Crystal Violet (99.8%) Congo Red (98.9%) Tartrazine (93.1%)	Na_2SO_4 (10.5%) NaCl (7.3%)	Donnan effect / Size exclusion	[42]
PEI-gCNN/GA	Surface crosslinking	20,000	162.7	Congo Red (99.69%) Alcian Blue (99.47%) Methylene Blue (98.80%)	NaCl (6.43%)		[47]
Hexane-PSf	Solvent treatment	11,000	52	Congo Red (99.87%) Direct Red 23 (99.81%)	NaCl (5.1%) Na_2SO_4 (9.8%)	Donnan effect / Size exclusion	[48]

hydrophobic interactions between aromatic rings in their molecular structure [27,48]. In such cases, the size of dye aggregates in solution does not directly correspond to their molecular weight, thereby enhancing the rejection performance of LNF membranes with relatively large MWCO. This phenomenon explains why the LNF membranes listed in Table 2, despite having large MWCOs, still maintain good dye rejection performance. For instance, He *et al.* [40] developed loose polyester (PE) membranes via an IP process using epigallocatechin gallate as a monomer, achieving high water permeance of 41.7 Lm^{-2}h^{-1} bar^{-1} and excellent dye rejection (98.5% for CR, 93.4% for Methylene Blue (MB), and 94.8% for Evans Blue) with a lower salt rejection of 7.4% for NaCl. Incorporating nanomaterials, such as multi-walled carbon nanotubes (MWCNTs) and graphene oxide (GO), into LNF membranes enhances hydrophilicity, reduces transport resistance, and improves pore size distribution, thereby increasing flux and achieving superior dye and salt selectivity [41]. For example, Cai et al. [42] developed an LNF membrane using sodium alginate as the substrate and polyethylene glycol (PEG) as a pore-forming agent, reinforced with cellulose nanofibers and MWCNT-COOH. The membrane achieved a high water permeance of 51.6 Lm^{-2}h^{-1} bar^{-1} and excellent dye rejection: 99.8% for crystal violet, 98.9% for CR, 93.1% for Sunset Yellow, and 85.7% for MB, along with low salt rejection: 10.5% for Na_2SO_4 and 7.3% for NaCl. Some studies have also shown that LNF membranes can significantly enhance separation performance under high salinity and extreme pH conditions while maintaining high water permeance and exhibiting good stability [43]. For instance, Lu et al. [44] developed an LNF membrane using 5,5′,6,6′-tetrahydroxy-3,3,3′,3′-tetramethyl-1,1′-spirobisindane, and isophthaloyl dichloride as monomers, achieving high water permeance of ~ 210 L m^{-2}h^{-1} bar^{-1} and over 99% dye rejection across pH levels of 2–9 and NaCl concentrations of 1000–5000 ppm.

Although NF membrane technology has made significant progress in dye wastewater treatment, numerous challenges remain. Current studies primarily focus on the rejection of anionic dyes, while research on the separation of cationic dyes/salts is relatively limited. Anionic dyes tend to form aggregates, facilitating their separation from salts, whereas cationic dyes, due to their higher dispersibility, pose greater separation challenges. Moreover, most studies focus on single-dye systems, whereas real wastewater typically contains mixtures of various dyes. Therefore, future research should prioritize the precise regulation of membrane pore size and charge to enhance the separation efficiency of cationic dyes/salts. Additionally, it should explore separation technologies for different dyes to better address the practical needs of treating complex wastewater.

3.2. NaCl/Na_2SO_4 separation

In the dyeing and printing processes, NaCl enhances the dye uptake rate by promoting dye adsorption onto fibers, while Na_2SO_4 regulates the ionic strength and stability of the dye solution, ensuring uniform dye distribution and achieving consistent dyeing results [2,27]. However, after dyeing, these inorganic salts typically remain in wastewater, resulting in a loss of resources. To enable the recovery of these salts, the design of NF membranes plays a crucial role [25]. Recent years have seen extensive research into optimizing the Cl^-/SO_4^{2-} separation selectivity of dense NF membranes, with relevant progress summarized in Table 3.

The high selectivity of NF membranes for separating NaCl and Na_2SO_4 primarily depends on the pore-sieving effect, the charge repulsion effect, and the dielectric effect. The pore-sieving effect relies on the slight difference in hydrated diameters of monovalent and divalent ions (approximately 0.1 nm) [49]. By constructing regular and orderly sub-nanometer pores, both permeability and Cl^-/SO_4^{2-} selectivity can be maximized. Optimizing the pore size distribution of dense membranes can effectively block the larger SO_4^{2-} ions while allowing the smaller Cl^- ions to pass through. For example, Xu et al. [50] developed NF membranes with a well-tailored pore size distribution and a nearly neutral surface charge. These membranes demonstrated outstanding performance in the precise separation of Cl^-/SO_4^{2-}, achieving a separation factor of 93.

In addition to the pore size sieving effect, the electrostatic shielding effect on the membrane surface also plays a crucial role in ion selectivity. By introducing negatively charged functional groups, electrostatic repulsion can enhance the rejection of higher valence ions. For example, Guo et al. [51] developed an NF membrane with enhanced negative charge through an IP process between TMC and a streptomycin/piperazine (PIP) mixture. The resulting membrane achieved a NaCl and Na_2SO_4 rejection of 17.17% and 97.84%, with a separation factor of 40 for NaCl/Na_2SO_4, which is 3.3 times higher than that of the control membrane. Furthermore, Yuan et al. [49] used cis,cis,cis,*cis*-1,2,3,4-cyclopentane tetracarboxylic acid chloride/PIP monomers in the IP process to fabricate an enhanced negatively charged NF membrane containing more interconnected voids ranging from 1.95 to 3.0 Å. This

Table 3
Overview of studies on the performance of dense NF membranes for $NaCl/Na_2SO_4$ separation.

Membranes	Fabrication method	MWCO (Da)	Separation performance					Ref
			Water permeance (L m^{-2}h^{-1} bar^{-1})	Na_2SO_4 rejection (%)	NaCl rejection (%)	Cl^-/SO_4^{2-} selectivity	Mechanisms	
TCi-NF	Substrate modification/IP	307	~10	99.3%	31.2%	49	Size exclusion	[60]
TMC–PIP/PSF-5	Substrate modification/IP	352	~2	98.71%	18.18%	377.8	Donnan/steric exclusion	[57]
CPTC-PIP	IP	333	14.65	98.9%	13.6%	197.11	Donnan/steric exclusion	[49]
PIP/BINOL-TMC	IP	364	17.01	~98%	8.01%	44	Donnan/steric exclusion	[61]
PIP/TTSBI-TMC	IP	1000	9.9	98.0%	58.0%	Na_2SO_4/NaCl = 21.0	Donnan exclusion	[62]
PA/MPC(M2)	IP	219	8.5	98.9%	5.6%	93	Steric exclusion	[50]
SM-PIP/TMC	IP/heat treatment	498.50	8.94	97.84%	17.17%	40	Donnan/steric exclusion	[51]
SCOF/PA	IP	275	~7	99.6%	~ 30%	312.6	Donnan/steric exclusion	[63]
PIP-TMC (Heating)/PES	IP/heat treatment	226	15.8	99.5%	47.8%	Na_2SO_4/NaCl = 104.4	Donnan/steric exclusion	[64]
RCC2-TPC ISMs	layer-by-layer	352	3.1	98.6%	42.4%	277.3	Steric exclusion	[65]

structure enhances the rejection of SO_4^{2-}, which has a higher charge density and allows the passage of Cl^-, resulting in an excellent Cl^-/SO_4^{2-} separation with a high separation factor of 197.11.

The role of the dielectric effect in NF membranes is primarily reflected in two aspects: the ion solvation energy barrier and the mirror force effect. Specifically, the ion solvation energy barrier resists the movement of the ion by increasing the energy required to enter a less solvating region inside the membrane, while the mirror force effect attracts the ion toward the surface due to the interaction with its image charge. Both effects arise due to the extreme spatial constraints and nanoscale limitations present in membrane separation and are influenced by electrostatic repulsion [25]. In the dielectric effect, both the ion solvation energy and mirror force are proportional to the square of the ion charge number. Therefore, the dielectric effect is more pronounced for the rejection of multivalent ions [52,53]. As a result, ions with higher charges, such as divalent SO_4^{2-} ions, experience stronger electrostatic effects, making it more difficult for them to pass through the membrane pores, and thus enhancing the Cl^-/SO_4^{2-} separation selectivity of the membrane. During the NF membrane separation process, the dielectric effect works in conjunction with size exclusion and electrostatic repulsion mechanisms, enhancing ion selectivity [54,55].

The hydrophilicity of NF membranes also plays a significant role in separation performance. Although enhancing hydrophilicity generally improves water flux, it may reduce the Cl^-/SO_4^{2-} separation selectivity. This happens because hydrophilic membranes strengthen the interaction between the membrane surface and hydrated SO_4^{2-} ions, increasing the interfacial adsorption capacity of SO_4^{2-} and reducing the electrostatic repulsion effect, which in turn lowers selectivity [56–58]. For example, Chen et al. [59] fabricated membranes from a poly(alkyl-biphenyl pyridine) backbone via the Menshutkin reaction, after which 4-vinylbenzyl chloride (VBC) was used for *insitu* thermal quaternization crosslinking. The membrane hydrophilicity increased with a higher VBC content. When the molar ratio of VBC increased from 0.3 to 1, the ion adsorption equilibrium constants decreased from 15 to 9. The decreased constants indicate increased relative adsorption of SO_4^{2-} in the membrane, and hence a decreased Cl^-/SO_4^{2-} selectivity. Overall, in the design and optimization of NF membranes, it is necessary to consider the combination of pore size sieving, charge repulsion, dielectric effects, and hydrophilicity for Cl^-/SO_4^{2-} selectivity to achieve a balance between separation selectivity and water flux, ensuring that the NF membranes meet the requirements for the treatment of textile wastewaters.

3.3. *Heavy metal recovery*

Adding metal ions to dye molecules can expand the color range of dyes while enhancing properties such as adsorption performance and colorfastness during washing. As a result, metallized dyes and binders (or mordants) are widely used in the dyeing industry, leading to significant concentrations of metal ions in dyeing wastewater [66]. Considering industrial wastewater as a potential resource for recovering valuable metals to mitigate future supply shortages is gaining attention [67]. To this end, membrane separation technology, which exploits differences in metal ions' size, charge, and polarizability, enables efficient metal recovery driven by concentration, pressure, or potential gradients [68].

Dense NF membranes exhibit excellent performance in metal ion separation due to strong size exclusion and charge repulsion effects [69]. Table 4 summarizes the progress of research in NF membranes for heavy metals removal. For example, Niu *et al.* [70] developed an NF membrane by employing 1,2,3,4-cyclobutane tetracarboxylic acid chloride as the monomer in the IP process with PEI. The resulting positively charged NF membrane had an effective pore size of 0.285 nm. It demonstrated excellent heavy metal removal efficiencies, achieving a removal performance of 98.78% for Mn^{2+}, 98.32% forZn^{2+}, 97.74% for Ni^{2+}, 95.67% for Cu^{2+}, and 90.49% for Cd^{2+}. In addition, the metal ion removal efficiency can be significantly enhanced by the formation of metal ion chelates. For instance, introducing the naturally non-toxic phytic acid molecule onto the surface of NF membranes allows the formation of stable O-M^{2+}-O bonds with divalent metal ions (M^{2+}). This metal ion-chelation effect, combined with size exclusion and the Donnan effect, enables efficient capture of metal ions. For example, Zhang et al. [71] showed that the introduction of phytic acid on the membrane resulted in a removal efficiency of nearly 100% for Cd^{2+}, Cu^{2+}, and Pb^{2+}.

A challenge in heavy metal recovery is the high migration rate of H^+ ions during the operation of NF membranes, as their small size results in significantly higher permeation compared to most metal ions (e.g., Cu^{2+}, Zn^{2+}). The permeation of H^+ ions through the membrane causes an increase in the OH^- concentration, with metal ions accumulating near the membrane surface. With the rise in pH, these metal ions may undergo hydrolysis, forming metal hydroxide precipitates that lead to membrane fouling [69]. To address this issue, acidic cleaning solutions can be used to dissolve and remove the deposited metal hydroxides, making the development of acid-resistant NF membranes particularly

Table 4
Overview of studies on the performance of NF membranes for heavy metal removal.

