



Unlocking the potential of thin-film composite reverse osmosis membrane performance: Insights from mass transfer modeling

Kexin Yuan^a, Yulei Liu^a, Haoran Feng^a, Yi Liu^a, Jun Cheng^a, Beiyang Luo^a, Qinglian Wu^{a,b}, Xinyu Zhang^c, Ying Wang^d, Xian Bao^{a,*}, Wanqian Guo^a, Jun Ma^a

^a State Key Laboratory of Urban Water Resource and Environment, School of Environment, Harbin Institute of Technology, Harbin 150090, China

^b College of Architecture and Environment, Sichuan University, Chengdu 610065, China

^c School of Municipal and Environmental Engineering, Shandong Jianzhu University, Jinan 250101, China

^d College of Water Conservancy and Hydropower Engineering, Sichuan Agricultural University, Yaan 625014, China

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ABSTRACT

Thin-film composite (TFC) reverse osmosis (RO) membranes have attracted considerable attention in water treatment and desalination processes due to their specific separation advantages. Nevertheless, the trade-off effect between water flux and salt rejection poses huge challenges to further improvement in TFC RO membrane performance. Numerous research works have been dedicated to optimizing membrane fabrication and modification for addressing this issue. In the meantime, several reviews summarized these approaches. However, the existing reviews seldom analyzed these methods from a theoretical perspective and thus failed to offer effective optimization directions for the RO process from the root cause. In this review, we first propose a mass transfer model to facilitate a better understanding of the entire process of how water and solute permeate through RO membranes in detail, namely the migration process outside the membrane, the dissolution process on the membrane surface, and the diffusion process within the membrane. Thereafter, the water and salt mass transfer behaviors obtained from model deduction are comprehensively analyzed to provide potential guidelines for alleviating the trade-off effect between water flux and salt rejection in the RO process. Finally, inspired by the theoretical analysis and the accurate identification of existing bottlenecks, several promising strategies for both regulating RO membranes and optimizing operational conditions are proposed to further exploit the potential of RO membrane performance. This review is expected to guide the development of high-performance RO membranes from a mass transfer theory standpoint.

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1. Introduction

The scarcity of freshwater resources has emerged as one of the most urgent global issues requiring immediate resolution [1]. Increasing attention is shifting to alternative water sources *via* seawater desalination and wastewater reclamation [2,3], especially in coastal and inland arid regions. Membrane-based technologies, including reverse osmosis (RO), nanofiltration (NF), and ultrafiltration (UF) are extensively employed for water purification [4–6], owing to their high separation and energy efficiencies. Notably, the RO membrane plays a leading role in the acquirement of high-quality water benefiting from its excellent salt rejection in comparison to other membrane technologies [7].

The polyamide thin-film composite (TFC) membrane, fabricated by interfacial polymerization (IP) [8,9], has become the predominant choice for RO applications. This type of membrane features a thin but dense polyamide functional layer that endows it with remarkable separation ability [10]. However, the TFC RO membrane performance is limited by the trade-off effect between water flux and salt rejection. The trade-off effect leads to an inevitable compromise in water flux when pursuing superior salt rejection [11]. In addition, this effect increases the energy consumption and economic cost associated with RO systems.

To improve the water flux and salt rejection of TFC RO membranes, multiple researchers have been studying strategies from different perspectives. Several typical approaches for increasing water flux contained enhancing membrane surface hydrophilicity [12,13], constructing water channels within the polyamide layer [14], and decreasing effective membrane thickness [15]. Meanwhile, methods such as modulating crosslinking degree of the

* Corresponding author.

E-mail address: baoxian24@163.com (X. Bao).

polyamide layer [16] and manipulating membrane surface charge [17] benefited salt rejection improvement. Nonetheless, these solutions seemed to be relatively powerless in simultaneously improving both the water flux and salt rejection of RO membranes. For instance, the incorporation of nanomaterials within the polyamide layer yielded significantly elevated water flux but weakened salt rejection [18]. To provide insightful perspectives in this scope, several reviews summarized existing research works that focused on aspects involving IP reaction regulation and membrane surface modification [19,20], and concluded macroscopic strategies for enhancing membrane performance. However, there remains a scarcity of a micro-level analysis in existing reviews, such as model analysis, to explore the comprehensive behaviors of water and solutes permeating through RO membranes, and thus to accurately identify key influential factors to mitigate related issues, which is highly desired in guiding the development of more advanced RO systems.

Based on the above analysis, this review undertakes a model-derivation method to investigate the mass transfer theory and adopts a model-analysis approach to guide the optimization strategies of RO membrane performance. Initially, a comprehensive model is proposed to depict the mass transfer processes of water and salt through the RO membrane. Secondly, based on the model parameters, this review comprehensively analyzes the limiting factors of water and salt transport through RO membranes, obtaining key impacting parameters such as diffusion and partition coefficients at the microscopic level. Building on this foundation, individual model parameters and potential multi-parameter optimization methods that can both improve water flux and salt rejection are presented. Finally, the existing strategies for RO membrane performance improvement in current research are summarized. In the meantime, combing the shortcomings of the current strategies and the above model analysis, this review offers potential research directions for obtaining high-performance TFC RO membranes from the aspects of membrane fabrication, system parameter optimization, and external field assistance. This paper aims to provide a unique and comprehensive perspective for achieving high-performance RO membranes.

2. The model of mass transfer

To systematically describe the water and salt mass transfer processes through RO membranes as shown in Fig. 1a, an appropriate mass transfer model is highly desired. One of the classical models is the SD model, proposed in 1965 [21], which describes water and salt transport through dense RO membranes. However, the SD model is a simplified representation based on certain assumptions [22], such as neglecting the CP effect. As a result, the simplified model is not reliable when predicting the mass transfer behaviors

of water and salt under the influence of multiple factors. Moreover, the diffusion behaviors of water and salt transport through RO membranes are extremely complex, thus requiring fine model derivation to assist in predicting crucial factors that enhance membrane performance from the root. Currently, there is a lack of relevant fine-grained models. Compared with the SD model, a more refined model needs to consider the convective effect between water and salt transport, membrane structure effects, CP effect, and external field-assisted effects. To match the above requirements, this section establishes a novel and systematic model to describe the mass transfer behaviors of water and salt permeation RO membranes.

2.1. Water transport model and its modification

Diffusion is described by the NP equation, and the transport of water and salt is driven by the chemical potential according to the suggestion of irreversible thermodynamics, thus (Eq. 1) [23]:

$$J = -c_m u \frac{\partial \mu}{\partial x} \quad (1)$$

where J is the molar flux across the RO membrane, c_m is the concentration in the RO membrane, u is the molar activity rate, μ is the chemical potential, and x is the distance perpendicular to the direction of the RO membrane. The negative sign (*i.e.*, $-$) indicates that the positive flux is driven by the negative chemical potential gradient. Following the Einstein equation $D_m = RTu$ [24], Eq. 1 can be rewritten as (Eq. 2)

$$J = -\frac{D_m c_m}{RT} \frac{\partial \mu}{\partial x} \quad (2)$$

where D_m is the diffusion coefficient in the RO membrane, R is the gas constant, and T is the absolute temperature.

In terms of Eq. 2, the permeate water flux J_w is given by (Eq. 3):

$$J_w = -\frac{D_{m,w} c_{m,w}}{RT} \frac{\partial \mu_w}{\partial x} = \frac{D_{m,w} c_{m,w}}{RT} \frac{\Delta \mu_w}{\Delta x} \quad (3)$$

where $D_{m,w}$ is the water diffusion coefficient in the RO membrane, $c_{m,w}$ is the water concentration in the RO membrane, μ_w is the chemical potential of water, $\Delta \mu_w$ is the chemical potential difference of water across RO membrane, and Δx is the membrane thickness.

When a solute i is mixed in water, μ_w is defined as Eq. 4 [25]:

$$\mu_w = \mu_w^0 + V_w P + RT \ln a_i \quad (4)$$

where μ_w^0 is the chemical potential of water at the saturation vapor pressure, V_w is the partial molar volume of water, P is the pressure, and a_i is the activity of the solute.

The osmotic pressure difference $\Delta \pi$ originates from the difference in the logarithm of the activity passing through the RO membrane, resulting in Eq. 5 [25]:

$$\Delta \pi = \frac{RT}{V_w} [\ln(a_{p,i}) - \ln(a_{f,i})] \quad (5)$$

where $a_{f,i}$ and $a_{p,i}$ is the activity of ion i in the feed solution and permeate solution, respectively.

Coupling Eqs. 4 and 5 with Eq. 3 leads to Eq. 6:

$$J_w = \frac{D_{m,w} c_{m,w} V_w}{RT \Delta x} (\Delta P - \Delta \pi) = A (\Delta P - \Delta \pi) \quad (6)$$

where ΔP is the pressure difference across the RO membrane, and A is the water permeability coefficient.

Eq. 6 is the water transport equation in the SD model. Although the RO membrane is considered to be a non-porous membrane in

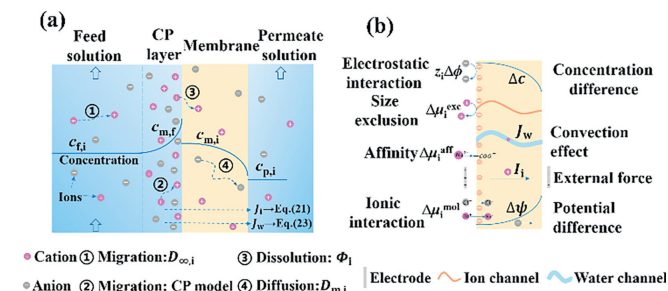


Fig. 1. (a) Schematic of the mass transfer processes of salt ions and water through RO membranes illustrating the migration process, the dissolution process on the RO membrane surface, and the diffusion process within the polyamide layer. J_i and J_w represent salt flux and water flux across the RO membrane. (b) Mechanisms of the ion dissolution on the RO membrane surface and the driving forces for ion diffusion through RO membranes.

the SD model, there are micropore defects on the membrane surface due to its complex synthesis process. Hence, J_w can be expressed by Eq. 7 [26]:

$$J_w = A(\Delta P - \sigma \Delta \pi) \quad (7)$$

where the reflection coefficient σ is given by $\sigma = 1 - \Phi_i K_{c,i}$ and σ can be interpreted as the fraction of solute reflected by the RO membrane [27]. In the expression of σ , Φ_i and $K_{c,i}$ represent the ion partition coefficient between the membrane and the feed/permeate solution and convective factor, respectively.