Membranes	Fabrication method	MWCO (Da)	Separation performance			Ref
			Water permeance ($L\ m^{-2}h^{-1}\ bar^{-1}$)	Rejection (%)	Mechanisms	
PPSU/carboxylated-GO	Phase inversion	400	3.5	As^{5+}(99%) Cr^{4+} (98%) Zn^{2+} (87%) Cd^{2+} (82%) Pb^{2+} (82%)	Donnan/steric exclusion	[73]
HPEI-MWCNT (0.6%)	Phase inversion	600	7.57	Zn^{2+} (99.06%) Cd^{2+} (96.72%) Cu^{2+} (95.84%) Ni^{2+} (94.63%) Pb^{2+} (93.39%)	Donnan exclusion	[74]
PEI-BTC	IP	370	15.69	Mn^{2+}(98.78%) Zn^{2+}(98.32%) Ni^{2+}(97.74%) Cu^{2+}(95.67%) Cd^{2+}(90.49%)	Donnan/steric exclusion	[70]
M_0-(PEI/PA)$_2$	IP /LbL assembly	/	8.86	Cd^{2+}(100.00%) Cu^{2+}(100.00%) Pb^{2+}(99.99%)	Coordination /Donnan/steric exclusion	[71]
H_PAMAM G2	IP/surface grafting	135	3.6	Pb^{2+} (99.43%) Cd^{2+} (99.55%) Cu^{2+} (99.58%)	Donnan/steric exclusion	[75]
PEI-TMC-CC	IP/surface grafting	258	10.0	Cd^{2+} (98.3%) Pb^{2+} (95.9%) Ni^{2+} (98.1%) Zn^{2+} (98.5%) Cu^{2+} (99.1%)	Donnan/steric exclusion	[76]
MD0.01	IP/surface grafting	212	17.1	Ni^{2+} (94.8%) Zn^{2+} (94.5%) Cu^{2+} (92.9%) Pb^{2+} (85.1%)	Donnan/steric exclusion	[77]
NH_2 –MIL-125(Ti)/PEI/TMA	surface grafting	2000	12.2	Ni^{2+} (90.9%)	Donnan/steric exclusion	[78]
DPC-TFC	surface grafting	210	3.30	Ni^{2+} (95.8%) Cu^{2+} (96%) Cr^{3+} (98.0%)	Donnan/steric exclusion	[79]
P84/PEI	surface grafting	510	10.8	Pb^{2+} (99.0%) Ni^{2+} (96.7%) Zn^{2+} (96.2%) Cu^{2+} (99.8%)	Donnan/steric exclusion	[69]

critical. For example, Zhao *et al.* [72] developed an acid-stable NF membrane by enhanced crosslinking density using a two-step IP process. First, a tannic acid/diethylenetriamine interlayer was formed to enhance the wettability of the polyethersulfone (PES) substrate, promoting uniform deposition of PEI with higher density. The subsequent IP between PEI and cyanuric chloride resulted in a membrane with a more compact polyamide layer, and improved acid stability. This membrane demonstrated over 93% rejection of heavy metal ions (Pb^{2+}, Cu^{2+}, Fe^{3+}, Zn^{2+}, Cr^{3+}) due to its optimized pore size and Donnan effect while maintaining excellent stability during a 15-day acid test in 0.1 M HCl.

Despite the significant advantages of NF membranes in metal ion separation, several challenges remain. First, in practical applications, membrane technology should balance high selectivity with high water flux, which is a key area of current research. By optimizing pore size distribution and enhancing surface charge density, future advancements can further improve separation performance. Second, given the coexistence of various metal ions in wastewater, designing high-selectivity NF membranes capable of precise metal ion separation represents a promising direction. Third, in complex wastewater environments, developing membranes with enhanced chemical resistance and anti-fouling properties will be a critical focus for future research.

3.4. Integrated process for resource recovery from textile wastewater

Integrated treatment systems overcome the limitations of standalone NF processes through synergistic effects, which is particularly interesting for diversified resource recovery from various textile wastewater. Taking into account the complex composition of textile wastewater, the combination of chemical or biological methods with membrane technology provides greater flexibility, while significantly enhancing the overall treatment efficiency [80]. Progress and advancements in these integrated technologies are summarized in Table 5.

Pressure-driven membrane processes play a vital role in textile wastewater resource recovery, with NF membranes standing out for their exceptional performance. While UF membranes are effective in removing suspended solids, microorganisms, and larger particles, serving as a pre-treatment step, NF membranes excel in achieving efficient resource recovery and water purification [34]. Integrated membrane systems (UF-NF) effectively address challenges in wastewater resource utilization while offering significant economic benefits [80]. For instance, Curić et al. [81] studied the application of a UF-NF hybrid system for the treatment of textile wastewater, achieving over 95% removal of COD, BOD_5, and color. The resulting high-quality water could then be recycled for dyeing processes. Economic analysis revealed that this system reduced costs by €4,980 compared to the UF/RO process while maintaining excellent dyeing performance. Similarly, Ağtaş *et al.* [82] employed a UF-NF system to recover alkaline chemicals (NaOH) from textile wastewater, achieving a 50% sodium recovery using a ceramic NF membrane (1000 Da). The system also achieved a removal efficiency of 67% for TOC, 71% for COD, and 92% for color. The recovered alkaline solution could be reused in caustic processes, effectively reducing chemical costs by 50%.

Moreover, the integration of NF membranes with other treatment processes, such as electrodialysis (ED) and electrocoagulation (EC), has demonstrated excellent resource recovery performance. For example, Lin et al. [83] proposed an integrated LNF-ED process for resource

Table 5
Overview of studies on the performance of NF-integrated technologies for resource recovery from textile wastewater.

Integrated process	NF membranes	Operating conditions	Feed	Removal performance	Recycle application	Ref
EC-NF	LNF NP010	9 bar Dead end	The Mehr Nasaj textile factory	Color (87%) COD (74%) Turbidity (99%) TSS (95%)	The NF permeate can be reused in the fabric dyeing process	[84]
MBR-NF	NF90–2540	6.4–8.1 bar Crossflow	Biologically pretreated textile wastewater	COD (97%) Color (97%) TP (87%)	The treated effluent complied with the standards for reclaimed water use	[87]
LNF-BMED	Sepro NF 6	6 bar Cross-flow	Simulated textile effluent	Salt ($R \leq 2.2\%$) Dyes(>99.93%) Bases (1.28 $mol \cdot L^{-1}$) Acids (1.19 $mol \cdot L^{-1}$)	The extracted dye, the regenerated water, and acids/bases can be reused in the dyeing process	[86]
NF-ED	Commercial LNF membrane	6 bar Cross-flow	Simulated textile effluent	Dye (98.4%) Concentrated NaCl	The produced pure water was recycled back into the nanofiltration-diafiltration unit	[85]
UF/NF	NF270	10 bar Crossflow	Discharge effluent of a textile factory	COD (94.6%) BOD5 (95.4%) SO_4^{2-} (98.1%) Color (80.0–90.0%)	The NF effluent can be reused in the dyeing of new cotton	[81]
EC-NF	nylon 6,6	0.1 bar	Simulated dye wastewater	Dye (79.4%)	The recycled dyes can be used again in the dyeing process	[88]
UF-NF	Ceramic NF	2.5 bar Crossflow	Caustic main bath discharges from textile factory	TOC (67%) COD (71%) Total hardness (42%) Color (92%)	The recovered caustic solution can be recycled in caustic processes by mixing it with concentrated NaOH	[82]
NF-Electrochemical	Hydracore50	8 bar Dead end	Simulated textile effluent	Dye (98%)	The recycled dyes can be reused in new cotton dyeing processes	[89]
MBR-NF-UV	NF270	5–7 bar	Woolen textile mill wastewater	TDS (40%) Turbidity (99%) Color (80%) COD (97%)	The NF permeate can be reused in the fabric dyeing process	[90]

Notes: Membrane bioreactor: MBR, Ultraviolet Disinfection: UV, Total Suspended Solids: TSS, Total phosphorus: TP.

recovery from high-salinity textile wastewater. Specifically, the ED process which utilizes an electric field to drive ion migration, efficiently separates salts from wastewater and enables salt recovery. In this combined approach, the LNF membrane, with a MWCO of 800 Da, played a critical role in selectively rejecting dyes while allowing salts to permeate rapidly. This enabled the efficient pre-concentration and purification of dyes, enriching them approximately ninefold (from 2.01 to 17.9 g/L with a purity of 98.4%). The ED process then further concentrated the NaCl to 86.5 g/L with a high purity of 99.96% and simultaneously provided pure water. Together, the LNF and ED processes complemented each other, facilitating dye concentration, salt recovery, and water loop closure to achieve near-zero liquid discharge. Compared to the traditional ED process, bipolar membrane electrodialysis (BMED) generates acids and bases during the electrolysis process, enabling the simultaneous recovery of acids, bases, and salts, thereby enriching the variety of recoverable resources. Lin et al. [84] developed a hybrid LNF-BMED process for resource recovery from textile wastewater. The LNF membrane (Sepro NF 6) rejected dyes (>99.93%) while allowing free salt passage (rejection $\leq$ 2.2%). The addition of pure water (with a volume factor of 5.0) achieved $\sim$ 99.0% salt removal from dye/salt mixtures. BMED then converted the NF permeate into pure water, and acidic (1.19 $mol{\cdot}L^{-1}$) and basic solutions (1.28 $mol{\cdot}L^{-1}$), effectively closing the salt and water loop.

Another approach is electrocoagulation (EC), which employs metal ions (e.g., Al^{3+} or Fe^{2+}) that are generated during the electrolysis process as coagulants, and combines these with flotation effects to remove suspended solids and colloids from wastewater [85]. As a pretreatment process, electrocoagulation effectively reduces the fouling risk in subsequent membrane separation processes, such as NF, thereby improving membrane flux and service life. For example, Tavangar et al. [86] combined the EC technique with the LNF membrane, significantly enhancing the separation efficiency of dyes/salts. After pretreatment with the EC step, the process achieved a removal efficiency of 64% for COD and 94% for color, while the NF membrane achieved over 87% dye removal and a low salt rejection of less than 4%. This hybrid process effectively reduced membrane fouling, improved flux, and significantly enhanced resource recovery efficiency.

Although membrane technologies have been widely applied in wastewater treatment, no universally applicable solution currently exists for textile wastewater recovery. Moreover, current research primarily focuses on integrating commercial NF membranes, yet customizing NF membranes to target specific resources can yield higher efficiency. Furthermore, studies on integrated NF processes remain limited, leaving many recoverable resources in textile wastewater unexplored. Investigating diverse integration strategies that combine NF membranes with other technologies, such as physical methods (e.g., filtration and sedimentation), chemical methods (e.g., oxidation), and biological methods (e.g., biofilms), could enable more efficient and comprehensive resource recovery from textile wastewater.

4. The fabrication of NF membranes

Based on the research progress on NF membranes in textile wastewater treatment, it is evident that achieving efficient resource recovery requires higher demands on the membrane in terms of pore size distribution, charge density, hydrophilicity, and functional groups. NF membranes primarily consist of a substrate and separation layer. By optimizing the substrate preparation, constructing the separation layer via the IP technique, modifying the membrane surface (e.g., by surface coating, grafting), and applying post-treatment methods (e.g., thermal, solvent treatment) (Fig. 4), the membrane structure and performance can be effectively adjusted to improve the resource recovery efficiency from textile wastewater. In the following section, these membrane fabrication methods and their effects on membrane performance will be discussed in detail, aiming to enhance their effectiveness in resource recovery through targeted approaches.

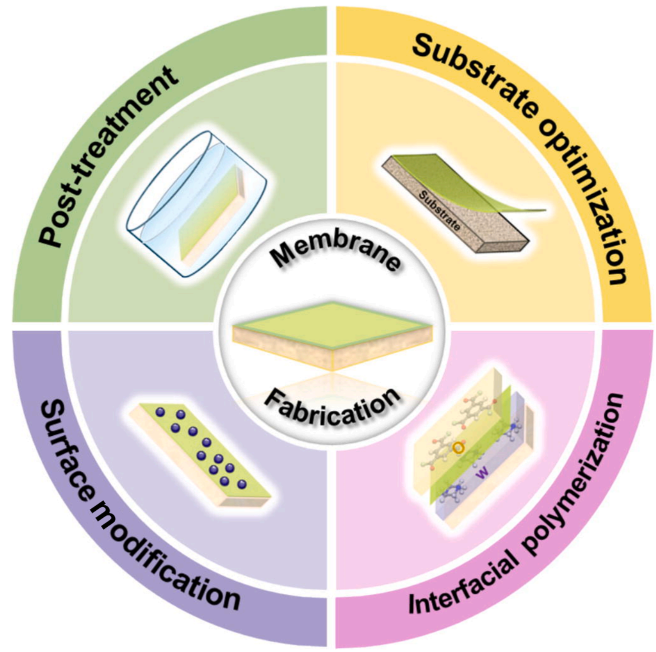

Fig. 4. Fabrication methods of NF membranes.

4.1. Substrate preparation

The substrate is crucial for providing the mechanical strength and stability of NF membranes, directly influencing water flux and separation performance through its porosity, pore size distribution, and surface characteristics [23]. In textile wastewater treatment, where complex mixtures of dyes, salts, and contaminants are present, optimizing substrate properties becomes even more critical. Techniques such as phase inversion process adjustment, monomer storage in substrate, and substrate functionalization help fine-tune the pore structure and charge characteristics of NF membranes, improving separation performance while ensuring high water permeability [95,96].