2.2. Salt transport model and its modification

2.2.1. Solution-diffusion model

The chemical potential $\mu_{m,i}$ of an ion in the membrane resembles that of water. When the concentration gradient is considered and the pressure gradient within the membrane is ignored [28], Eq. 2 can be represented as Eq. 8:

$$J_i = -D_{m,i} c_{m,i} \frac{\partial \ln c_{m,i}}{\partial x} = -D_{m,i} \frac{\partial c_{m,i}}{\partial x} \approx D_{m,i} \frac{\Delta c_{m,i}}{\Delta x} \quad (8)$$

where J_i is the molar flux of ion i , $D_{m,i}$ is the diffusion coefficient of ion i in the membrane, $c_{m,i}$ is the concentration of ion i in the membrane, and $\Delta c_{m,i}$ is the concentration difference of ion i in the membrane.

Since the ion concentration in the membrane is challenging to measure, the partition coefficient is introduced into Eq. 8, and obtain Eq. 9:

$$J_i = D_{m,i} \frac{\Delta c_{m,i}}{\Delta x} = D_{m,i} \Phi_i \frac{c_{f,i} - c_{p,i}}{\Delta x} = B(c_{f,i} - c_{p,i}) \quad (9)$$

where B is the salt transport coefficient, Φ_i is the partition coefficient between the membrane and the feed/permeate solution, and $c_{f,i}$ and $c_{p,i}$ are the concentration of ion i in the feed solution and permeate solution, respectively.

The partition coefficient Φ_i is defined by the chemical potential at the membrane-solution interface (Eq. 10) [29]:

$$\Phi_i = c_{m,i}/c_{f,i} = \exp(-z_i \Delta \Phi - \Delta \mu_i^{\text{exc}} - \Delta \mu_i^{\text{mol}} - \Delta \mu_i^{\text{aff}}) \quad (10)$$

where z_i is the ion charge, $\Delta \Phi$ is the Donnan potential. As depicted in Fig. 1b, $z_i \Delta \Phi$ relates to electrostatic interaction, $\Delta \mu_i^{\text{exc}}$ represents size exclusion, $\Delta \mu_i^{\text{mol}}$ expresses the interaction between ions at the interface, and $\Delta \mu_i^{\text{aff}}$ denotes affinity, including hydrogen bonding, hydrophobic interactions, and complexation effects. When only considering the Donnan and steric effects, Eq. 10 simplifies to Eq. 11 [30]:

$$\Phi_i = (1 - \lambda_i)^2 \exp\left(-\frac{z_i F}{RT} \Delta \Phi\right) \quad (11)$$

where λ_i is the ratio of ion radius r_i to membrane pore radius r_p , and F is the Faraday constant.

Eq. 9 is the salt transport equation in the SD model, which exhibits several shortcomings, including: (I) its neglect of the CP effect; (II) its inability to fully describe the mass transfer process of ions through charged RO membranes; (III) its disregard for micropore defects on the RO membrane surface; (IV) its lack of consideration for the impact of membrane structure on ion diffusion; (V) its omission of friction effects between ions and membrane, and ions and free water; and (VI) its ignorance of external driving forces of salt transport across the RO membrane.

2.2.2. Concentration polarization model

During the RO desalination process in Fig. 1a, the salt concentration in the CP layer increases due to salt retention by the RO membrane [31], causing a higher salt concentration at the feed solution-membrane surface ($c_{m,f}$) compared to that in the feed

solution ($c_{f,i}$). This suggests that the equation of Φ_i is inaccurate and can be corrected to $\Phi_i = c_{m,i}/c_{f,i}$. Meanwhile, this implies that the CP model is employed to obtain the real salt concentration at the feed solution-membrane surface. In a steady state, $c_{m,f}$ can be derived from the material balance and the mass transfer coefficient k (Eq. 12)

$$CP = \frac{c_{m,f} - c_{p,i}}{c_{f,i} - c_{p,i}} = e^{J_w/k} \quad (12)$$

Eq. 12 is the CP model derived from thin film theory [32,33], which restricts the operating conditions to maintaining a high cross-flow rate of the feed solution [34]. In a cross-flow filtration system, k can be calculated as follows (Eq. 13) [35]:

$$Sh = aRe^b Sc^c = kd/D_s \quad (13)$$

where Sh is Sherwood number, Re is Reynolds number, Sc is Schmidt number, d is hydraulic diameter, D_s is the diffusion coefficient of solute in water, and a , b , c can be cited from the literature [36,37].

2.2.3. Modification of the solution-diffusion model

As previously discussed, the SD model only partially captures the transport behavior of salt through the RO membrane. To further enhance the understanding of salt transfer, the model proposed in this section takes into account several shortcomings highlighted in Section 2.2.1.

The driving forces for ion transport through charged RO membranes are the concentration and potential gradients. Based on Eqs. 2 and 8 is transformed into

$$J_i = -\frac{D_{m,i} c_{m,i}}{RT} \left(RT \frac{\partial \ln c_{m,i}}{\partial x} + z_i F \frac{\partial \psi}{\partial x} \right) = -D_{m,i} \left(\frac{\partial c_{m,i}}{\partial x} + \frac{z_i c_{m,i} F}{RT} \frac{\partial \psi}{\partial x} \right) \quad (14)$$

where ψ is the electric potential.

Firstly, micropore defects on the RO membrane surface are incorporated to modify Eq. 14:

In the presence of micropore defects on the RO membrane surface, it is essential to account for the volume flow part of salt ions. Within the micropores, ions are dragged by water transport, which is the convection effect presented in Fig. 1b. After considering the volume flow factor, Eq. 14 becomes Eq. 15:

$$J_i = c_{m,i} J_w - D_{m,i} \left(\frac{\partial c_{m,i}}{\partial x} + \frac{z_i c_{m,i} F}{RT} \frac{\partial \psi}{\partial x} \right) \quad (15)$$

Secondly, when considering the structural properties of membrane pores, ion-membrane interaction, and ion-water interaction, Eq. 15 is modified to Eq. 16 [38,39]:

$$J_i = K_{c,i} c_{m,i} J_w - K_{d,i} \varepsilon_e D_{\infty,i} \left(\frac{\partial c_{m,i}}{\partial x} + z_i c_{m,i} \frac{\partial \psi}{\partial x} \right) \quad (16)$$

where $K_{c,i}$ and $K_{d,i}$ are the convective and diffusive hindrance factors, respectively, $\varepsilon_e = \varepsilon/\tau^2$ represents the reduction factor, ε is porosity, τ is tortuosity, and $D_{\infty,i}$ is the bulk ion diffusivity.

Here, an expression of $D_{\infty,i}$ is provided in Eq. 17 [40]:

$$D_{\infty,i} = \frac{RT u_i}{|z_i| F} \quad (17)$$

where u_i is the ionic mobility.

Eq. 16 corresponds to the equation of the extended Nernst-Planck equation (ENP) in other studies [41–43], which is widely utilized to describe the ion mass transfer process. However, Eq. 16 ignores the influence of external forces such as electric field forces in coupled RO membrane systems. To offer a more comprehensive RO membrane mass transfer equation, the factor is considered in this review.

Finally, the impact of external forces on salt transport is discussed. When only considering the chemical potential gradient $\nabla\mu_{m,i}$ and the external force I_i , the general statistical model of salt transport is given below (Eq. 18) [44]:

$$\frac{u_i}{D_{m,i}} = -\frac{1}{RT}(\nabla\mu_{m,i} - I_i) \quad (18)$$

Substituting the formulation of $J_i = c_{m,i}u_i$ [45] into Eq. 18 yields (Eq. 19):

$$J_i = -\frac{D_{m,i}c_{m,i}}{RT}\frac{d\mu_{m,i}}{dx} + \frac{D_{m,i}c_{m,i}I_i}{RT} \quad (19)$$

By coupling Eqs. 16 and 19 give Eq. 20:

$$J_i = -K_{d,i}\varepsilon_e D_{\infty,i}\left(\frac{\partial c_{m,i}}{\partial x} + z_i c_{m,i}\frac{\partial \psi}{\partial x}\right) + K_{c,i}c_{m,i}J_w + \frac{D_{m,i}c_{m,i}I_i}{RT} \quad (20)$$

Eq. 20 is equal to Eq. 21:

$$J_i = \frac{K_{d,i}\varepsilon_e D_{\infty,i}\Phi_i}{\Delta x}(\Delta c + z_i c_{m,f}\Delta\psi) + K_{c,i}c_{m,i}J_w + \frac{D_{m,i}c_{m,i}I_i}{RT} \quad (21)$$

where Δc is the concentration difference of ion i between feed and permeate, with $\Delta c = c_{m,f} - c_{p,i}$, and Φ_i gives $\Phi_i = c_{m,i}/c_{m,f}$. The expressions of Δc and Φ_i take the CP effect into account. Under Eq. 21, the salt transport coefficient B is indicated as Eq. 22:

$$B = \frac{K_{d,i}\varepsilon_e D_{\infty,i}\Phi_i}{\Delta x} \quad (22)$$

Similarly, water transport through the RO membrane involves three processes: migration, dissolution, and diffusion processes. Taking Eq. 21 as a reference, J_w can be rewritten as Eq. 23:

$$J_w = \frac{D_{m,w}c_{m,w}V_w}{RT\Delta x}(\Delta P - \sigma\Delta\pi) = \frac{K_{d,i}\varepsilon_e D_{\infty,w}\Phi_w c_{f,w}V_w}{\Delta x} \frac{\Delta P - \sigma\Delta\pi}{RT} \quad (23)$$

where Φ_w is the partition coefficient of water on the membrane surface derived from Eq. 10 without considering the Donnan effect. The water permeability coefficient A becomes Eq. 24:

$$A = \frac{K_{d,i}\varepsilon_e D_{\infty,w}\Phi_w c_{f,w}V_w}{\Delta x} \quad (24)$$

Eqs. 21 and 23 are refined mass transfer equations in this review, which incorporate several corrections based on the SD model. Eq. 21 comprehensively describes salt transport across the RO membrane. Compared to the solution-friction (SF) model described in the existing literature [46,47], the driving forces for the salt mass transfer process include not only salt concentration difference, potential difference, and convective effect, but also an external force. By introducing the external force parameter into mass transfer equations, a systematic mass transfer model can be offered for the coupling systems such as the electric drive membranes. However, the limitation of this model is its inability to evaluate the significance of convection and friction effects on mass transfer. To better compare the difference between the SD model, the SF model, and this model proposed in our paper, we summarize some parameters in these models in Table S1 (Supporting information).

2.2.4. Salt rejection of the RO process

The observed salt rejection R_{obs} is defined as Eq. 25 [48]:

$$R_{obs} = 1 - \frac{c_{p,i}}{c_{f,i}} \quad (25)$$

In RO modeling, the 'permeate equation' is simple and practical as Eq. 26 [26,49]:

$$c_{p,i} = \frac{J_i}{J_w} \quad (26)$$

Combining Eqs. 12, 21, 25, and 26 yields Eq. 27:

$$R_{real} = \frac{J_w - (Bz_i\Delta\psi + K_{c,i}J_w\Phi_i + I_iD_{m,i}\Phi_i/RT)}{J_w + Be^{J_w/k} + (e^{J_w/k} - 1)(Bz_i\Delta\psi + K_{c,i}J_w\Phi_i + I_iD_{m,i}\Phi_i/RT)} \quad (27)$$

where R_{real} is the real salt rejection. Eq. 27 is obtained by coupling the improved salt transport equation (Eq. 21) with the CP model (Eq. 12). For reference, the solute transport equation in the SD model combined with the CP equation gives $R_{real} = J_w/(J_w + Be^{J_w/k})$, which is the salt rejection equation in other papers [50]. Compared with this equation, Eq. 27 derived in this review comprehensively reflects the parameters affecting salt mass transfer in RO membranes. Moreover, this equation is the simplification of Eq. 27, which verifies the correctness of Eq. 27.

In summary, this section offers a comprehensive analysis of mass transfer theories in RO membranes by discussing and revising water and salt mass transfer models, thus bridging the gap in the refined description of water and salt mass transfer behaviors within RO membranes and getting improved salt and water mass transfer equations (i.e., Eqs. 21, 23 and 27). As depicted in Fig. 1a, the out-of-membrane migration process in the feed solution, the near-membrane migration process, the dissolution process on the membrane surface, and the diffusion process within the membrane of ions are denoted by the micro-controllable parameters $D_{\infty,i}$, k , Φ_i , and $D_{m,i}$, respectively. As per the improved salt and water mass transfer equations (i.e., Eqs. 23 and 27), the micro-controllable diffusion and partition coefficients can individually or collectively affect the macroscopic salt rejection R_{real} and water flux J_w . Therefore, Sections 3, 4, and 5 combine these micro-parameters with the modified model to detailedly analyze the microscopic impact mechanism of membrane microstructure performance, salt ion characteristics, and RO system operating parameters on R_{real} and J_w , thereby obtaining strategies to address the trade-off effect between water flux and salt rejection.

3. Migration process outside TFC RO membrane

As the initial stage of mass transfer in the RO process, the out-of-membrane migration process of salt and water refers to the diffusion process occurring perpendicular to the RO membrane surface. As shown in Fig. 1a, the salt migration process contains diffusion in the feed solution and near-membrane transfer, both of which can impact the rejection ability of RO membranes by modulating the direction and rate of ion migration. According to Eqs. 22 and 27, a reduced migration coefficient of salt ions in the feed solution ($D_{\infty,i}$) yields a smaller salt transport coefficient (B), subsequently leading to greater real salt rejection (R_{real}). It is also known that more severe CP further increases the ion concentration at the membrane surface on the feed side ($c_{m,f}$), which causes a higher ion concentration in the permeate solution ($c_{p,i}$) and thus reduces the observed salt rejection (R_{obs}) (Eq. 25). Simultaneously, an increase in $c_{m,f}$ enhances the osmotic pressure difference across the membrane ($\Delta\pi$), thereby lowering the water flux (J_w) (Eq. 23). Thus, high salt rejection and water flux of the RO membrane can be achieved by controlling $D_{\infty,i}$ and $c_{m,f}$, with their limiting factors detailedly discussed.

The feed temperature (T) in the RO system profoundly affects salt and water mass transfer processes. As T rises, the increased water flux J_w and decreased salt rejection R_{real} are attributed to (i) the elevation of the diffusion coefficient of water $D_{\infty,w}$ (Eq. 23) and salt $D_{\infty,i}$ (Eqs. 17, 22 and 27) in the bulk feed solution, which is the result of intensified molecular motion and collision; (ii) the decline of water viscosity via increasing its internal energy; (iii) the change of the structure of the membrane polyamide layer, reflected by a higher membrane average pore size [51]. Due to the opposite

trend of temperature's impact on water flux and salt rejection, the control of feed temperature in RO systems is important in actual applications.

In a steady state, as indicated in Fig. 1a, the ion concentration in the feed solution ($c_{f,i}$) is uniform and there is no concentration gradient in the direction perpendicular to the membrane surface without considering the CP layer. As $c_{p,i}$ is negligible in the initial condition for the RO system, the essential of $c_{f,i}$ is the ion concentration difference between feed and permeate (Δc). Eq. 21 shows that the molar flux of ions (J_i) intensifies with Δc . A rising J_i implies the increase in $c_{p,i}$ outpaces the increase in $c_{f,i}$, which lowers R_{obs} , as demonstrated in Fig. S1a (Supporting information). The effect of Δc (i.e., $c_{f,i}$) on J_w can be discerned from Eq. 23 and Fig. S1b (Supporting information). Specifically, $\Delta \pi$ rises with Δc , causing J_w to decrease. However, it is worth noting that the CP effect cannot be ignored at a high feed salt concentration $c_{f,i}$, and the charge screening effect and membrane swelling effect need to be considered. The CP effect elevates the ion concentration at the membrane surface on the feed side, subsequently increasing the concentration difference Δc and osmotic pressure difference $\Delta \pi$, and decreasing salt rejection R_{obs} and water flux J_w , respectively. Influential factors for CP include the flow state and the concentration of the feed solution. The flow state can be categorized as laminar and turbulent, determined by the Reynolds number (Re). The turbulent state exhibits a larger value of Re , elevating the mass transfer coefficient k and a subsequent decrease in the ion concentration at the membrane surface on the feed side $c_{m,f}$ (Eq. 12). The charge screening effect, caused by the high feed salt concentration, is that the charge of RO membrane surface would be screened by the abundant counter-ions [52], thus weakening the Donnan exclusion effect and decreasing the salt rejection of RO membranes. The charge screening effect also reduces the electrostatic repulsion between polymer functional groups with the same charge, leading to the swelling of RO membranes and loosening the structure of the polyamide layer [52,53]. Due to the increased membrane pore size caused by the loose structure of the polyamide layer, the permeation of both water and salt ions intensifies with their higher dissolution and diffusion rates. However, several studies [54,55] have suggested that the high rigidity of the RO membrane minimizes its swelling and the change in the water flux and salt rejection is not evident. As a result, membrane swelling only serves as a reference factor for RO membranes, while the contribution of CP and charge screening effects to the influence of mass transfer behaviors of salt and water needs to be considered.

It is also mentioned how the hydraulic pressure difference across the membrane (ΔP) affects J_w . As revealed by Eq. 23, J_w increases linearly with ΔP without limitations, though a maximum value J_w exists. For the application of RO membrane in an aqueous solution, the pressure required for the maximum value of J_w is impeded by the low molecular weight of water [22]. Therefore, it is reasonable to assume an approximately linear relationship between J_w and ΔP within a certain range, as illustrated in Fig. S1b. Moreover, considering the high selectivity of RO membranes, it is acceptable to ignore pressure-induced effects on salt transport [22].

The external force parameter (I_i) in Eq. 21 represents an extrinsic factor, including electric, magnetic, and gravitational forces, which is not inherent to the membrane system. When electrodes are placed in the feed and permeate solutions, an electric field is generated between the anode and cathode, inducing directional ion movement due to the electric force [56,57]. Therefore, controlling the electric field's direction and strength enhances salt rejection R_{real} (Eq. 27) and facilitates efficient separation between ions.