Phase inversion is the most commonly used method for substrate preparation. This process involves dissolving a solid polymer in a solvent to prepare a casting solution, followed by immersing the dissolved polymer material into a non-solvent, which transforms it from a liquid or soluble state to a solid state, resulting in a substrate. The key is precisely controlling the solvent-to-non-solvent ratio, temperature, humidity, and evaporation time to regulate the pore size [97]. For example, Hołda *et al.* [91] found that when the polymer concentration of polysulfone (PSf) increased from 13 to 25wt%, the rejection of the dye Rose Red increased from 37 to 92%. When the evaporation time was extended from 0 to 120 s, the rejection increased from 47 to 76%, due to the formation of a dense membrane structure (Fig. 5**a**). These results indicate that optimizing phase inversion conditions can significantly improve the membrane separation performance. However, conventional polymer membranes, such as PSf and PES, typically have non-interconnected pores, which limit the water permeance [98]. Although optimizing phase inversion parameters can improve performance to some extent, membranes with low porosity still limit water permeance. To address this issue, PEG additives are added to the casting solution to enhance the porosity and uniformity of pore size distribution, improve hydrophilicity. For example, Hu *et al.* [92] used non-solvent induced phase inversion to prepare polysulfone-block-polyethylene glycol (PSf-b-PEG) membranes, which exhibited a highly porous structure (Fig. 5**b**), an average effective pore size of 3.8 nm, and a water permeability of 49.3 L $m^{-2}h^{-1}$ bar^{-1}. The prepared membrane also demonstrated excellent dye/salt separation performance, achieving 98% CR and near-complete passage of Na_2SO_4. Moreover, incorporating nanofillers into substrates

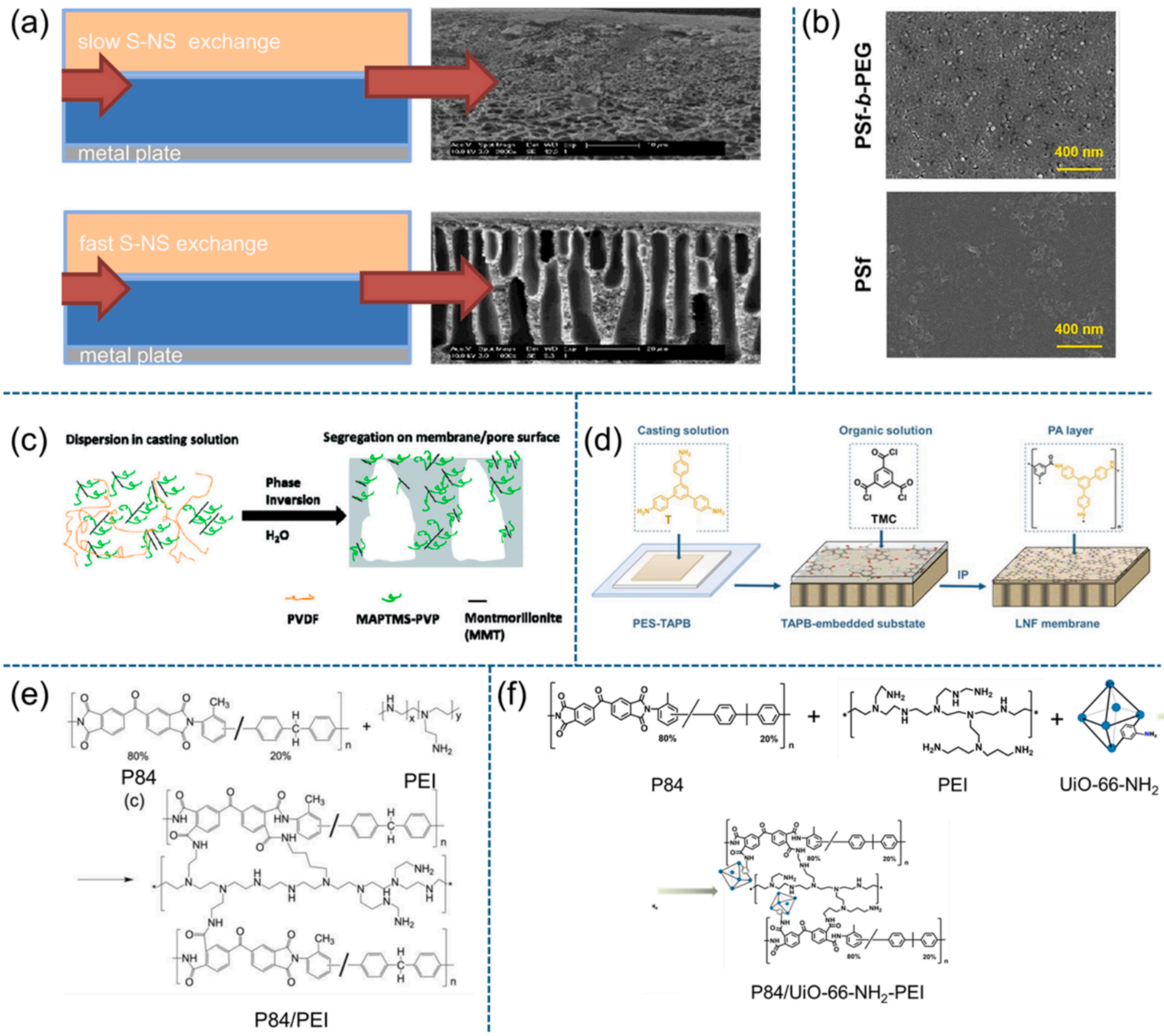

Fig. 5. Overview of various substrate preparation methods. (a) Membrane morphologies for substrates prepared with phase inversion employing slow and fast exchange of the solvent (S) and non-solvent (NS) [91]. (b)SEM images of a polysulfone-block-polyethylene glycol (PSf-b-PEG) and polysulfone (PSf) membrane [92]. (c) Schematic diagram of the phase inversion process using a polyvinylpyrrolidone grafted montmorillonite (PVP-g-MMT) dispersion in a polyvinylidene fluoride (PVDF) casting solution [93]. (d) Schematic diagram of the fabrication of LNF membranes, by incorporating the monomer 1,3,5-tris(4-aminophenyl)benzene (TAPB) in a PES matrix and performing IP reaction using TMC [45]. (e) A possible chemical structure of PEI/P84 membranes [69]. (f) Chemical structures of the P84/UiO-66-NH_2-PEI membranes [94].

to form mixed matrix membranes (MMM) enhances the thermodynamic compatibility between the polymer and solvent, accelerates the phase inversion process, and improves the hydrophilicity of the matrix [99]. Wang *et al*. [93] used a hydrophilic nanocomposite additive, PVP-g-MMT, namely polyvinylpyrrolidone grafted montmorillonite, and compared the resulting membrane with a control PVDF membrane (Fig. 5**c**). The modified membrane significantly enhanced hydrophilicity and achieved a bovine serum albumin (BSA) removal of 90%, with significantly improved antifouling performance.

Furthermore, the substrate can serve as a monomer reservoir and play an important role during the further cross-linking process. By storing monomers in the substrate, the problem regarding the monomer insolubility in water can be addressed, which simplifies the reaction process. For example, Liu *et al.* [45] incorporated the non-planar triamine monomer 1,3,5-tris(4-aminophenyl)benzene (TAPB) into the PES casting solution and performed an IP reaction with TMC (Fig. 5**d**). The resulting separation layer demonstrated enhanced free volume and porosity, resulting in a high water permeance of 185.8 L $m^{-2}h^{-1}$ bar^{-1}, while maintaining excellent salt/dye separation performance, with a CR rejection of 99% and NaCl rejection of 12.4%. Lastly, the selection of substrates with surface functional groups (such as hydroxyl, carboxyl, or amino groups), which can undergo crosslinking reactions with the separation layer, can enhance the membrane stability. For example, various studies report that the hydrolysis of P84 polyimide, which forms stable amide bonds with amino groups in the monomers (Fig. 5**e and 5f**), greatly improves the heavy metal ion recovery ability of the membranes, with removal above 95% [40,69,94]. This functional design enhances the stability of the separation layer while improving the selectivity of the membrane.

Constructing NF membranes with small pore sizes and high pore density helps improve solute rejection while maintaining high water permeance. Moreover, hydrophilic substrates effectively reduce the attachment of dyes and other contaminants, thereby improving antifouling properties and extending the membrane service life. Therefore, carefully selecting substrates with suitable pore size characteristics, good hydrophilicity and rich functional groups establishes a solid foundation for fabricating separation layers with enhanced stability in resource recovery from textile wastewater.

4.2. Interfacial polymerization

In a typical IP process, amine monomers in the aqueous phase (e.g., PIP or m-phenylenediamine (MPD)) diffuse into the organic phase and react rapidly with TMC at the water–oil interface via the Schotten–Baumann reaction to form a polyamide (PA) layer. As the amine monomers continue to diffuse and react with acyl chlorides, a cross-linked network gradually starts to form, increasing in density and eventually hindering diffusion. The slower polymerization rate results in the formation of an ultrathin separation layer with nanoscale thickness and self-limiting growth [102,103]. This technique is widely used in the fabrication of commercial membranes (e.g., NF270) due to its fast and efficient preparation process. However, commercial membranes are typically negatively charged, which limits their rejection performance and makes them prone to fouling when treating streams containing positively charged dyes or heavy metal ions [104–106]. To overcome these challenges, two strategies have been widely employed, such as the selection of suitable monomers and the introduction of nanoparticles. By successfully adjusting the surface charge, porosity, pore size uniformity, and membrane thickness, these strategies have significantly improved the water permeability and separation performance of NF membranes, optimizing the trade-off between efficient separation of dyes, salts, and heavy metals from textile wastewater. It is important to consider the charge properties, solubility, diffusion rate, molecular configuration, and functional groups of the monomers, while also optimizing the distribution of nanoparticles within the membrane.

First, the selection of monomers, e.g., PIP and PEI, determines the charge properties of NF membranes. For example, when PIP reacts with TMC, unreacted acyl chloride groups hydrolyze to form carboxylate ions ($-COO^-$), resulting in a negatively charged membrane surface [107]. Such membranes can efficiently remove negatively charged dyes and exhibit good rejection performance for Na_2SO_4. In contrast, PEI, which is rich in amino groups, can form positively charged membranes through amino protonation when crosslinked with TMC [100]. The resulting membrane demonstrates excellent recovery of positively charged dyes and heavy metals.

Second, the solubility and molecular weight of the monomers directly affect the diffusion behavior during the IP process, which ultimately influences the structure of the selective layer. For example, small and highly soluble monomers, such as PIP, can rapidly diffuse in the aqueous phase and react extensively with the monomers in the organic phase, forming a denser selective layer [103]. In contrast, high molecular weight monomers such as PEI exhibit lower diffusion rates but form thin selective layers with higher porosity, thereby achieving higher water permeance. For example, Jiang *et al.* [100] found that the larger molecular weight of PEI resulted in slower diffusion rates, due to significant steric hindrance, and a reduced thickness of the PA layer (9.0 nm) (Fig. 6**a**). The water permeability was approximately 2 to 10 times higher than previously reported values of positively charged NF membranes, with a high rejection of heavy metals (e.g., $ZnCl_2$ and $NiCl_2$) exceeding 95%. Additionally, compared to linear monomers, monomers with rigid structures and non-planar or twisted molecular configurations create more intermolecular voids within the polymer network during polymerization. These voids facilitate the formation of microporous structures, thereby enhancing the porosity and permeability of the membranes [108]. For example, Niu *et al.* [101] used rigid bisphenol and PIP to react with TMC through the IP process (Fig. 6**b**), achieving membranes with enhanced microporosity and interconnected pores. Optimizing the bisphenol/amine ratio increased the free volume and pore connectivity, improving water permeance by 2.7-fold while maintaining a Na_2SO_4 removal of 99.2%.

Third, the reactivity of monomers significantly influences the pore structure of NF membranes. Monomers containing hydroxyl groups (e.g., alcohol or phenolic hydroxyl groups), typically form loose layers in the IP reaction due to their lower reactivity, larger steric hindrance, and hydrogen bonding interference. These layers exhibit a high water permeance while maintaining excellent selectivity. Zhao *et al.* [36] prepared LNF membranes using renewable quercetin containing five hydroxyl groups (Fig. 6**c**). These membranes improved dye/salt separation efficiency by 288%, while reducing water consumption by 42.9%, contributing to enhanced dye recovery and cost reduction. Polyester (PE) membranes based on ester bonds also demonstrated excellent chlorine resistance due to the absence of active chlorine attack sites, with chlorine standing exposure of up to 960,000 ppm/h [109]. Fourth, introducing functional monomers in the IP reaction can impart additional properties to the membrane, such as antibacterial and antifouling capabilities. For example, streptomycin, when reacted with TMC, forms a selective layer with high dye/salt selectivity (over 99% rejection for dyes and less than 5 % rejection for salts). The resulting membrane exhibited excellent antifouling properties, with a flux recovery rate of 98.7%, and 99.9% of antibacterial performance [110].