Except for T , $c_{f,i}$, and I_i , the charge of ions and membrane surface also affects the migration process. Electrostatic repulsion occurs when ions and the membrane have the same charge, follow-

ing a decrease in $D_{\omega,i}$ and an increase in R_{real} . The strength of electrostatic repulsion is determined by ionic charge (z_i) and membrane charge density, both of which are associated with the pH of the feed solution [56–58]. Fig. S1c (Supporting information) shows the effect of pH on $NH_4^+-NH_3$ speciation, and Fig. S1d (Supporting information) depicts the relationship between pH and the protonation/deprotonation of functional groups on the RO membrane surface. As the pH in the feed decreases, solutes tend to exist in the form of NH_4^+ and amino groups on the surface of the TFC membrane change into RNH_3^+ . Consequently, enhanced salt rejection is achieved with an increase in the electrostatic repulsion between solutes and the RO membrane surface. Conversely, high pH results in the deprotonation of both carboxyl groups and NH_4^+ , yielding the weakening of the electrostatic repulsion [59]. In addition, the ligand complexation effects between ions for the alternation in ion charge is the promising approach to increase salt rejection of RO membranes. Besides the effect of pH, the charge of the RO membrane surface is related to the monomer type of the polymer and the feed salt concentration. It is well known that *m*-phenylenediamine (MPD), piperazine (PIP), and trimesoyl chloride (TMC) are commonly used monomers in the fabrication of TFC RO membranes [60,61], as well as the impact of the feed salt concentration on the membrane surface charge has been discussed above.

To sum up, starting from the model analysis, this section explores the specific performance of microscopic controllable migration coefficients of salt and water (i.e., $D_{\omega,i}$ and $D_{\omega,w}$) on water flux and salt rejection. In other words, the influence of macro-parameters on water flux and salt rejection is developed to $D_{\omega,i}$ and $D_{\omega,w}$. Combined with the above model analysis, the water flux and salt rejection can be simultaneously elevated by increasing $D_{\omega,w}$ while decreasing $D_{\omega,i}$, which can be obtained by reducing $c_{f,i}$. These two approaches are viable solutions to the trade-off effect between water permeation and salt rejection. Furthermore, water flux exhibits a linear progression with ΔP within a certain range, and increased salt rejection is attainable via enhancing electrostatic repulsion between salt and membrane by changing the feed pH or membrane monomer type, as well as utilizing external forces to control the migration rate and direction of ions. Lastly, the mass transfer coefficient k serves as a microscopical representation of the CP effect. The turbulent state of the feed solution reduces k and subsequently weakens the CP effect.

4. Dissolution process on TFC RO membrane surface

Upon completion of the migration process, salt and water begin to dissolve on the RO membrane surface. Compared with the dissolution process in the SD model, the dissolution process in our paper refers to the process of ions entering the RO membrane from the feed solution through the membrane pores. It is important to note that by inhibiting salt dissolution and promoting water dissolution, the trade-off between water flux and salt rejection may be well coordinated. In this section, the partition coefficients (i.e., ϕ_i and ϕ_w) are employed to measure the solubility of salt and water. Eqs. 22 and 24 reveal that ϕ_i and ϕ_w influence the salt transport coefficient (B) and water permeability coefficient (A), respectively. The following discussion addresses the limiting factors of the salt dissolution process (i.e., the parameters in the equation of ϕ_i) and the membrane properties affecting water solubility.

The electrostatic interaction, $z_i \Delta \phi$, not only regulates salt and water migration processes outside the membrane but also modulates their dissolution on the membrane surface. Specifically, Eqs. 10 and 27 show that enhanced electrostatic repulsion elevates the real salt rejection (R_{real}) by inhibiting ion partitioning (Fig. 2a). To amplify the electrostatic interaction between salt ions and the membrane, adjustments in the pH of the feed and the polymer monomer type can be employed, as discussed in Section 3. Fur-

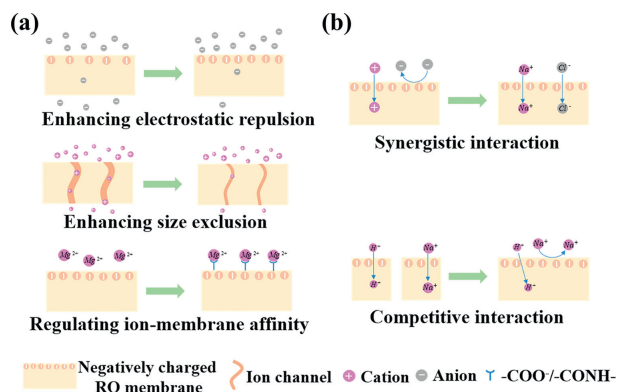


Fig. 2. (a) Improvement of salt rejection by regulating the dissolution of ions on the RO membrane surface. (b) Synergistic and competitive interactions of ions on the RO membrane surface.

thermore, constructing an additional charged layer on the membrane surface can also boost electrostatic interaction [62].

The size exclusion, $\Delta\mu_i^{\text{exc}}$, is paramount for salt transport. In aqueous solutions, ions exist as hydrated ions as a result of the ion-dipole moment force. It was reported that ions are partially dehydrated during the dissolution process [63,64], rendering the Stokes radius (r_i) as an indicator of ion size [46]. In this review, r_p symbolizes the membrane pore radius and λ_i denotes the ratio of r_i to r_p . For RO membrane pores, although the polyamide layer of the TFC RO membrane is considered to be non-porous in the SD model, Kim *et al.* [65] demonstrated that the membranes were composed of network pores and aggregate pores. According to Eq. 11 and Fig. 2a, raising λ_i reduces Φ_i , followed by an increase in R_{real} (Eq. 27).

The affinity, $\Delta\mu_i^{\text{aff}}$, incorporates hydrogen bonding, hydrophobic interactions, and complexation effects. As per Eq. 10, affinity affects the ion partitioning and therefore influences salt rejection of the RO membrane. Similarly, Eq. 23 indicates that the high water flux J_w can be induced by a higher water partition coefficient Φ_w , which can be achieved by enhancing the affinity between water molecules and the RO membrane surface. More specifically, the hydrogen bond is a special intermolecular force, which can enhance the penetration of water and salt ions by connecting water molecules or ions (e.g., ammonium ions) with functional groups (e.g., carboxyl groups) on the RO membrane surface. The hydrophobic interaction is an important mechanism for RO membranes to reject non-polar organic solutes [66,67]. This effect refers to the phenomenon that hydrophobic molecules are close to each other, in which the RO membrane with a larger contact angle can adsorb more hydrophobic molecules. As shown in Fig. 1b, the complexation effect between heavy metal ions (e.g., Mg^{2+}) and polyamide functional groups (e.g., carboxyl) may lead to scaling and the electrostatic screening effect on the RO membrane surface, thereby decreasing the salt rejection. Several factors (such as the ion polarity, the polarity and number of functional groups on the RO membrane surface) can be controlled to optimize the affinity between the solute and the RO membrane, which is beneficial to enhance the salt rejection of RO membranes.

The interaction between ions at the membrane interface, $\Delta\mu_i^{\text{mol}}$, also affects the dissolution process, as well as factors $\Delta\mu_i^{\text{exc}}$ and $\Delta\mu_i^{\text{aff}}$ (Eq. 10). Ionic interactions entail both competitive and synergistic interactions. Synergy implies the mutual enhancement of ionic mass transfer, whereas competition denotes the mutual impedance. For instance, in a NaCl solution, the fluxes of Na^+ and Cl^- through the RO membrane will increase concurrently to maintain the electrically neutral state of the feed solution and the membrane interior, as depicted in Fig. 2b. Furthermore, H^+

has a smaller hydration radius compared to Na^+ , thus weakening the size repulsion effect of RO membrane surface to H^+ . This indicates that H^+ has a superior mass transfer capability, which can be utilized to augment salt rejection (Fig. 2b).

The TFC RO membrane has typical ridge-valley roughness characteristics [68,69], with a structure analogous to vesicles. One approach to promote the water dissolution process involves augmenting the roughness of the polyamide layer, thus increasing its effective filtration area. Consequently, by tuning the roughness, such as by controlling the formation process of the membrane surface, high water flux is achievable. In addition, the dense vesicle wall enables the rough membrane surface to sustain high salt rejection. Besides the membrane roughness, the swelling of the RO membrane also affects water flux. The hydrophilicity of the RO membrane, measured by the contact angle, correlates positively with water flux. A smaller contact angle indicates greater hydrophilicity. Thus, by taking appropriate measures, such as applying hydrophilic materials to the membrane surface [70,71], a higher water flux can be attained.

In conclusion, the partition coefficients (i.e., Φ_i and Φ_w) function as micro-parameters governing the solubility of salt and water on the RO membrane surface. Additionally, Φ_i and Φ_w act on the salt and water permeability coefficients (i.e., B and A) through Eqs. 22 and 24, thereby impacting salt rejection and water flux. The model analysis in this section suggests that constraining Φ_i and concurrently boosting Φ_w can be accomplished by regulating membrane pore size and distribution or leveraging the affinity between the membrane and substances, which are effective ways to address the trade-off effect. Pore size and distribution, determined by the formation process of pores, impact the size exclusion effect to strengthen water flux and salt rejection. Meanwhile, controlling the ionic polarity, the water polarity, and the type, quantity, and distribution of the monomer groups on the RO membrane surface by adjusting the pH of the feed solution or changing the type of polymer monomer can augment the ion-membrane negative affinity and the water-membrane positive affinity, leading to heightened salt rejection and water flux. In addition to the size exclusion and affinity interactions, as shown in Figs. 2a and b, the enhancement of electrostatic repulsion between ions and the membrane or the reasonable regulation of ionic interactions will also inhibit Φ_i , resulting in high salt rejection. Moreover, improving the micromorphology of the RO membrane surface, such as increasing roughness or hydrophilicity, can also yield high water flux.