In addition to selecting appropriate monomers for the IP process, incorporating nanoparticles into the reaction to regulate the IP process can significantly enhance the performance of NF membranes. The

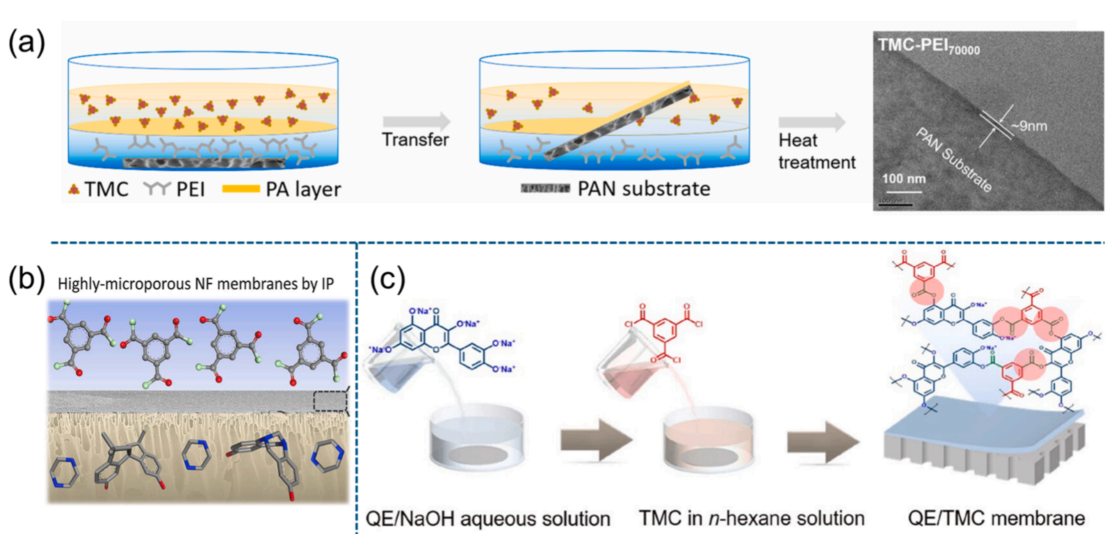

Fig. 6. Overview of various IP methods. (a) Schematic diagram of the preparation of a PEI/TMC membrane on a polyacrylonitrile (PAN) support, and a TEM image of the TMC-PEI_{70000} nanofilm [100]. (b) Schematic diagram of the IP process [101]. (c) Schematic diagram of the preparation of a quercetin (QE)/TMC loose PE membrane [36].

introduction of these nanoparticles offers several advantages, such as increased membrane surface area, optimized pore size distribution, and synergistic effects resulting from the inherent properties of the nanoparticles [113]. Besides the incorporation methods discussed in Section 4.1 for mixed matrix membranes, Nanoparticles are typically introduced into NF membranes using two main approaches (Fig. 7**a**), (1) dispersion of the nanoparticles in the aqueous or organic phase of the monomers during the IP process, and (2) pre-deposition on the porous substrate surface before the IP process.

Using the first approach, the nanoparticles are randomly encapsulated into the PA matrix, forming TFN membranes. This approach enhances the hydrophilicity and surface roughness of the membrane while increasing the effective filtration area and providing additional water transport channels, thereby improving water permeance [113]. For example, Zheng *et al.* [111] incorporated carbon dots modified with ammonium ions of varying alkyl chain lengths (C8-CDs) into the PA network (Fig. 7**b**). The C8-CDs induced the formation of nano-scale ridge structures on the membrane surface, increasing the filtration area. The modified membrane exhibited a high water permeance of 29.0 $L\ m^{-2}\ h^{-1}\ bar^{-1}$, with Na_2SO_4 rejection of 98.9% and $NaCl/Na_2SO_4$ selectivity of 83.1.

Using the second approach, the nanoparticles are uniformly deposited onto the surface of the porous substrate before the IP process. The nanoparticles then form the interlayer to form TFNi membranes. Compared to TFN membranes, the TFNi membranes provide more precise control during the IP process by enhancing the storage of amine monomers, regulating their diffusion, and preventing the PA matrix from penetrating the substrate structure. These features facilitate the formation of a uniform separation layer, effectively mitigating the trade-off between membrane flux and rejection. Additionally, the nanoparticle interlayer can act as a water-receiving layer by forming water pathways or channels within this interlayer, a phenomenon referred to as the "gutter effect". This effect reduces the transverse mass transfer resistance, which directly enhances water permeability through the membrane [114]. For instance, Yang *et al.* [112] developed polydopamine (PDA)-intercalated TFNi membranes (Fig. 7**c**), which exhibited a water permeability six times higher than that of control membranes, while maintaining a high Na_2SO_4 rejection.

The IP method is a crucial technique for fabricating NF membranes, and its regulation significantly influences the resource recovery from textile wastewater. Three key aspects can be identified. First, the membrane separation performance can be enhanced through optimization of the monomer selection and reaction conditions. The IP process can precisely control the pore size distribution and surface charge properties of membranes, according to the properties of the target solute (e.g., molecular size, surface charge, and chemical characteristics), which enables efficient recovery of specific resources. Second, the trade-off between high flux and selectivity can be overcome by selecting suitable monomers and incorporating functional nanoparticles. Through this approach, the IP method can form separation layers with high porosity and excellent selectivity, for example by selecting monomers with low diffusivity, low reactivity, and non-planar structures and incorporating nanoparticles with abundant porous structures. The resulting highly porous structure provides additional water transport pathways without compromising the rejection of target solutes, thereby achieving both high water flux and high selectivity. Last, the

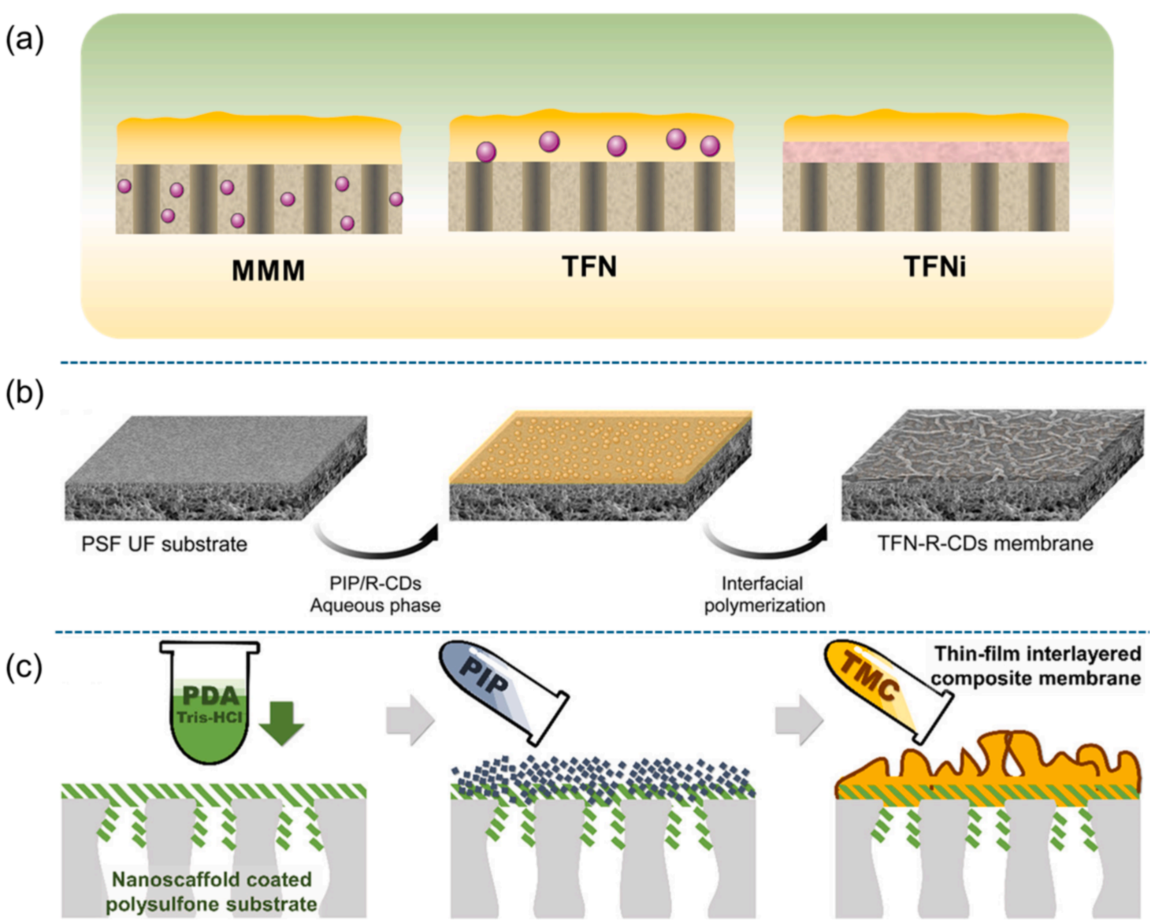

Fig. 7. (a) Schematic illustration of MMM, thin-film nanocomposite (TFN), and thin-film nanocomposite with interlayer (TFNi) membranes. (b) Schematic diagram of the preparation of a TFN membrane using IP reaction between PIP and TMC on PSf substrate, and incorporation of ammonium ion-modified carbon dots (R-CDs) [111]. (c) Schematic diagram on the fabrication of a polydopamine (PDA)-intercalated interlayered TFNi membrane [112].

adaptability of the membrane to complex wastewater systems can be enhanced. For example, the synergistic effects of functional monomers or nanoparticles effectively enhance the antibacterial, antifouling, and anti-degradation properties of the membrane, ensuring long-term operational stability. This improvement increases the continuity and economic viability of resource recovery processes.

4.3. Surface modification

Surface modification techniques, including coating, grafting, and layer-by-layer (LBL) assembly, enable precise adjustment of membrane properties, such as optimized pore structure distribution, enhanced charge density, increased hydrophilicity, and reduced dye molecule adsorption, thereby enhancing both separation efficiency and

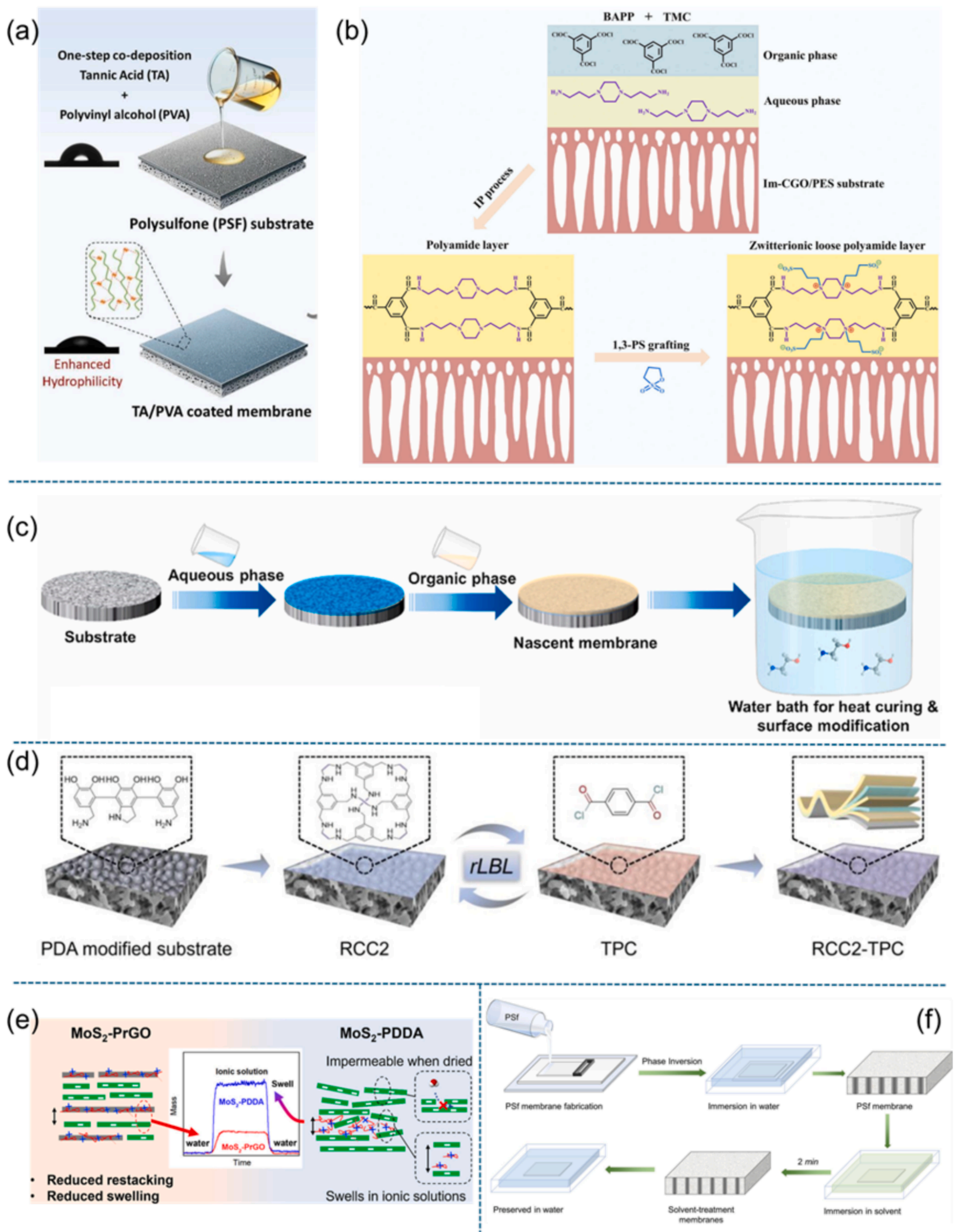

Fig. 8. Overview of various surface modification methods. (a) Schematic diagram of the fabrication process of a tannic acid (TA)/polyvinyl alcohol (PVA) coated PSf membrane [115]. (b) Schematic diagram of the membrane fabrication process through interfacial polymerization between 1,4-bis(3-aminopropyl)piperazine (BAPP) and TMC on an imidazole-modified carboxylated GO/PES (Im-CGO/PES) substrate, and subsequent grafting of 1,3-propanesulfonate (1,3-PS) [116]. (c) Schematic diagram of the membrane fabrication process through a combination of heat curing and surface modification [117]. (d) Schematic diagram of the membrane fabrication process using reactive layer-by-layer (rLBL) assembly to prepare RCC2-TPC membranes on a PDA-modified substrate [65]. (e) Swell resistance of negatively charged molybdenum disulfide (MoS_2) nanosheets assembled with either positively charged graphene oxide (PrGO) or positively charged polymer (PDDA) [118]. (f) Schematic diagram of the membrane fabrication process for post-treated PSf membranes using organic solvents [48].

antifouling/antibacterial performance [119,120].