5. Diffusion process within TFC RO membrane

Analyzing the diffusion process at the micro level is crucial for accurately identifying the restrictions on salt and water transport within RO membranes. In general, the diffusion process of salt and water within the RO membrane pertains to their movement in the free-volume pores of the polyamide layer. Typically, salt ions and water vibrate slightly within these pores, jumping between them under specific conditions, such as appropriate time, position, and speed [72,73]. The diffusion coefficients of ions and water in the membrane, $D_{m,i}$ and $D_{m,w}$, significantly influence real salt rejection (R_{real}) and water flux (J_w). Specifically, a reduction in $D_{m,i}$ enhances R_{real} (Eq. 27), while an increase in $D_{m,w}$ augments J_w (Eq. 23). Therefore, regulating $D_{m,i}$ and $D_{m,w}$ is imperative for achieving optimal performance in RO membranes. This section provides an in-depth analysis of the limiting factors of $D_{m,i}$ and $D_{m,w}$, excluding the common limiting factors between $D_{m,i}$ and the migration coefficient of ions in the bulk feed solution $D_{\omega,i}$ (i.e., temperature, concentration difference, and external forces) discussed in Section 3.

Firstly, this section discusses how the electric potential difference ($\Delta\psi$) affects $D_{m,i}$. As illustrated in Fig. 1b, the feed-side

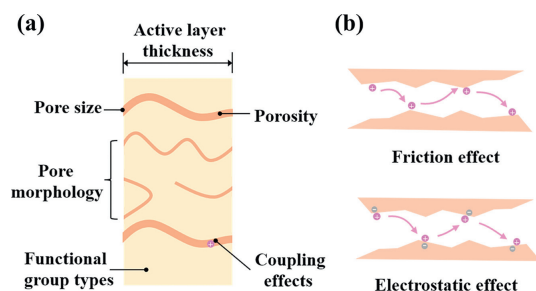


Fig. 3. (a) Internal structure properties of the RO membrane polyamide layer affecting salt ions diffusion. (b) The coupling effects between ions and membrane pores.

membrane surface generally exhibits a negative charge [60,61], while the permeate-side membrane surface is uncharged, creating a potential difference across the RO membrane. In a steady state of the RO system, both anions and cations move towards the permeate side. However, influenced by the potential difference, there is a tendency for the anions to migrate towards the permeate within the membrane and cations gravitate toward the feed side. Therefore, the potential difference has a negative effect on the anions and a positive effect on the cations.

Membrane structural properties, including polyamide layer thickness (Δx) and free volume pores, also impact $D_{m,i}$. Fig. 3 shows the schematic illustration of membrane structure properties affecting salt ions diffusion. According to Eqs. 22, 23 and 27, a decrease in Δx reduces R_{real} but increases J_w . In RO, the influence of Δx is less pronounced than the size exclusion effect due to the high denseness of the RO membrane surface. Nevertheless, Δx remains a crucial limiting factor for water transport. Despite the thin polyamide layer in TFC RO membranes, further optimization can yield higher water flux. Free-volume pores affect salt and water diffusion processes through pore size, pore volume fraction (i.e., porosity), pore morphology (e.g., tortuosity), and coupling effects between ion and membrane pore. Pore size is influenced by the synthesis process and monomer compositions [74], resulting in the size exclusion interaction. In this review, the symbols ε and τ represent porosity and tortuosity, respectively, and the reduction factor ε_e equals to $\varepsilon_e = \varepsilon/\tau^2$ [38]. Eqs. 22 and 27 show that a decrease in ε or an increase in τ causes R_{real} to rise, whereas the opposite holds for J_w (Eq. 23). This indicates that greater porosity and less tortuous membrane pore channels promote superior salt and water diffusion within the membrane. The coupling effects include the viscosity effect and friction effect, where the viscosity effect is due to the chemical affinity of ions to the membrane pore [75], such as the electrostatic force shown in Fig. 3b. The friction effect is caused by physical collisions of ions with rough inner pore walls [76] and will be detailed discussed below. Additionally, polymer mobility also impacts the salt and water diffusion processes by influencing the formation of free-volume pores. Overall, the measurements of increasing pore size and porosity, improving pore morphology, and selecting the appropriate polymer monomer can be employed to increase water flux.

In Section 2, convective and diffusive hindrance parameters (i.e., $K_{c,i}$ and $K_{d,i}$) are incorporated into salt and water mass transfer models, and these two parameters are functions of the ratio of ion radius r_i to pore radius r_p [27,77]. The diffusive hindrance parameter $K_{d,i}$ denotes that the friction effect between substances and the membrane matrix causes the reduction in salt and water permeation fluxes. It is also noteworthy that the energy dissipation caused by the friction effect between water and the membrane matrix leads to a decrease in the hydraulic pressure along the membrane thickness. This indicates that both hydraulic pressure gradient and friction effect govern the water transport within the RO membrane. The convective hindrance factor $K_{c,i}$ represents

the coupling effect of salt and water transport within RO membrane pores. Due to the presence of the convective effect, the salt flux increases with the enhanced water flux when the hydraulic pressure increases. This demonstrates the dependence of salt penetration on applied pressure, which is consistent with the solution-friction model [47] but starkly disparate from the SD model [28]. Based on the above analysis and Eq. 21, roughening the membrane's inner wall and reducing micropores in the RO membrane can boost salt rejection, and high water flux originates from the smooth membrane's inner wall.

In summary, the effects of $\Delta\psi$ and the internal membrane structure on the mass transfer behaviors of salt and water are represented by microscopic diffusion coefficients $D_{m,i}$ and $D_{m,w}$, respectively. To alleviate the trade-off effect, lowering $D_{m,i}$ while raising $D_{m,w}$ is advantageous. According to the above analysis of the improved salt transport equations, a wide range of available approaches for directly decreasing $D_{m,i}$ are proposed, such as diminishing pore size and porosity, rectifying pore tortuosity, reducing micropores on the membrane surface, or utilizing ion-membrane friction effects. Similarly, lowering the polyamide layer thickness, increasing pore size and porosity, optimizing pore tortuosity, and minimizing friction between water and the membrane wall are all strategies to augment $D_{m,w}$. Besides, regulating $\Delta\psi$ by managing the membrane surface charge and density can impact $D_{m,i}$, thus adjusting ion migration rate and direction within the RO membranes. These methods imply that $D_{m,i}$ and $D_{m,w}$ can be concurrently improved by coupling modulation of membrane structural parameters, presenting an alternative optimal solution for the trade-off effect between water flux and salt rejection.

6. Existing and potential strategies for enhancing membrane performance

The key to boosting the performance of TFC RO membranes is to address the trade-off effect between water flux and salt rejection. As discussed in Sections 3–5, the microscopic controllable coefficients indicating salt and water mass transfer processes through RO membranes are the migration coefficient, partition coefficient, and diffusion coefficient. The promotion effect of these micro-coefficients on salt rejection and water flux of RO membranes is driven by regulating the physicochemical properties of salt ions, the physicochemical and structural properties of RO membranes, the operating parameters of the RO system, and other factors (Table S2 in Supporting information). Based on this, this section explores the shortcomings of current research and proposes effective measures to improve RO performance in terms of process regulation of interfacial polymerization reactions, surface modification of TFC RO membrane, intensification of external fields, and optimization of other parameters (Fig. 4).

6.1. Process regulation of interfacial polymerization reactions

Currently, IP is the dominant method for fabricating TFC RO membranes with high salt rejection and water flux [78], typically adopting MPD and TMC as reaction monomers [79,80]. During the IP process, MPD diffuses from the aqueous phase to the organic phase [78], followed by polymerization occurring at the



Fig. 4. Strategies and results for enhancing membrane performance.

water-organic interface. On this basis, RO membrane performance can be optimized by regulating the IP reactions, such as selecting monomer types [81], adjusting operating parameters [82], and adding additives in both phases [8]. Essentially, the surface micro distribution coefficient (i.e., ϕ_i and ϕ_w) and internal micro diffusion coefficient (i.e., $D_{m,i}$ and $D_{m,w}$) in salt and water mass transfer equations are affected by the modulation of the IP reactions. In most cases, the regulation of IP reactions generally increases water flux while retaining significant salt retention, which is beneficial in coordinating the trade-off effect between water flux and salt rejection.

Improving RO membrane surface hydrophilicity or roughness is a typical method to boost ϕ_w . For example, the effective ways to improve the membrane surface hydrophilicity entailed both the introduction of hydrophilic groups on monomers [83] and the incorporation of hydrophilic nanofillers (e.g., zeolite [84–86], MOF [87,88], Ag [89]) in monomer solutions to fabricate thin-film nanocomposite (TFN) membranes. The mechanisms of the hydrophilic enhancement of the TFN membrane surface were the partial exposure of hydrophilic nanomaterials to the membrane surface [90] and the increase of carboxylic acid functional groups on the membrane surface [91]. Moreover, incorporating nanofillers into the polyamide layer can create channels for water transport, thereby impacting the microscopic diffusion coefficient $D_{m,w}$ of water in the RO membrane. A new type of TFN membrane, TFC membranes with nanofillers as an interlayer (TFNi) between the polyamide layer and the substrate [92–95], demonstrated a significant increase in water permeability. The elevation of water flux was also due to a higher $D_{m,w}$, which can be attributed to the optimized transport pathways and the improved IP conditions [96]. More specifically, the introduction of the interlayer with high permeability drove a reduction in water transfer resistance [92,97,98]. Additionally, the improved IP conditions can lead to the formation of a thinner polyamide layer with high cross-linking degrees than TFN membranes [92,94]. The comparison of TFN and TFNi membranes to enhance membrane performance is summarized in Table S3 (Supporting information).

Although numerous studies have been conducted to optimize IP conditions for improving RO membrane performance, the most common result in the current literature is a unilateral increase in permeability or selectivity, which is not the optimal solution to the trade-off effect. According to the model analysis in Sections 4 and 5, the trade-off effect can be mitigated by both reducing ϕ_i and enhancing ϕ_w , or simultaneously lowering $D_{m,i}$ and increasing $D_{m,w}$. In practical research works, an approach to ϕ_i and ϕ_w improvement involved using horizontally aligned MOF nanoflakes formed by self-assembly at the water-organic interface to hinder heat dissipation, thereby forming bubbles that resulted in a rougher and higher cross-linked polyamide layer, as indicated in Fig. S2 (Supporting information) [99]. This implies that upcoming studies can further co-optimize the microscopic partition and diffusion coefficients of salt and water to strengthen the permselectivity of RO membranes. Specifically, it is necessary to investigate novel monomers and broader control of monomer groups, which can modulate the friction effect of salt ions within the membrane's inner wall or enhance electrostatic interactions between ions and RO membranes. Aside from monomer types, adjustment parameters of the IP process can also co-optimize microscopic mass transfer coefficients of salt and water. As well known, a decrease in the organic phase temperature, monomer concentration, or reaction time reduces polyamide layer thickness [100], consequently raising $D_{m,w}$ and increasing water flux. At the same time, if future work deeply explores the influence mechanism of IP process parameters such as reaction time on the surface micromorphology and internal microstructure of RO membranes, simultaneous optimization of $D_{m,w}$ and $D_{m,i}$ or $D_{m,w}$ and ϕ_i can be realized, which

can lead to a breakthrough to the enhancement of RO membrane permselectivity.

6.2. Surface modification of TFC RO membranes

Membrane surface modification is considered to be an effective and promising strategy for obtaining high-performance RO membranes [101]. This approach includes physical and chemical methods, both of which improve membrane surface morphology and properties. The physical modification involves surface adsorption [102] and surface coating [103], where the modifier adheres to the membrane surface via a weaker bond (e.g., van der Waals forces and hydrogen bonding). Conversely, strong covalent bonds are employed to combine the polyamide layer and modifiers in chemical modification [101], such as hydrophilization treatment [104], oxidative modification [105], and surface grafting [106,107]. More detailed information on these two surface modification methods is summarized in Table S4 (Supporting information). Compared with physical modification, chemical modification is a more promising method due to the stability of the strong covalent bonds between the polyamide layer and the modifiers [101]. Chemical surface modification can effectively improve the micromorphological characteristics of the RO membrane surface, such as charge [108] and hydrophilicity [109]. The charged layer constructed on the RO membrane surface affects the microscopic migration parameters ($D_{w,w}$ and $D_{w,i}$) and the microscopic distribution parameters (ϕ_w and ϕ_i) in the water and salt mass transfer models (i.e., Eqs. 23 and 27), and the enhanced hydrophilicity of the RO membrane surface can also provide a considerable increase in ϕ_w .

According to the model analysis in Sections 3 and 4, the reduction of $D_{w,i}$ and ϕ_i and the elevation of $D_{w,w}$ and ϕ_w facilitate the resolution of the trade-off between water permeability and salt rejection. Both surface grafting and oxidative modification of polyamide RO membranes were practical techniques to accomplish this goal. For instance, Cheng and co-workers [110] employed persulfate as the oxidant to investigate the mechanism of modification, as shown in Fig. S3 (Supporting information). The elevated water flux and salt rejection were attributed to the enhanced hydrophilicity, charge, and size exclusion effect of the RO membrane surface, thus increasing ϕ_w and decreasing $D_{w,i}$ and ϕ_i . Specifically, the hydroxyl radical-induced amide bond breakage led to the excess of hydrophilic hydroxyl and negatively charged carboxyl groups on the RO membrane surface, as well as the sulfate-initiated hydroquinone structures resulting from redox polymerization of polyamides resulted in the formation of hydroquinone structures with a high crosslinking degree.

Although improvements in RO membrane performance are obtained through surface modification, there are still significant challenges to overcome. For the chemical method, surface grafting encounters restrictions in water flux enhancement as a result of the formation of the resistance layer, which causes a drop in ϕ_w to a certain extent. Hence, if the reduction in ϕ_w caused by the mass transfer resistance layer can be weakened or even absent, the trade-off effect between water flux and salt rejection can be effectively alleviated. Accordingly, the grafted layer could be looser and more hydrophilic, which can be achieved by exploring new graft materials, further modifying existing graft materials, optimizing grafting methods, or functionalizing the grafted layer (e.g., loading hydrophilic nanomaterials within the graft layer [111,112]). For example, Wu *et al.* [113] introduced cyclodextrin (CD) onto the RO membrane surface by secondary IP, forming a loose and highly hydrophilic graft layer atop the polyamide layer. The loose grafting layer indicates that there is no mass transfer resistance layer formed on the membrane surface to hinder water transport. As a result, this modification increased the water permeance of RO membranes by nearly threefold, and the rejection of NaCl was over

98%. Additionally, if the membrane surface modification could yield the combined improvement in membrane surface effects (*i.e.*, electrostatic interaction, size exclusion, and affinity) and membrane surface micromorphology (*i.e.*, hydrophilicity, roughness, *etc.*) discussed in Section 4, the microscopic mass transfer coefficients of salt and water will be boosted. It is vital for promoting the permselectivity of modified RO membranes.

6.3. Intensification of external fields

Nowadays, electric field technologies are relatively mature, which presents potential opportunities for integration with RO membranes. In Section 2, when deriving the refined salt and water mass transfer model, the external force parameter I_i is introduced into the salt transport equation. The external field-assisted system combines the RO membrane with external field technologies such as electric fields to regulate the mass transfer behaviors of salt and water by directly driving [57] or affecting their existing forms [114] through external fields. Table S5 (Supporting information) summarizes the mechanism and system performance of external field-assisted RO membranes to enhance RO membrane performance. The most widely used RO systems with the assistance of electric fields include a built-in electrodes system in the feed and permeate solutions, as well as a conductive RO membrane system.

As mentioned in Section 3, the electric field generated by electrodes on either side of the membrane has an effect on the microscopic mass transfer coefficients (*i.e.*, $D_{\omega,i}$, Φ_i , and $D_{m,i}$) of salt ions, thus impacting the rate and direction of ion diffusion, a phenomenon confirmed in the literature [57,115]. In the polyamide NF membrane, Li *et al.* [57] devised a system that combined an NF membrane with an electric field (EF) for efficient Li^+ rejection. The rejection rate of Li^+ achieved 97.01% due to the lowering of $D_{\omega,i}$, Φ_i , and $D_{m,i}$, which was the combined effect of the dragging force of EF and the size exclusion. In addition, the microstructure of the RO membrane surface, such as roughness, was also affected by the electric field [115]. It is reported that the surface of the RO membrane became smoother after the treatment of a strong electric field, which was a key factor contributing to changes in the water partition coefficient Φ_w . For a conductive membrane system, it can either directly utilize the membrane as an electrode [116] or employ carbon cloth at the membrane surface as an electrode [117], both of which can reduce $D_{\omega,i}$ and Φ_i via enhanced electrostatic repulsion.

Although external fields have great potential in intensifying the RO membrane performance, these coupled systems between external fields and RO membranes are still in their infancy in practical research works. First, the application of external electric fields on RO membranes has received limited attention, resulting in a lack of in-depth study of the mechanisms involved in these coupled systems. Consequently, it is necessary to have a more comprehensive understanding of how external fields specifically affect the microscopic mass transfer coefficients of salt and water. Second, the complexity of the operating process and the instability of the modified RO membrane (*e.g.*, the conductive RO membranes prepared by coating CNTs on the membrane surface [118]) are also major obstacles to the application of these coupled systems. Eventually, the energy consumption and economic cost of electric field-assisted RO systems are of particular concern in practical applications. It is necessary to calculate the energy consumption of these coupled systems to measure the feasibility of the actual application of the electric-field assisted RO systems.

6.4. Optimization of other parameters

The modulation of the microscopic coefficients of salt and water mass transfer to improve RO membrane performance can be

achieved not only by IP reaction regulation, membrane surface modification, and electric field enhancement, but also by optimization of system operating conditions (*e.g.*, temperature and pressure), feed solution characteristics (*e.g.*, concentration, flow state, and pH), and salt ions attributes (*e.g.*, size, charge, and charge density).

As noted in Section 3, the effective way to both decrease the microscopic migration coefficient $D_{\omega,i}$ of salt in the feed solution and increase the microscopic migration coefficient $D_{\omega,w}$ of water in the feed solution is to diminish the feed salt concentration, thus enhancing the permselectivity of RO membranes. Mitigation of the CP effect can also be achieved by elevating the mass transfer coefficient k , which is the result of the reduction of the feed salt concentration or the maintenance of the turbulent flow of the feed solution. Increasing the cross-flow velocity [119,120], inserting a spacer on the membrane surface [121–123], and adopting pulsed flow [124,125] are three methods for ensuring feed solution turbulence at the membrane surface. Table S6 (Supporting information) shows the mechanisms and results of the three methods. In addition, the concentration and pH of the feed solution add complexity to RO performance, as several RO system properties (*e.g.*, membrane swelling, pore size, osmotic pressure difference) vary with concentration and pH. Therefore, pre-processing is necessitated for controlling these above parameters. Pretreatment techniques [126] include conventional technologies such as coagulation and disinfection, and membrane-based methods such as UF [127]. Moreover, future work can also concentrate on ion size and charge to enable specific adjustment of salt microscopic mass transfer coefficients.

7. Conclusions and outlook

TFC RO membrane has a wide range of applications in the process of water purification because of its excellent performance. However, the trade-off effect between water flux and salt rejection is the primary obstacle to further improving RO membrane performance. To address this challenge, this review analyzes the mass transfer behaviors of salt and water permeating RO membranes by model derivation and obtains the key parameters limiting salt and water mass transfer, namely microscopic controllable migration, partition, and diffusion coefficients. Then, based on a model analysis of these micro-coefficients, this review accurately captures the deficiencies of optimizing membrane properties, external fields, and system operating conditions in regulating these microscopic coefficients, thereby purposing strategies to further mitigate the trade-off effect.