Surface coating is one of the most widely used and relatively simple methods for membrane surface modification. Various coating materials have been developed for modifying NF membranes, such as PEG-based coatings [121,122], hyperbranched polymer coatings [123,124], and PDA coatings formed through physical adsorption [125,126]. These coatings significantly enhance membrane hydrophilicity and surface smoothness [127,128]. For instance, Alkhouzaam et al. [115] coated a PSf membrane with tannic acid and polyvinyl alcohol, reducing the water contact angle from 68.2° to 49° (Fig. 8**a**). This effect led to an increase in the water permeance to 138 $Lm^{-2}h^{-1}$ bar^{-1} while achieving a CR rejection of 99%. However, the durability of this method is a concern, as the coating may degrade during long-term operation, diminishing its performance-enhancing effects.

In contrast, surface grafting involves chemical reactions to introduce functional polymers through covalent bonds on the membrane surface, resulting in a more stable modification. This method typically employs amidation or esterification reactions to graft functional polymers onto functional groups (e.g., amino or carboxyl groups) present on the membrane surface, enhancing membrane hydrophilicity and improving antifouling performance in textile wastewater treatment. For example, Geng et al. [116] introduced a reaction between 1,4-bis(3-aminopropyl) piperazine and TMC during the IP process to form a PA membrane with exposed tertiary amine groups (Fig. 8**b**). Subsequent quaternization increased the hydrophilicity, reducing the contact angle of the membrane from 63.0 to 47° and achieving a water permeance of 148.5 $Lm^{-2}h^{-1}$ bar^{-1}. The membrane demonstrated a high removal efficiency of 98.1% and 97.6% for humic acid and CR, respectively, and excellent antifouling performance, reflected through its high flux recovery rates of 93.3% and 91.8% for BSA and humic acid, respectively. Similarly, Zhan et al. [117] grafted monoethanolamine onto the carboxyl groups of a nascent PA membrane, enhancing the membrane hydrophilicity (Fig. 8**c**). The rough surface morphology and increased pore size improved water permeance from 7.9 $Lm^{-2}h^{-1}$ bar^{-1} to 19.5 $Lm^{-2}h^{-1}$ bar^{-1}, while maintaining a Na_2SO_4 rejection of 97.5%.

The LBL technique, achieved by sequentially depositing different materials onto the membrane surface to form multilayered structures, provides a highly versatile modification approach. This method leverages interactions such as electrostatic forces, hydrogen bonding, and hydrophobic effects to achieve precise control over membrane performance [129]. For example, Zhang et al. [65] developed an ion-sieving membrane based on porous organic cages via LBL assembly (Fig. 8**d**). The resultant membrane exhibited a narrow pore size distribution (μ_p = 0.66 nm, σ_p = 1.27) and a significantly negative surface potential (−30 mV), demonstrating a high Cl^-/SO_4^{2-} selectivity for 277.3. Furthermore, the multilayer structure resulting from LBL assembly can enhance the mechanical strength and chemical stability of NF membranes. For instance, Wang et al. [118] assembled negatively charged MoS_2 nanosheets with positively charged graphene oxide (PrGO) nanosheets via electrostatic attraction to create an $MoS_2 - PrGO$ membrane. Due to the size, charge density, and orderly stacking of the nanosheets, the membrane exhibited excellent stability under high salinity conditions (750 mM), with a swelling ratio of less than 60% (Fig. 8**e**), high water permeance (70 $Lm^{-2}h^{-1}$ bar^{-1}), and an 80% rejection of the dye Victoria Blue. This approach provides insights into the development of membrane materials resistant to high-salinity environments.

Surface modification techniques play a crucial role in optimizing the performance of NF membranes for resource recovery from textile wastewater. These techniques contribute to the membrane performance in three key aspects. First, the separation efficiency of the membrane can be enhanced through surface modification through the improvement of the hydrophilicity, porosity, and charge distribution of the membrane surface. Specifically, this can be achieved through coating hydrophilic layers, grafting charged or hydrophilic functional polymers, or assembling multilayer structures with high charge density through LBL assembly. These modifications enhance the rejection of dyes and salts while achieving an effective balance between high water permeability and high selectivity. Second, the membrane robustness can be improved, by introducing hydrophilic coatings (e.g., PEG or PDA), grafting antibacterial groups (e.g., quaternary ammonium salts), and assembling functional nanomaterials (e.g., silver nanoparticles) via LBL assembly, which significantly enhance the antifouling and antibacterial properties of membranes. Additionally, increasing the cross-linking density of the membrane, introducing acid-resistant groups (e.g., sulfonic groups), or employing electrostatic LBL assembly to create well-ordered multilayer composite membranes, improves stability and separation performance under high-salinity or chemically harsh environments.

4.4. *Post-treatment methods*

Post-treatment methods, including heat treatment, solvent treatment, chemical cleaning, and oxidation, are simple and effective modification techniques for NF membranes [130]. Among these, heat treatment (e.g., at a temperature of 60 to 70 °C) is often used as an auxiliary method following the IP process to enhance the cross-linking degree of the membrane, thereby improving its stability in textile wastewater treatment [131].

Solvent treatment has garnered significant attention due to its simple and efficient nature, with its primary approaches being solvent activation and solvent annealing. Solvent activation can enhance water permeance while maintaining high rejection. This process causes swelling of the skin layer of the membrane, increasing the free volume of the membrane and creating a more open structure, thereby significantly enhancing water flux. However, the swelling-induced reduction in network modulus makes the polymer chains more flexible, eliminating loose regions and enhancing solute rejection capabilities [132]. The effect of solvent activation can be adjusted by selecting solvents with appropriate solubility, which is closely related to the Hansen solubility parameters [133]. For example, Shin et al [134] selected benzyl alcohol for its appropriate solvency power to enhance PA layer swelling while effectively minimizing structural deformation. This approach resulted in a substantial increase in water permeance by 140 % while simultaneously preserving a high NaCl rejection of 99.6 %. Moreover, solvent annealing induces the rearrangement of polymer chains through favorable interactions between the solvent and the polymer, forming a denser, lower-energy structure that enhances separation performance [135]. This mechanism includes strengthening interchain interactions (e.g., hydrogen bonding or π-π stacking) and promoting the mobility of cross-linking agents within the matrix, further increasing the degree of cross-linking [136,137]. For instance, in the treatment of dye wastewater, Liu *et al.* [48] conducted a post-treatment using n-hexane to PSf membranes (Fig. 8**f**), leading to a high rejection of 99% for Direct Red 23 and CR, even under highly alkaline conditions (pH = 13). It should be noted that factors such as solvent type and treatment duration affect the degree of solvation and chain rearrangement, thereby determining the extent of membrane densification and performance optimization [138,139].

Post-treatment methods can effectively enhance the separation efficiency of NF membranes. For example, solvent activation increases the free volume of the membrane through surface swelling, significantly improving water permeability, while enhancing the membrane structure to increase the rejection of dyes and salts. Heat treatment and solvent annealing improve the cross-linking degree and structural stability of membranes, thereby enhancing their durability under high-salinity and extreme pH environments. Therefore, post-treatment techniques can significantly improve the stability and separation performance of NF membranes used for resource recovery of textile wastewater, providing robust technical support.

5. Outlook and future perspective

While NF membranes show great promise for resource recovery and water reuse in textile wastewater treatment, realizing their full potential requires addressing several technical challenges and optimizing specific membrane characteristics. In the following, key areas of future research will be explored, focusing on enhancing membrane performance and developing integrated processes for large-scale applications.

Optimizing the relationship between pore size distribution and dye cluster separation efficiency: The separation performance of NF membranes is significantly influenced by the inherent properties of the target substances. In practical applications, the rejection of NF membranes for dyes is often higher than theoretically predicted. This discrepancy is primarily attributed to the aggregation of dye molecules into clusters in solution, which improves the actual separation efficiency. However, unresolved issues remain, including the degree of dye aggregation, the number of clusters formed, and the impact of membrane pore size on the passage of these clusters. Therefore, future research should focus on optimizing pore size distribution and systematically investigating the critical relationship between pore size and dye cluster size to maximize separation efficiency.

Enhancing the alkali resistance of NF membranes: Mercerized wastewater often contains high concentrations of alkaline substances, with NaOH content typically ranging from 3 to 5%. While dyeing factories can concentrate and recover NaOH through evaporation, the final discharged wastewater remains strongly alkaline. This introduces the need for NF membranes with a certain level of alkali resistance. Increasing the negative charge density on the membrane surface (e.g., by introducing carboxyl or sulfonic groups) can leverage electrostatic repulsion to reduce direct contact between OH^- ions and the membrane material, thus lowering the risk of alkaline hydrolysis. Additionally, introducing monomers with alkali resistance leads to the formation of denser cross-linked networks, reducing the swelling degree of the membrane in alkaline environments, while simultaneously constructing a hydrophilic membrane surface. Hydrophilic groups can form hydrogen bonds with water molecules, enhancing the interaction between the membrane material and water, thus reducing chemical degradation of the membrane under alkaline conditions.

Improving membrane antifouling performance: During dye wastewater treatment, dye molecules tend to adsorb onto the membrane surface, forming a “cake layer”, which leads to membrane fouling, flux decline, and reduced performance. To address this issue, two approaches can be adopted. First, efficient pretreatment technologies can remove suspended solids and macromolecular contaminants from the feed solution, ultimately reducing the fouling load on the membrane. Second, foulant-resistant membranes, such as hydrophilic NF membranes, which reduce dye molecule adsorption through a hydrated layer and enhance charge repulsion, can be prepared. For example, constructing dual-charge membranes or biomimetic fish-scale structures can achieve graded pore distribution and further improve the membrane antifouling ability.

Enhancing solvent resistance of NF membranes: As most of the dye molecules adsorbed on the membrane dissolve well in organic solvents, membrane cleaning typically requires chemical backwashing. However, the strong affinity between the separation layer and organic solvents can lead to membrane swelling, which in turn results in a declined separation performance. Therefore, future research should focus on developing NF membranes with higher solvent resistance for textile wastewater treatment. For example, incorporating rigid twisted and non-planar structures (such as helical rings, bridged rings, or benzene rings) can inhibit the mobility of polymer chains, reducing solvent penetration and swelling effects, thus improving solvent resistance. Furthermore, incorporating highly cross-linked membrane layers can effectively limit molecular chain swelling and reduce organic solvent erosion through physical barriers. Additionally, organic–inorganic hybrid materials combine the flexibility of organic polymers with the high chemical stability of inorganic components (such as silica, alumina, or MOF materials), significantly enhancing the solvent resistance of the NF membranes.

Promoting full-process optimization research: Research on NF membranes for textile wastewater treatment is mostly limited to laboratory-scale studies, typically focusing on individual processes such as dye removal or heavy metal recovery. These studies often fail to integrate these processes into a comprehensive wastewater treatment system. While promising, the results do not fully reflect the complexity of real-world applications, such as the impact of fluctuations in wastewater composition, temperature, and pH on membrane performance and longevity. As technology advances toward large-scale applications, future research should focus on exploring the entire process flow, from pretreatment, and membrane filtration, to resource recovery. This requires the development of integrated processes that should consider the performance of individual membranes and also their synergy with other treatment technologies, such as microfiltration, electrodialysis, or biological treatment. Full-process research will support researchers in optimizing membrane performance within real wastewater treatment systems, ensuring long-term stability, cost-effectiveness, and efficient resource recovery.

6. Conclusions

This review provides a comprehensive overview of the role of NF membranes in resource recovery from textile wastewater. Compared to traditional processes such as evaporation, chemical precipitation, and adsorption, NF membranes offer significant advantages, including lower energy consumption, reduced chemical use, and high selectivity. NF membranes enable efficient resource recovery: LNF membranes allow high-flux dye recovery, while dense NF membranes excel in the selective separation of salts and heavy metals recovery. Integrating NF membranes with other technologies, such as UF, EC, ED, and BMED, can enhance recovery efficiency while expanding the range of recoverable resources. Additionally, advancements in membrane modification, encompassing substrate preparation, interfacial polymerization, surface modification, and post-treatment methods, have significantly refined key membrane properties, such as pore size distribution, surface charge, and hydrophilicity. These targeted improvements have enhanced the performance of NF membranes in resource recovery applications.

Despite these advancements, challenges remain. Trade-offs between flux and rejection, stability under extreme operating conditions, and membrane fouling require further investigation. Future efforts should prioritize the development of robust NF membranes, optimization of hybrid treatment systems, and validation of performance on an industrial scale. By addressing these challenges, NF membranes hold the potential to transform textile wastewater treatment, delivering environmental and economic benefits, advancing sustainable water management, and contributing to the circular economy.

CRediT authorship contribution statement

Yanyan Liu: Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Junyong Zhu:** Writing – review & editing. **MingShuo Chi:** Visualization. **Gilles Van Eygen:** Writing – review & editing. **Kecheng Guan:** Writing – review & editing. **Hideto Matsuyama:** Writing – review & editing, Funding acquisition.