From this review, several prospects are summarized to guide future studies.

- (i) The model discussed in this paper emphasizes the mass transfer behaviors of salt and water in aqueous solutions, which has a reference value for the study of the mass transfer process of solute and solvent in organic solutions. Moreover, the solute rejected by the RO membrane includes not only salt ions but also trace organic contaminants that threaten the safety of drinking water and public health. Obviously, this modified model is also applicable to the rejection of trace organic contaminants by RO membranes. Specifically, the surface partition effects of organic micropollutants through RO membrane also include size exclusion, electrostatic repulsion, affinity, and intermolecular force. Meanwhile, the driving force by which organic micropollutants traverse the RO membrane contains concentration difference, potential difference, convection effect, and external field driving forces. Therefore, future research can combine data analysis, simulation verification, and characterization methods to further

explore the suitability of this modified model for organic micropollutant rejection.

- (ii) At the micro level, to advance the development of high-performance RO membranes, future studies should emphasize the internal relationship among the microscopic coefficients of salt and water transport, and comprehensively consider the effects of migration, dissolution, and diffusion coefficients on the mass transfer behaviors of salt and water. At the same time, the modulation of these microscopic coefficients in practical studies should not only innovate the methods of membrane preparation and modification but also deeply explore the influence of external parameters (such as external forces and system operating parameters) and solvent and solute characteristics on them.
- (iii) At the macro level, to advance the development of high-performance RO membranes, we propose several prospects about the different strategies for improving RO membrane performance discussed in Section 6. For the process regulation of IP reactions, the existing data predominantly stem from singular experiments, thus yielding inadequate information to fully analyze the influence of IP reaction process parameters on membrane performance. In addition, the limitations in the selection of reaction monomers and co-solvents, the uniformity and stability in the distribution of nanofillers within the RO membrane polyamide layer, and the insufficient exploration of the impact of IP reaction parameters on the internal structure of RO membranes are all shortcomings that upcoming studies should overcome. For the surface modification of TFC RO membranes, researchers should not only focus on the investigation of novel modified materials and methods that can better boost the dissolution of salt and water on the RO membrane surface but also deeply reveal the potential mechanism of high-performance of RO membranes through a combination of characterization and calculation. For the intensification of external fields, the coupling system of RO membranes and external fields has emerged as a building block for RO systems recently. However, to promote the development of this system, a molecular-level approach to illustrate the effects of external fields on the properties of solute, solvent, and membrane material underlying this system is needed.
- (iv) When employing RO membranes in practical engineering, energy consumption, time costs, and economic costs are factors that limit their application. Therefore, these factors must be considered when taking optimization measures to obtain high-performance RO membranes. For instance, the complexity of operational steps and high economic costs are challenges for incorporating additives into the RO membrane. As a result, the adoption of new technologies, such as the use of UV during the IP process to simplify the modification process, is another point worth exploring in future work. In the surface grafting process, improving or innovating the grafting process can directly reduce time-consuming and save costs, of which catalyst-assisted grafting is a potential method. It is also important to identify the lifetime, energy consumption, and economic costs of external field-coupled RO membrane systems, and the development of new membrane materials may be beneficial for the operational stability of the coupled system and reduce costs.

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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Supplementary materials

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References

- [1] C.J. Vörösmarty, P.B. McIntyre, M.O. Gessner, et al., *Nature* 467 (2010) 555–561.
- [2] S.B. Grant, J.D. Saphores, D.L. Feldman, et al., *Science* 337 (2012) 681–686.
- [3] Q.L. Wu, W.Q. Guo, X. Bao, et al., *Bioresour. Technol.* 224 (2017) 727–732.
- [4] M.A. Shannon, P.W. Bohn, M. Elimelech, et al., *Nature* 452 (2008) 301–310.
- [5] S. Shao, F. Zeng, L. Long, et al., *Environ. Sci. Technol.* 56 (2022) 12811–12827.
- [6] C.Y. Tang, Z. Yang, H. Guo, et al., *Environ. Sci. Technol.* 52 (2018) 10215–10223.
- [7] M. Qasim, M. Badrelzaman, N.N. Darwish, et al., *Desalination* 459 (2019) 59–104.
- [8] Z. Tan, S. Chen, X. Peng, et al., *Science* 360 (2018) 518–521.
- [9] Z. Yang, X.H. Ma, C.Y. Tang, *Desalination* 434 (2018) 37–59.
- [10] D. Li, Y. Yan, H. Wang, *Prog. Polym. Sci.* 61 (2016) 104–155.
- [11] Z. Yang, H. Guo, C.Y. Tang, *J. Membr. Sci.* 590 (2019) 117297.
- [12] G. Kang, H. Yu, Z. Liu, et al., *Desalination* 275 (2011) 252–259.
- [13] X. Shan, S.L. Li, W. Fu, et al., *J. Membr. Sci.* 608 (2020) 118209.
- [14] Z. Yang, H. Guo, Z.K. Yao, et al., *Environ. Sci. Technol.* 53 (2019) 5301–5308.
- [15] B. Khorshidi, T. Thundat, B.A. Fleck, et al., *Sci. Rep.* 6 (2016) 22069.
- [16] S. Bing, J. Wang, H. Xu, et al., *J. Membr. Sci.* 555 (2018) 318–326.
- [17] M. Mehrabi, V. Vatanpour, O.O. Teber, et al., *J. Membr. Sci.* 664 (2022) 121066.
- [18] H. Wu, B. Tang, P. Wu, *J. Membr. Sci.* 428 (2013) 341–348.
- [19] M. Asadollahi, D. Bastani, S.A. Musavi, *Desalination* 420 (2017) 330–383.
- [20] X. Li, Z. Wang, X. Han, et al., *J. Membr. Sci.* 640 (2021) 119765.
- [21] H.K. Lonsdale, U. Merten, R.L. Riley, *J. Appl. Polym. Sci.* 9 (1965) 1341–1362.
- [22] D. Paul, *J. Membr. Sci.* 241 (2004) 371–386.
- [23] M. Planck, *Ann. Phys. Chem.* 275 (1890) 161–186.
- [24] S. Gisladdottir, T. Loftsson, E. Stefansson, A. Graefé's, *Clin. Exp. Ophthalmol.* 247 (2009) 1677–1684.
- [25] W. Mickols, *Ind. Eng. Chem. Res.* 55 (2016) 11139–11149.
- [26] K.S. Spiegler, O. Kedem, *Desalination* 1 (1966) 311–326.
- [27] W.M. Deen, *AIChE J.* 33 (1987) 1409–1425.
- [28] J.G. Wijmans, R.W. Baker, *J. Membr. Sci.* 107 (1995) 1–21.
- [29] S. Castaño Osorio, P.M. Biesheuvel, E. Spruijt, et al., *Water Res.* 225 (2022) 119130.
- [30] S. Basu, M.M. Sharma, *J. Membr. Sci.* 124 (1997) 77–91.
- [31] W. Li, X. Su, A. Palazzolo, et al., *J. Membr. Sci.* 569 (2019) 71–82.
- [32] V. Giraldez, M.D. Afonso, *J. Membr. Sci.* 300 (2007) 20–27.
- [33] I. Sutzkover, D. Hasson, R. Semiat, *Desalination* 131 (2000) 117–127.
- [34] S. Kim, E.M.V. Hoek, *Desalination* 186 (2005) 111–128.
- [35] Z.V.P. Murthy, S.K. Gupta, *Desalination* 109 (1997) 39–49.
- [36] S. Ganguly, P.K. Bhattacharya, *J. Membr. Sci.* 97 (1994) 185–198.
- [37] V.S. Minnikanti, S. DasGupta, S. De, *J. Membr. Sci.* 157 (1999) 227–239.
- [38] Y.S. Oren, P.M. Biesheuvel, *Phys. Rev. Appl.* 9 (2018) 024034.
- [39] J. Wang, D.S. Dlamini, A.K. Mishra, et al., *J. Membr. Sci.* 454 (2014) 516–537.
- [40] S. Bhattacharjee, J.C. Chen, M. Elimelech, *AIChE J.* 47 (2001) 2733–2745.
- [41] L. Dresner, *Desalination* 10 (1972) 27–46.
- [42] M.S. Hall, V.M. Starov, D.R. Lloyd, *J. Membr. Sci.* 128 (1997) 23–37.
- [43] T. Tsuru, S.I. Nakao, S. Kimura, *J. Chem. Eng. Jpn.* 24 (1991) 511–517.
- [44] E.A. Mason, H.K. Lonsdale, *J. Membr. Sci.* 51 (1990) 1–81.
- [45] L. Putić, S. Alnouri, V. Stijepović, et al., *Comput. Chem. Eng.* 148 (2021) 107264.
- [46] L. Wang, T. Cao, J.E. Dykstra, et al., *Environ. Sci. Technol.* 55 (2021) 16665–16675.
- [47] L. Wang, J. He, M. Heiranian, et al., *Sci. Adv.* 9 (2023) ead8488.
- [48] Z. Mai, S. Gui, J. Fu, et al., *Desalination* 469 (2019) 114094.
- [49] V.M. Starov, N.V. Churaev, *Adv. Colloid Interface Sci.* 43 (1993) 145–167.
- [50] P.M. Biesheuvel, S. Porada, M. Elimelech, et al., *J. Membr. Sci.* 647 (2022) 120221.
- [51] R.R. Sharma, R. Agrawal, S. Chellam, *J. Membr. Sci.* 223 (2003) 69–87.
- [52] W. Cheng, C. Liu, T. Tong, et al., *J. Membr. Sci.* 559 (2018) 98–106.
- [53] A.E. Childress, M. Elimelech, *Environ. Sci. Technol.* 34 (2000) 3710–3716.
- [54] E. Dražević, K. Košutić, V. Freger, *Water Res.* 49 (2014) 444–452.
- [55] V. Freger, *Environ. Sci. Technol.* 38 (2004) 3168–3175.
- [56] Q. Li, H. Liu, B. He, et al., *J. Membr. Sci.* 641 (2022) 119880.
- [57] Q. Li, H. Liu, Y. Ji, et al., *Desalination* 535 (2022) 115825.
- [58] M. Mänttäri, A. Pihlajamäki, M. Nyström, *J. Membr. Sci.* 280 (2006) 311–320.