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] C. Aydiner, E.C. Dogan, B.K. Mert, B. Pala, T.N. Demirozlu, E. Balci, S.T. Yakin, C. Tongel, A.O. Narci, Holistic managements of textile wastewater through circular, greener and eco-innovative treatment systems developed by minimal to zero liquid discharge, Chem. Eng. J. 486 (2024) 150165.

[2] U. Ewuzie, O.D. Saliu, K. Dulta, S. Ogunniyi, A.O. Bajeh, K.O. Iwuozor, J. O. Ighalo, A review on treatment technologies for printing and dyeing wastewater (PDW), J. Water Process Eng. 50 (2022) 103273.

[3] H. Tang, M. Shan, Q. Cheng, R. Wen, S. Liu, H. Zeng, J. Yu, J. Luo, Rapid pretreatment strategy to control nanofiltration membrane fouling in recycling of real textile wastewater: Comparison and mechanisms, Chem. Eng. J. 152913 (2024).

[4] J. Georgin, D.S.P. Franco, Y. Dehmani, P. Nguyen-Tri, N. El Messaoudi, Current status of advancement in remediation technologies for the toxic metal mercury in the environment: a critical review, Sci. Total Environ. 174501 (2024).

[5] L. Siliņa, I. Dāboliņa, E. Lapkovska, Sustainable textile industry–wishful thinking or the new norm: a review, J. Eng. Fiber. Fabr. 19 (2024) 15589250231220359.

[6] S. Varjani, P. Rakholiya, T. Shindhal, A.V. Shah, H.H. Ngo, Trends in dye industry effluent treatment and recovery of value added products, J. Water Process Eng. 39 (2021) 101734.

[7] S. Zhang, Q. Du, K. Cheng, M. Antonietti, F. Yang, Efficient phosphorus recycling and heavy metal removal from wastewater sludge by a novel hydrothermal humification-technique, Chem. Eng. J. 394 (2020) 124832.

[8] T. Adane, A.T. Adugna, E. Alemayehu, Textile industry effluent treatment techniques, J. Chem. 2021 (2021) 5314404.

[9] J. Georgin, D.S.P. Franco, M.S. Manzar, L. Meili, N. El Messaoudi, A critical and comprehensive review of the current status of 17β-estradiol hormone remediation through adsorption technology, Environ. Sci. Pollut. r. 31 (2024) 24679–24712.

[10] N. El Messaoudi, D.S.P. Franco, S. Gubernat, J. Georgin, Z.M. Şenol, Z. Ciğeroğlu, D. Allouss, M. El Hajam, Advances and future perspectives of water defluoridation by adsorption technology: A review, Environ. Res. 118857 (2024).

[11] E. Kurtulbaş, Z. Ciğeroğlu, S. Şahin, N. El Messaoudi, V. Mehmeti, Monte Carlo, molecular dynamic, and experimental studies of the removal of malachite green using g-C3N4/ZnO/Chitosan nanocomposite in the presence of a deep eutectic solvent, Int. J. Biol. Macromol. 274 (2024) 133378.

[12] W. Lu, N. Chen, C. Feng, Y. Deng, Z. Feng, Y. Hu, T. Liu, W. Hu, A bifunctional graphene-based cathode for wastewater treatment in heterogeneous electro-fenton: taking textile, old landfill leachate and simulated antibiotic wastewater as examples, Chem. Eng. J. 468 (2023) 143780.

[13] T. Mohapatra, P. Ghosh, Photo-Fenton remediation of textile wastewater in fluidized-bed reactor using modified laterite: hydrodynamic study and effect of operating parameters, Chem. Eng. J. 473 (2023) 145324.

[14] Y. Miyah, N. El Messaoudi, M. Benjelloun, J. Georgin, D.S.P. Franco, Y. Acikbas, H.S. Kusuma, M. Sillanpää, MOF-derived magnetic nanocomposites as potential formulations for the efficient removal of organic pollutants from water via adsorption and advanced oxidation processes: a review, Mater. Today Sustain. (2024) 100985.

[15] S. Min, H. Lee, L. Deng, W. Guo, B. Xu, H. Ng, Ch. Mehmood, Z. Zhong, R. Zamora, E. Khan, S. Dash, J. Kim, M. Pishnamazi, P. Park, S. Chae, Advanced strategies for mitigation of membrane fouling in anaerobic membrane bioreactors for sustainable wastewater treatment, Chem. Eng. J. 149996 (2024).

[16] A. Ghazal, A. Shaheen, S. AlBlooshi, M. Almehrzi, R.A. Ismail, N. AlAmoodi, S. Hong, F. AlMarzooqi, Plasmonic titanium nitride-based membranes for solar-driven domestic wastewater distillation treatment, Chem. Eng. J. 484 (2024) 149594.

[17] Y. Miyah, N. El Messaoudi, M. Benjelloun, Y. Acikbas, Z.M. Şenol, Z. Ciğeroğlu, E. A. Lopez-Maldonado, Advanced applications of hydroxyapatite nanocomposite materials for heavy metals and organic pollutants removal by adsorption and photocatalytic degradation: a review, Chemosphere 142236 (2024).

[18] N. El Messaoudi, M. Ulfa, A. Hamzah, Z.A.A. Hamid, D.V. Ramadhani, L. Suryanegara, M. Mahardika, A.T. Melenia, A.W. Pratama, D. Prasetyoko, Fabrication a sustainable adsorbent nanocellulose-mesoporous hectorite bead for methylene blue adsorption, Case Stud. Chem. Environ. Eng. 10 (2024) 100850.

[19] T. Wu, Z. Hu, J. Yang, Y. Jia, Z. Dong, Y. Tang, Y. Zhang, Insight into the roles of Cl− for the degradation of acid Red 14 in an electrochemical advanced oxidation system: mechanisms and DFT studies, Chem. Eng. J. 158079 (2024).

[20] O.M. Rodríguez-Narváez, A.R. Picos, N. Bravo-Yumi, M. Pacheco-Alvarez, C. A. Martínez-Huitle, J.M. Peralta-Hernández, Electrochemical oxidation technology to treat textile wastewaters, Curr. Opin. Electroche. 29 (2021) 100806.

[21] N.Y. Donkadokula, A.K. Kola, I. Naz, D. Saroj, A review on advanced physico-chemical and biological textile dye wastewater treatment techniques, Rev. Environ. Sci. Biotechnol. 19 (2020) 543–560.

[22] D. Xu, J. Zheng, X. Zhang, D. Lin, Q. Gao, X. Luo, X. Zhu, G. Li, H. Liang, B. Van der Bruggen, Mechanistic insights of a thermoresponsive interface for fouling control of thin-film composite nanofiltration membranes, Environ. Sci. Technol. 56 (2022) 1927–1937.

[23] Y. Liu, S. Yuan, M. Chi, Y. Wang, G. Van Eygen, R. Zhao, X. Zhang, G. Li, A. Volodine, S. Hu, J. Zheng, B. Van der Bruggen, Efficient capture of endocrine-disrupting compounds by a high-performance nanofiltration membrane for wastewater treatment, Water Res. 227 (2022) 119322.

[24] Y. Liu, X. Zhang, M. Chi, H. Matsuyama, Y. Guo, K. Simoens, A. Volodine, R. Dewil, J. Zheng, Z. Dai, Advancing drinking water safety: Facile fabrication of nanofiltration membrane for enhanced antibiotics removal and efficient water softening, Desalination 591 (2024) 118024.

[25] Z. Zhang, Y. Song, L. Xie, Q. Liu, J. Li, B. Zhang, A loose polyethersulfone hybrid nanofiltration membrane incorporated with polyethyleneimine-decorated silica nanoparticles for highly-efficient dye/salt separation, Chem. Eng. J. 487 (2024) 150643.

[26] T. Tavangar, M. Karimi, M. Rezakazemi, K.R. Reddy, T.M. Aminabhavi, Textile waste, dyes/inorganic salts separation of cerium oxide-loaded loose nanofiltration polyethersulfone membranes, Chem. Eng. J. 385 (2020) 123787.

[27] S. Guo, Y. Wan, X. Chen, J. Luo, Loose nanofiltration membrane custom-tailored for resource recovery, Chem. Eng. J. 409 (2021) 127376.

[28] X. Feng, D. Peng, J. Zhu, Y. Wang, Y. Zhang, Recent advances of loose nanofiltration membranes for dye/salt separation, Sep. Purif. Technol. 285 (2022) 120228.

[29] P. Jin, J. Zheng, Q. Gao, A.K. An, J. Zhu, B. Van Der Bruggen, Loose nanofiltration membranes for the treatment of textile wastewater: a review, J. Membr. Sci. Res. 8 (2022) 538529.

[30] N. El Messaoudi, Y. Miyah, M. Benjelloun, J. Georgin, D.S. Franco, Z.M. Şenol, Z. Ciğeroğlu, M. El Hajam, S. Knani, P. Nguyen-Tri, A comprehensive review on designing nanocomposite adsorbents for efficient removal of 4-nitrophenol from water, Nano-Struct. Nano-Objects. 40 (2024) 101326.

[31] N. El Messaoudi, Y. Miyah, Z.M. Şenol, Z. Ciğeroğlu, E.S. Kazan-Kaya, S. Gubernat, J. Georgin, D.S. Franco, Comprehensive analytical review of heavy metal removal efficiency using agricultural solid waste-based bionanocomposites, Nano-Struct. Nano-Objects. 38 (2024) 101220.

[32] A. Azanaw, B. Birlie, B. Teshome, M. Jemberieg, Textile effluent treatment methods and eco-friendly resolution of textile wastewater, Case Stud. Chem. Environ. Eng. 6 (2022) 100230.

[33] N. Jahan, M. Tahmid, A.Z. Shoronika, A. Fariha, H. Roy, M.N. Pervez, Y. Cai, V. Naddeo, M.S. Islam, A comprehensive review on the sustainable treatment of textile wastewater: zero liquid discharge and resource recovery perspectives, Sustainability. 14 (2022) 15398.

[34] M. Behera, J. Nayak, S. Banerjee, S. Chakrabortty, S.K. Tripathy, A review on the treatment of textile industry waste effluents towards the development of efficient mitigation strategy: An integrated system design approach, J. Environ. Chem. Eng. 9 (2021) 105277.

[35] Z. Ma, H. Chang, Y. Liang, Y. Meng, L. Ren, H. Liang, Research progress and trends on state-of-the-art membrane technologies in textile wastewater treatment, Sep. Purif. Technol. 333 (2024) 125853.

[36] R. Zhao, Y. Li, Y. Mao, G. Li, T. Croes, J. Zhu, X. You, A. Volodin, J. Zheng, B. Van der Bruggen, Recycling the high-salinity textile wastewater by quercetin-based nanofiltration membranes with minimal water and energy consumption, Environ. Sci. Technol. 56 (2022) 17998–18007.

[37] C. Yang, W. Xu, Y. Nan, Y. Wang, X. Chen, Novel negatively charged nanofiltration membrane based on 4, 4′-diaminodiphenylmethane for dye removal, Sep. Purif. Technol. 248 (2020) 117089.

[38] S. Castano Osorio, P.M. Biesheuvel, E. Spruijt, J.E. Dykstra, A., van der Wal, Modeling micropollutant removal by nanofiltration and reverse osmosis membranes: considerations and challenges, Water Res. 225 (2022) 119130.

[39] Y. Chen, F. Liu, Y. Wang, H. Lin, L. Han, A tight nanofiltration membrane with multi-charged nanofilms for high rejection to concentrated salts, J. Membrane Sci. 537 (2017) 407–415.

[40] J. He, H. Wu, F. Ni, F. Shen, Y. Zhang, Z. Cheng, M. Huang, L. Zhao, L. Luo, X. An, Mechanistic insight into developing a novel loose nanofiltration membrane for effective dye/salt separation by epigallocatechin gallate, Sep. Purif. Technol. 318 (2023) 123983.

[41] Y. He, X. Lin, Fabricating compact covalent organic framework membranes with superior performance in dye separation, J. Membrane Sci. 637 (2021) 119667.

[42] R. Cai, X. Tan, Y. Chen, Y. Zhou, X. Liu, J. Hu, J. Lu, M. Ding, C. Meng, W. Liu, Y. Chen, Self-supported hydrogel loose nanofiltration membrane for dye/salt separation, Sep. Purif. Technol. 328 (2024) 124982.

[43] M. Ji, Z. Wang, Y. Zhu, L. Shan, Y. Lu, Y. Zhang, Y. Zhang, J. Jin, Thin-film composite nanofiltration membrane with unprecedented stability in strong acid for highly selective dye/NaCl separation, J. Membrane Sci. 645 (2022) 120189.

[44] Y. Lu, W. Fang, J. Kong, F. Zhang, Z. Wang, X. Teng, Y. Zhu, J. Jin, A microporous polymer ultrathin membrane for the highly efficient removal of dyes from acidic saline solutions, J. Membrane Sci. 603 (2020) 118027.

[45] Y. Liu, G. Van Eygen, S. Yuan, H. Wang, M. Chi, D. Xu, B. Van der Bruggen, Facile and novel fabrication of high-performance loose nanofiltration membranes for textile wastewater recovery, Sep. Purif. Technol. 308 (2023) 122867.

[46] S. Tang, Y. Chen, H. Zhang, T. Zhang, P. Wang, H. Sun, A novel loose nanofiltration membrane with high permeance and anti-fouling performance based on aqueous monomer piperazine-2-carboxylic acid for efficient dye/salt separation, Chem. Eng. J. 475 (2023) 146111.