- [59] O. Coronell, M.I. González, B.J. Mariñas, et al., *Environ. Sci. Technol.* 44 (2010) 6808–6814.
- [60] A.E. Childress, M. Elimelech, *J. Membr. Sci.* 119 (1996) 253–268.
- [61] O. Coronell, B.J. Mariñas, X. Zhang, et al., *Environ. Sci. Technol.* 42 (2008) 5260–5266.
- [62] X. Bao, Q. Wu, W. Shi, et al., *Water Res.* 153 (2019) 1–10.
- [63] C. Lu, C. Hu, C.L. Ritt, et al., *J. Am. Chem. Soc.* 143 (2021) 14242–14252.
- [64] L.A. Richards, A.I. Schaefer, B.S. Richards, et al., *Small* 8 (2012) 1701–1709.
- [65] S.H. Kim, S.Y. Kwak, T. Suzuki, *Environ. Sci. Technol.* 39 (2005) 1764–1770.
- [66] C. Bellona, J.E. Drewes, P. Xu, et al., *Water Res.* 38 (2004) 2795–2809.
- [67] Z. Zhang, J. Hu, S. Liu, et al., *Chin. Chem. Lett.* 32 (2021) 2882–2886.
- [68] F. Pacheco, R. Sougrat, M. Reinhard, et al., *J. Membr. Sci.* 501 (2016) 33–44.
- [69] F.A. Pacheco, I. Pinnau, M. Reinhard, et al., *J. Membr. Sci.* 358 (2010) 51–59.
- [70] G.L. Jadav, P.S. Singh, *J. Membr. Sci.* 328 (2009) 257–267.
- [71] G. Kang, M. Liu, B. Lin, et al., *Polymer* 48 (2007) 1165–1170.
- [72] F. Foglia, B. Frick, M. Nania, et al., *Nat. Commun.* 13 (2022) 2809.
- [73] W. Gao, F. She, J. Zhang, et al., *J. Membr. Sci.* 487 (2015) 32–39.
- [74] H. Zhang, M.S. Wu, K. Zhou, et al., *Environ. Sci. Technol.* 53 (2019) 6374–6382.
- [75] R. Epsztein, R.M. DuChanois, C.L. Ritt, et al., *Nat. Nanotechnol.* 15 (2020) 426–436.
- [76] A. Noy, *J. Phys. Chem. C* 117 (2013) 7656–7660.
- [77] H. Brenner, L.J. Gaydos, *J. Colloid Interface Sci.* 58 (1977) 312–356.
- [78] X. Lu, M. Elimelech, *Chem. Soc. Rev.* 50 (2021) 6290–6307.
- [79] R.J. Petersen, *J. Membr. Sci.* 83 (1993) 81–150.
- [80] A. Widjaya, T. Hoang, G.W. Stevens, et al., *Sep. Purif. Technol.* 89 (2012) 270–281.
- [81] L. Li, S. Zhang, X. Zhang, et al., *J. Membr. Sci.* 289 (2007) 258–267.
- [82] Z. Ali, Y. Al Sunbul, F. Pacheco, et al., *J. Membr. Sci.* 578 (2019) 85–94.
- [83] Y. Zhao, Z. Zhang, L. Dai, et al., *J. Membr. Sci.* 536 (2017) 98–107.
- [84] B.H. Jeong, E.M.V. Hoek, Y. Yan, et al., *J. Membr. Sci.* 294 (2007) 1–7.
- [85] T. Pang, X. Yang, C. Yuan, et al., *Chin. Chem. Lett.* 32 (2021) 328–338.
- [86] C. Xu, C. Zhou, S. Wang, et al., *Chin. Chem. Lett.* 30 (2019) 1204–1206.
- [87] J. Duan, Y. Pan, F. Pacheco, et al., *J. Membr. Sci.* 476 (2015) 303–310.
- [88] Y. Qin, Y. Wan, J. Guo, et al., *Chin. Chem. Lett.* 33 (2022) 693–702.
- [89] E.S. Kim, G. Hwang, M.G. El-Din, et al., *J. Membr. Sci.* 394 (2012) 37–48.
- [90] J. Yin, B. Deng, *J. Membr. Sci.* 479 (2015) 256–275.
- [91] M.L. Lind, A.K. Ghosh, A. Jawor, et al., *Langmuir* 25 (2009) 10139–10145.
- [92] S. Karan, Z. Jiang, A.G. Livingston, *Science* 348 (2015) 1347–1351.
- [93] Z. Yang, Z.W. Zhou, H. Guo, et al., *Environ. Sci. Technol.* 52 (2018) 9341–9349.
- [94] J. Yuan, M. Wu, H. Wu, et al., *J. Mater. Chem. A* 7 (2019) 25641–25649.
- [95] Z. Zhou, Y. Hu, C. Boo, et al., *Environ. Sci. Technol. Lett.* 5 (2018) 243–248.
- [96] Z. Yang, P.F. Sun, X. Li, et al., *Environ. Sci. Technol.* 54 (2020) 15563–15583.
- [97] Z. Yang, F. Wang, H. Guo, et al., *Environ. Sci. Technol.* 54 (2020) 11611–11621.
- [98] M. Zhang, W. Jin, F. Yang, et al., *Environ. Sci. Technol.* 54 (2020) 7715–7724.
- [99] Y. Wen, R. Dai, X. Li, et al., *Sci. Adv.* 8 (2022) eabm4149.
- [100] S. Habib, S.T. Weinman, *Desalination* 502 (2021) 114939.
- [101] G.D. Kang, Y.M. Cao, *Water Res.* 46 (2012) 584–600.
- [102] H.D. Raval, M.R. Raviya, H.C. Rathod, *Adv. Polym. Technol.* 37 (2018) 3106–3114.
- [103] X. Han, Z. Wang, J. Wang, *J. Membr. Sci.* 651 (2022) 120453.
- [104] D. Mukherjee, A. Kulkarni, W.N. Gill, *J. Membr. Sci.* 97 (1994) 231–249.
- [105] H. Rho, S.J. Im, O. Alrehaili, et al., *Environ. Sci. Technol.* 55 (2021) 6984–6994.
- [106] S. Belfer, J. Gilron, Y. Purinson, et al., *Desalination* 139 (2001) 169–176.
- [107] S. Belfer, Y. Purinson, R. Fainshtein, et al., *J. Membr. Sci.* 139 (1998) 175–181.
- [108] Z. Yang, W. Fang, Z. Wang, et al., *J. Membr. Sci.* 620 (2021) 118862.
- [109] X. Bao, Q. She, W. Long, et al., *Water Res.* 190 (2021) 116678.
- [110] W. Cheng, H. Xu, P. Wang, et al., *Environ. Sci. Technol.* 56 (2022) 8864–8874.
- [111] H. Majid, N. Heidarzadeh, V. Vatanpour, et al., *Chemosphere* 302 (2022) 134931.
- [112] V. Vatanpour, A. Sanadgol, *Desalination* 491 (2020) 114442.
- [113] H. Wu, Y. Liu, H. Zhang, et al., *J. Membr. Sci.* 660 (2022) 120862.
- [114] M. Seyyedi, T. Wu, J.A. Brant, *J. Membr. Sci.* 668 (2023) 121274.
- [115] M.T. Darestani, T.C. Chilcott, H.G.L. Coster, *J. Membr. Sci.* 449 (2014) 158–168.
- [116] M. Xu, P. Zhao, C.Y. Tang, et al., *Chin. Chem. Lett.* 33 (2022) 3818–3822.
- [117] X. Bao, W. Long, H. Liu, et al., *J. Membr. Sci.* 637 (2021) 119639.
- [118] Y. Liu, F. Liu, N. Ding, et al., *Chin. Chem. Lett.* 31 (2020) 2539–2548.
- [119] W. Li, X. Su, A. Palazzolo, et al., *Desalination* 417 (2017) 102–114.
- [120] S.S. Sablani, M.F.A. Goosen, R. Al-Belushi, et al., *Desalination* 141 (2001) 269–289.
- [121] A.H. Haidari, S.G.J. Heijman, W.G.J. van der Meer, *Sep. Purif. Technol.* 192 (2018) 441–456.
- [122] O. Kavianiipour, G.D. Ingram, H.B. Vuthaluru, *J. Membr. Sci.* 526 (2017) 156–171.
- [123] C.P. Singh, A. Yadav, A. Kumar, *Colloids Surf. A* 650 (2022) 129664.
- [124] T.J. Kennedy, R.L. Merson, B.J. McCoy, *Chem. Eng. Sci.* 29 (1974) 1927–1931.
- [125] B. Liberman, L. Eshed, G. Greenberg, *Desalination* 479 (2020) 114336.
- [126] Q.L. Wu, W.Q. Guo, H.S. Zheng, et al., *Bioresour. Technol.* 216 (2016) 653–660.
- [127] S.F. Anis, R. Hashaikeh, N. Hilal, *Desalination* 452 (2019) 159–195.