[47] W.T. Lin, P. Fu, W.L. Li, Y.H. Yu, Z.L. Zhang, H.Y. Fan, X.J. Huang, Z.K. Xu, L. S. Wan, Cross-linked g-C3N4 nanofibers enable thermal stable composite membranes for high-performance loose nanofiltration, Chem. Eng. J. 494 (2024) 153197.

[48] Y. Liu, R. Dewil, X. Zhang, Y. Li, R. Todd, M. Chi, D. Xu, G. Li, P. Jin, J. Zheng, B. Van der Bruggen, Facile post-treatment of PSf membranes with hexane for fractionation and concentration of alkaline textile wastewater, Chem. Eng. J. 475 (2023) 146274.

[49] B. Yuan, S. Zhang, C. Jiang, P. Hu, J. Cui, S. Zhao, N. Wang, Q.J. Niu, Alicyclic polyamide nanofilms with an asymmetric structure for Cl−/SO42− separation, AIChE J 68 (2022) e17419.
[50] P. Xu, S. Duan, Z. Li, M. Hu, P. Zhang, L. Dai, Z. Mai, K. Guan, H. Matsuyama, Charge-sign-independent separation of mono-and divalent ions with nanofiltration membranes, Adv. Funct. Mater. 2416458 (2024).
[51] S. Guo, J. Du, F. Yan, Z. Wang, J. Wang, Fabrication of anti-fouling polyamide nanofiltration membrane by incorporating streptomycin as a novel co-monomer, Chinese J Chem. Eng. 50 (2022) 185–196.
[52] X. Zhai, S. Lin, X. Li, Z. Wang, The hidden role of the dielectric effect in nanofiltration: a novel perspective to unravel new ion separation mechanisms, Environ. Sci. Technol. 58 (2024) 15874–15884.
[53] N.S. Suhalim, N. Kasim, E. Mahmoudi, I.J. Shamsudin, A.W. Mohammad, F. Mohamed Zuki, N. Jamari, Rejection mechanism of ionic solute removal by nanofiltration membranes: an overview, Nanomaterials 12 (2022) 437.
[54] K. Wang, X. Wang, B. Januszewski, Y. Liu, D. Li, R. Fu, M. Elimelech, X. Huang, Tailored design of nanofiltration membranes for water treatment based on synthesis–property–performance relationships, Chem. Soc. Rev. 51 (2022) 672–719.
[55] L. Pino-Soto, A. Schwarz, C. Vargas, F. Saravia, H. Horn, R. Bórquez, Influence of multivalent-electrolyte metal solutions on the superficial properties and performance of a polyamide nanofiltration membrane, Sep. Purif. Technol. 272 (2021) 118846.
[56] C. Liu, L. Shi, R. Wang, Crosslinked layer-by-layer polyelectrolyte nanofiltration hollow fiber membrane for low-pressure water softening with the presence of SO42− in feed water, J. Membrane Sci. 486 (2015) 169–176.
[57] B. Yuan, N. Wang, S. Zhao, P. Hu, J. Jiang, J. Cui, X. Zhang, M. You, X. Lou, Q. J. Niu, Polyamide nanofiltration membrane fine-tuned via mixed matrix ultrafiltration support to maximize the sieving selectivity of Li+/Mg^{2+} and Cl−/SO_4^{2-}, Desalination 538 (2022) 115929.
[58] Z. Liu, Z. Mi, L. Meng, Y. Huang, D. Zhang, J. Wang, K. Zhang, J. Xiao, P. Liu, Z. Rao, H. He, S. Wang, Quaternary ammonium salts modification preparing charged Janus nanofiltration membrane for the simultaneous separation of divalent anions and cations, J. Membrane Sci. 672 (2023) 121440.
[59] Q. Chen, Y. Zhu, C. Jiang, W. Song, Q. Ye, H. He, Z. Ding, R. Fu, Z. Liu, L. Ge, Pilot-scale poly (alkyl-biphenyl pyridine)-based monovalent anion perm-selective membranes with exceptional Cl−/SO42− selectivity in ion-distillation, J. Membrane Sci. 702 (2024) 122787.
[60] J. Zhang, Y. Yang, Q. Zhang, D. Yang, X. Shang, J. Yang, X.-M. Wang, F. Dai, J. Zhao, Y. Zhao, Thin film composite nanofiltration membrane with tannic acid self-assembled coating as an interlayer achieves high selectivity by enhancing size exclusion effect, J. Membrane Sci. 701 (2024) 122742.
[61] Y. Chen, S.-L. Li, D. Cheng, J. Li, M. Wang, Q. Duan, G. Gong, Y. Hu, Thin film composite polyesteramide membrane with the incorporation of rigidly-contorted binaphthol-based monomer for enhanced nanofiltration separation performance, Sep. Purif. Technol. 322 (2023) 124376.
[62] A. Tang, C. Fang, W. Feng, J. Lu, J. Li, L. Zhu, Engineering novel thin-film composite membranes with crater-like surface morphology using rigidly-contorted monomer for high flux nanofiltration, Desalination 509 (2021) 115067.
[63] S. Xu, H. Lin, G. Li, J. Wang, Q. Han, F. Liu, Anionic covalent organic framework as an interlayer to fabricate negatively charged polyamide composite nanofiltration membrane featuring ions sieving, Chem. Eng. J. 427 (2022) 132009.
[64] Y. Zhang, Y. Chen, M. Wang, W. Su, H. Li, P. Li, X. Zhang, Preparation of high temperature resistant polyamide composite nanofiltration membranes by thermally assisted interfacial polymerization, J. Membrane Sci. 687 (2023) 122020.
[65] Y. Zhang, Z. Hao, I. Hussein, Z. Wang, S. Zhao, Tunable ionic sieving membrane via reactive layer-by-layer assembly of porous organic cages, Adv. Funct. Mater. 34 (2024) 2315750.
[66] B.A.M. Al-Rashdi, D.J. Johnson, N. Hilal, Removal of heavy metal ions by nanofiltration, Desalination 315 (2013) 2–17.
[67] R.M. DuChanois, N.J. Cooper, B. Lee, S.K. Patel, L. Mazurowski, T.E. Graedel, M. Elimelech, Prospects of metal recovery from wastewater and brine, Nat. Water. 1 (2023) 37–46.
[68] X. Lu, B. Liu, X. Zhu, L. Wang, H. Chang, Z. Yang, D. Xu, R. Wu, F. Shao, J. Xu, Multiple modulating energy-efficient nanofiltration membranes during high-quality drinking water towards high mineral/organic matter selectivity, Desalination 588 (2024) 117970.
[69] J. Zheng, Y. Li, D. Xu, R. Zhao, Y. Liu, G. Li, Q. Gao, X. Zhang, A. Volodine, B. Van der Bruggen, Facile fabrication of a positively charged nanofiltration membrane for heavy metal and dye removal, Sep. Purif. Technol. 282 (2022) 120155.
[70] P. Li, H. Lan, K. Chen, X. Ma, B. Wei, M. Wang, P. Li, Y. Hou, Q.J. Niu, Novel high-flux positively charged aliphatic polyamide nanofiltration membrane for selective removal of heavy metals, Sep. Purif. Technol. 280 (2022) 119949.
[71] H. Zhang, S. Zhu, J. Yang, A. Ma, W. Chen, Enhanced removal efficiency of heavy metal ions by assembling phytic acid on polyamide nanofiltration membrane, J. Membrane Sci. 636 (2021) 119591.
[72] Y. Zhao, G.S. Lai, C. Li, R. Wang, Acid-resistant polyamine hollow fiber nanofiltration membrane for selective separation of heavy metals and phosphorus, Chem. Eng. J. 453 (2023) 139825.
[73] A.K. Shukla, J. Alam, M. Alhoshan, L.A. Dass, F.A.A. Ali, U. Mishra, M.A. Ansari, Removal of heavy metal ions using a carboxylated graphene oxide-incorporated polyphenylsulfone nanofiltration membrane, Environ. Sci.:Water Res Technol. 4 (2018) 438–448.
[74] M. Peydayesh, T. Mohammadi, O. Bakhtiari, Water desalination via novel positively charged hybrid nanofiltration membranes filled with hyperbranched polyethyleneimine modified MWCNT, J. Ind. Eng. Chem. 69 (2019) 127–140.
[75] W.P. Zhu, J. Gao, S.P. Sun, S. Zhang, T.S. Chung, Poly (amidoamine) dendrimer (PAMAM) grafted on thin film composite (TFC) nanofiltration (NF) hollow fiber membranes for heavy metal removal, J. Membrane Sci. 487 (2015) 117–126.
[76] J. Li, Y. Song, D. Xu, X. Zhang, J. Du, R. Liu, R. Zhao, Q. Chen, A. Volodine, R. Dewil, Q. Gao, B. Van der Bruggen, Choline chloride modification of nanofiltration membranes for improving heavy metal ions separation in wastewater, J. Membrane Sci. 708 (2024) 123079.
[77] B.Q. Huang, Y.J. Tang, A.R. Gao, Z.X. Zeng, S.M. Xue, C.H. Ji, C.Y. Tang, Z.L. Xu, Dually charged polyamide nanofiltration membranes fabricated by microwave-assisted grafting for heavy metals removal, J. Membrane Sci. 640 (2021) 119834.
[78] X.Y. Gong, Z.H. Huang, H. Zhang, W.L. Liu, X.H. Ma, Z.L. Xu, C.Y. Tang, Novel high-flux positively charged composite membrane incorporating titanium-based MOFs for heavy metal removal, Chem. Eng. J. 398 (2020) 125706.
[79] Y. Qi, L. Zhu, X. Shen, A. Sotto, C. Gao, J. Shen, Polythyleneimine-modified original positive charged nanofiltration membrane: removal of heavy metal ions and dyes, Sep. Purif. Technol. 222 (2019) 117–124.
[80] B. Keskin, M.E. Ersahin, H. Ozgun, I. Koyuncu, Pilot and full-scale applications of membrane processes for textile wastewater treatment: a critical review, J. Water Process Eng. 42 (2021) 102172.
[81] I. Ćurić, D. Dolar, J. Bošnjak, Reuse of textile wastewater for dyeing cotton knitted fabric with hybrid treatment: coagulation/sand filtration/UF/NF-RO, J. Environ. Manage. 295 (2021) 113133.
[82] M. Ağtaş, Ö. Yılmaz, M. Dilaver, K. Alp, İ. Koyuncu, Pilot-scale ceramic ultrafiltration/nanofiltration membrane system application for caustic recovery and reuse in textile sector, Environ. Sci. Pollut. r. 28 (2021) 41029–41038.
[83] J. Lin, Q. Chen, X. Huang, Z. Yan, X. Lin, W. Ye, S. Arcadio, P. Luis, J. Bi, B. Van der Bruggen, Integrated loose nanofiltration-electrodialysis process for sustainable resource extraction from high-salinity textile wastewater, J. Hazard. Mater. 419 (2021) 126505.
[84] J. Lin, W. Ye, J. Huang, B. Ricard, M. Baltaru, B. Greydanus, S. Balta, J. Shen, M. Vlad, A. Sotto, L. patricia, B. Van der Bruggen, Toward resource recovery from textile wastewater: dye extraction, water and base/acid regeneration using a hybrid NF-BMED process, ACS Sustain, Chem. Eng. 3 (2015) 1993–2001.
[85] 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 (2022) 102478.
[86] T. Tavangar, K. Jalali, M.A.A. Shahmirzadi, M. Karimi, Toward real textile wastewater treatment: membrane fouling control and effective fractionation of dyes/inorganic salts using a hybrid electrocoagulation–nanofiltration process, Sep. Purif. Technol. 216 (2019) 115–125.
[87] K. Li, Q. Liu, F. Fang, X. Wu, J. Xin, S. Sun, Y. Wei, R. Ruan, P. Chen, Y. Wang, M. Addy, Influence of nanofiltration concentrate recirculation on performance and economic feasibility of a pilot-scale membrane bioreactor-nanofiltration hybrid process for textile wastewater treatment with high water recovery, J. Clean. Prod. 261 (2020) 121067.
[88] M.S. Saad, L. Balasubramaniam, M.D.H. Wirzal, N.S. Abd Halim, M.R. Bilad, N.A. H. Md Nordin, Z. Adi Putra, F.N. Ramli, Integrated membrane–electrocoagulation system for removal of celestine blue dyes in wastewater, Membranes 10 (2020) 184.
[89] V. Buscio, M. García-Jiménez, M. Vilaseca, V. López-Grimau, M. Crespi, C. Gutiérrez-Bouzán, Reuse of textile dyeing effluents treated with coupled nanofiltration and electrochemical processes, Materials 9 (2016) 490.
[90] N.C. Cinperi, E. Ozturk, N.O. Yigit, M. Kitis, Treatment of woolen textile wastewater using membrane bioreactor, nanofiltration and reverse osmosis for reuse in production processes, J. Clean. Prod. 223 (2019) 837–848.
[91] A.K. Hołda, B. Aernouts, W. Saeys, I.F. Vankelecom, Study of polymer concentration and evaporation time as phase inversion parameters for polysulfone-based SRNF membranes, J. Membrane. Sci. 442 (2013) 196–205.
[92] Y. Liu, J. Wang, Y. Wang, H. Zhu, X. Xu, T. Liu, Y. Hu, High-flux robust PSf-b-PEG nanofiltration membrane for the precise separation of dyes and salts, Chem. Eng. J. 405 (2021) 127051.
[93] P. Wang, J. Ma, F. Shi, Y. Ma, Z. Wang, X. Zhao, Behaviors and effects of differing dimensional nanomaterials in water filtration membranes through the classical phase inversion process: a review, Ind. Eng. Chem. Res. 52 (2013) 10355–10363.
[94] Y. Liu, Y. Liu, H. Wang, M. Chi, H. Matsuyama, Y. Guo, Y. Li, R. Liu, C. Wouters, Y. Chen, B. Van der Bruggen, One-pot fabrication of highly permeable P84/UiO-66-NH2-PEI membrane for the efficient removal of heavy metals from wastewater, Sep. Purif. Technol. 354 (2024) 129022.
[95] L.E. Peng, Z. Yao, Z. Yang, H. Guo, C.Y. Tang, Dissecting the role of substrate on the morphology and separation properties of thin film composite polyamide membranes: seeing is believing, Environ. Sci. Technol. 54 (2020) 6978–6986.
[96] D. Wu, Y. Huang, S. Yu, D. Lawless, X. Feng, Thin film composite nanofiltration membranes assembled layer-by-layer via interfacial polymerization from polyethylenimine and trimesoyl chloride, J. Membrane. Sci. 472 (2014) 141–153.
[97] R.E. Kesting, Phase inversion membranes, Mater. Sci. Synthetic Membranes Chapter 7 (1985) 131–164.
[98] L.E. Peng, Z. Yang, L. Long, S. Zhou, H. Guo, C.Y. Tang, A critical review on porous substrates of TFC polyamide membranes: mechanisms, membrane performances, and future perspectives, J. Membrane. Sci. 641 (2022) 119871.
[99] L.P. Zhang, Z. Liu, X.L. Zhou, C. Zhang, Q.W. Cai, R. Xie, X.J. Ju, W. Wang, Y. Faraj, L.Y. Chu, Novel composite membranes for simultaneous catalytic degradation of organic contaminants and adsorption of heavy metal ions, Sep. Purif. Technol. 237 (2020) 116364.

[100] Z. Wang, X. You, C. Yang, W. Li, Y. Li, Y. Li, J. Shen, R. Zhang, Y. Su, Z. Jiang, Ultrathin polyamide nanofiltration membranes with tunable chargeability for multivalent cation removal, J. Membrane. Sci. 642 (2022) 119971.

[101] C. Jiang, L. Tian, Y. Hou, Q.J. Niu, Nanofiltration membranes with enhanced microporosity and inner-pore interconnectivity for water treatment: excellent balance between permeability and selectivity, J. Membrane. Sci. 586 (2019) 192–201.

[102] R. Zhang, S. Yu, W. Shi, W. Wang, X. Wang, Z. Zhang, L. Li, B. Zhang, X. Bao, A novel polyesteramide thin film composite nanofiltration membrane prepared by interfacial polymerization of serinol and trimesoyl chloride (TMC) catalyzed by 4-dimethylaminopyridine (DMAP), J. Membrane. Sci. 542 (2017) 68–80.

[103] X. Wu, T. Chen, G. Dong, M. Tian, J. Wang, R. Zhang, G. Zhang, J. Zhu, Y. Zhang, A critical review on polyamide and polyesteramide nanofiltration membranes: emerging monomeric structures and interfacial polymerization strategies, Desalination 577 (2024) 117379.

[104] T. Chidambaram, Y. Oren, M. Noel, Fouling of nanofiltration membranes by dyes during brine recovery from textile dye bath wastewater, Chem. Eng. J. 262 (2015) 156–168.

[105] D. Xu, Y. Xie, X. Jin, J. Zheng, Q. Gao, P. Jin, X. Zhu, Z. Zhang, X. Li, G. Li, H. Liang, B. Van der Bruggen, Polyphenol-mediated defect patching of graphene oxide membranes for sulfonamide contaminants removal and fouling control, J. Hazard. Mater. 469 (2024) 133890.

[106] D. Xu, Y. Xie, X. Jin, J. Ren, J. Song, X. Tang, Z. Zhang, X. Li, G. Li, H. Liang, A comparison of typical ultrafiltration processes in drinking water treatment: Implications for fouling control and disinfection performance, Sep. Purif. Technol. 338 (2024) 126426.

[107] H. Zhang, Y. Chen, S. Tang, H. Sun, P. Li, Y. Hou, Q.J. Niu, Regulation of interfacial polymerization process based on reversible enamine reaction for high performance nanofiltration membrane, J. Membrane. Sci. 664 (2022) 121070.

[108] X. Shui, J. Li, M. Zhang, C. Fang, L. Zhu, Tailoring ultrathin microporous polyamide films with rapid solvent transport by molecular layer-by-layer deposition, J. Membrane. Sci. 628 (2021) 119249.

[109] J. Shen, G. Wang, X. You, B. Shi, J. Xue, J. Yuan, Y. Li, J. Guan, Y. Ma, Y. Su, R. Zhang, Z. Jiang, Thermal-facilitated interfacial polymerization toward high-performance polyester desalination membrane, J. Mater. Chem. A 9 (2021) 8470–8479.

[110] Y. Liu, J. Du, H. Wu, C. Cong, H. Zhang, J. Wang, Z. Wang, Antifouling streptomycin-based nanofiltration membrane with high permselectivity for dye/salt separation, Sep. Purif. Technol. 297 (2022) 121443.

[111] H. Zheng, Z. Mou, Y.J. Lim, N. Srikanth, W. Zhang, S. Guo, R. Wang, K. Zhou, High-precision and high-flux separation by rationally designing the nanochannels and surface nanostructure of polyamide nanofiltration membranes, Small Sci. 2 (2022) 2200026.

[112] Z. Yang, F. Wang, H. Guo, L.E. Peng, X.H. Ma, X.X. Song, Z. Wang, C.Y. Tang, Mechanistic insights into the role of polydopamine interlayer toward improved separation performance of polyamide nanofiltration membranes, Environ Sci Technol 54 (2020) 11611–11621.

[113] Q. Zhang, L. Fan, Z. Yang, R. Zhang, Y.N. Liu, M. He, Y. Su, Z. Jiang, Loose nanofiltration membrane for dye/salt separation through interfacial polymerization with in-situ generated TiO_2 nanoparticles, Appl. Surf. Sci. 410 (2017) 494–504.

[114] X. Wei, Y. Liu, J. Zheng, X. Wang, S. Xia, B. Van der Bruggen, A critical review on thin-film nanocomposite membranes enabled by nanomaterials incorporated in different positions and with diverse dimensions: performance comparison and mechanisms, J. Membrane. Sci. 661 (2022) 120952.

[115] A. Alkhouzaam, M. Khraisheh, Development of eco-friendly coating for the fabrication of high performing loose nanofiltration membranes for dye-contaminated wastewater treatment, Desalination 581 (2024) 117609.

[116] C. Geng, F. Zhao, H. Niu, J. Zhang, Y. Liu, L. Liu, H. Dong, Z. Li, H. Chen, Zwitterionic loose polyamide nanofiltration membrane with good antifouling properties for efficient removal of humic acid and dyes, J. Environ. Chem. Eng. 11 (2023) 110285.

[117] Z.M. Zhan, Y.J. Tang, K.K. Zhu, S.M. Xue, C.H. Ji, C.Y. Tang, Z.L. Xu, Coupling heat curing and surface modification for the fabrication of high permselectivity polyamide nanofiltration membranes, J. Membrane. Sci. 623 (2021) 119073.

[118] M. Wang, Y.J. Song, W. Jiang, F. Fornasiero, J.J. Urban, B. Mi, Layer-by-layer assembly of nanosheets with matching size and shape for more stable membrane structure than nanosheet-polymer assembly, ACS Appl. Mater. Interfaces. 16 (2024) 26568–26579.

[119] S. Wang, L. Li, S. Yu, B. Dong, N. Gao, X. Wang, A review of advances in EDCs and PhACs removal by nanofiltration: mechanisms, impact factors and the influence of organic matter, Chem. Eng. J. 406 (2021) 126722.

[120] M.M. Koli, S.P. Singh, Surface-modified ultrafiltration and nanofiltration membranes for the selective removal of heavy metals and inorganic groundwater contaminants: a review, Environ. Sci-Wat. Res. 9 (2023) 2803–2829.

[121] W. Zhang, G.-L. Ji, J. Wang, Y. He, L. Liu, F. Liu, In-situ formation of epoxy derived polyethylene glycol crosslinking network on polyamide nanofiltration membrane with enhanced antifouling performance, J. Membrane Sci. 658 (2022) 120713.

[122] K.H. Lasisi, T.F. Ajibade, K. Zhang, 3, 3′-diaminodiphenyl sulfone engagement in polysulfonamide-based acid-resistant nanofiltration membrane fabrication for efficient separation performance and heavy metal ions removal from wastewater, J. Membrane Sci. 661 (2022) 120909.

[123] W. Wang, J. Hao, Q. Sun, M. Zhao, H. Liu, C. Li, X. Sui, Carbon nanofibers membrane bridged with graphene nanosheet and hyperbranched polymer for high-performance osmotic energy harvesting, Nano Res. 16 (2022) 1205–1211.

[124] Y. He, E. Zhang, X. Feng, L. Chen, Z. Jiang, Facile optimization of grafted chain length on antifouling properties based on hyperbranched polyglycerol, J. Membrane Sci. 666 (2023) 121157.

[125] H. Guo, Y. Deng, Z. Tao, Z. Yao, J. Wang, C. Lin, T. Zhang, B. Zhu, C.Y. Tang, Does hydrophilic polydopamine coating enhance membrane rejection of hydrophobic endocrine-disrupting compounds? Environ. Sci. Technol. Lett. 3 (2016) 332–338.

[126] H. Guo, Y. Deng, Z. Yao, Z. Yang, J. Wang, C. Lin, T. Zhang, B. Zhu, C.Y. Tang, A highly selective surface coating for enhanced membrane rejection of endocrine disrupting compounds: mechanistic insights and implications, Water Res. 121 (2017) 197–203.

[127] G.R. Xu, J.N. Wang, C.J. Li, Strategies for improving the performance of the polyamide thin film composite (PA-TFC) reverse osmosis (RO) membranes: surface modifications and nanoparticles incorporations, Desalination 328 (2013) 83–100.

[128] H.B. Madalosso, R. Machado, D. Hotza, C. Marangoni, Membrane surface modification by electrospinning, coating, and plasma for membrane distillation applications: a state-of-the-art review, Adv. Eng. Mater. 23 (2021) 2001456.

[129] C. Wang, M.J. Park, H. Yu, H. Matsuyama, E. Drioli, H.K. Shon, Recent advances of nanocomposite membranes using layer-by-layer assembly, J. Membrane. Sci. 661 (2022) 120926.

[130] Y. Ren, J. Zhu, S. Feng, X. Chen, J. Luo, Y. Wan, Tuning pore size and surface charge of poly(piperazinamide) nanofiltration membrane by enhanced chemical cleaning treatment, J. Membrane Sci. 643 (2022) 120054.

[131] T.K. Arsene, T. Chen, J. Zhu, Y. Zhang, Elevated water transport of polyamide nanofiltration membranes via aqueous organophosphorus mediated interfacial polymerization, Desalination 584 (2024) 117754.

[132] S. Guo, X. Chen, Y. Wan, S. Feng, J. Luo, Custom-tailoring loose nanofiltration membrane for precise biomolecule fractionation: new insight into post-treatment mechanisms, ACS Appl. Mater. Interfaces. 12 (2020) 13327–13337.

[133] P. Gorgojo, M.F. Jimenez-Solomon, A.G. Livingston, Polyamide thin film composite membranes on cross-linked polyimide supports: improvement of RO performance via activating solvent, Desalination 344 (2014) 181–188.

[134] M.G. Shin, S.H. Park, S.J. Kwon, H.E. Kwon, J.B. Park, J.H. Lee, Facile performance enhancement of reverse osmosis membranes via solvent activation with benzyl alcohol, J. Membrane Sci. 578 (2019) 220–229.

[135] Y. Liu, H. Wu, Z. Wang, J. Wang, Regulating solvent activation by the mechanical force for the fabrication of reverse osmosis membranes with high permeability and selectivity, J. Membrane Sci. 638 (2021) 119732.

[136] J. Li, M. Zhang, W. Feng, L. Zhu, L. Zhang, PIM-1 pore-filled thin film composite membranes for tunable organic solvent nanofiltration, J. Membrane Sci. 601 (2020) 117951.

[137] Y. Liu, H. Matsuyama, P. Jin, M. Chi, D. Xu, J. Zheng, Z. Dai, Tailored design of nanofiltration membrane for endocrine disrupting compounds removal: Mechanisms, current advancements, and future perspectives, Sep. Purif. Technol. 361 (2025) 131471.

[138] H. Mariën, I.F. Vankelecom, Transformation of cross-linked polyimide UF membranes into highly permeable SRNF membranes via solvent annealing, J. Membrane Sci. 541 (2017) 205–213.

[139] Y. Liu, H. Matsuyama, Y. Liu, Y. Li, J. Zheng, Z. Dai, B. Van der Bruggen, Advances in positively charged nanofiltration membranes: targeted strategies for optimized water treatment, Desalination 600 (2025) 118519.