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Chapter 9

Fouling and Cleaning in Osmotically Driven Membranes

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Additional information is available at the end of the chapter

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Abstract

Fouling is a phenomenon that occurs in all membrane processes. It is a complex problem, which limits the full operation of this technology. Fouling in pressure-driven membranes (PDMs) has been studied extensively, and the occurrence is well understood in that methods of mitigation have been proposed; however, limitations still occur for their full implementation. The use of osmotically driven membranes (ODMs) for water treatment is an emerging technology, which has shown some advantages such as low hydraulic pressure operation, high solute rejection and high recovery over PDMs. However, like in PDMs, fouling still presents a challenge. This chapter is aimed at evaluating the impact of fouling on the ODM performance, exploring the factors and mechanisms governing the fouling behaviour, developing approaches for mitigating fouling, elucidating the effect of membrane fouling and providing mitigation strategies as well as the causes of fouling in ODMs.

Keywords: membrane fouling, fouling mitigation, forward osmosis, pressure retarded osmosis, pretreatment

1. Introduction

The use of osmotically driven membranes (ODMs), such as forward osmosis (FO), pressure retarded osmosis (PRO), direct osmotic concentration (DOC) and osmotic dilution (ODN), for water treatment is an emerging technology that has shown some advantages such as low hydraulic pressure operation and hence low energy consumption, high solute rejection and high recovery over pressure-driven membranes (PDMs) [1–5]. The ODMs are seen to gradually outperform the conventional PDMs. For instance, Mi and Elimelech [6], in their review, noted that forward osmosis is said to consume only about 20% of the electrical energy

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required by other processes such as desalination. These processes could use low quality heat like the waste heat from power plants as their energy inputs. The advantage associated with it has been the higher recovery, and because of this, less discharge of brine to the environment is noticeable [6].

Until recently, the focus of most studies has been on PDMs; however, a shift in research is being noticed and more research is emerging regarding the application of ODMs. However, the studies on ODMs published has been intensified mainly on issues such as choice of draw solutions, membrane properties and other factors relating to the application of ODMs. Fouling mechanisms in these membranes has, on the contrary, received less attention. On the other hand, fouling in PDMs has been studied extensively and methods of mitigation and control are being adopted for their implementation [6].

Fouling is a phenomenon that occurs in all membrane processes. It is a complex problem that limits the full operation of this technology. Fouling can be caused by the accumulation of suspended particles or colloids, organic molecules and also soluble inorganic compounds, microorganisms, or a combinations of all these on the membrane [7]. Different substances have been identified to cause fouling in membranes and as such, this can result in different fouling mechanisms in the membranes. For example, fouling could occur as a result of the deposition of foulants onto the surface of the membrane thus forming a cake layer. This phenomenon is commonly referred to as external fouling. It could occur within the pores of the membrane. In this instance, the foulant sizes could be relatively smaller than the pores of the membranes, hence penetrates the pores of the membrane thereby leading to pore blocking. This type of fouling is called internal fouling [7].

Fouling occurs in all membrane operations, however, the tendency and its behaviour varies due to the mode of operation, the nature of the membranes and the nature of the foulants. Mi and Elimelech [8] studied the chemical and physical aspects of organic fouling of FO membranes using alginate, bovine serum albumin (BSA), and Aldrich humic acid (AHA) as the exemplary organic foulants. In that study, the effect of chemical and physical interactions such as intermolecular adhesion forces, calcium binding and the membranes initial permeate flux were investigated. Similarly, the membrane orientation on organic fouling of FO membranes was investigated. They observed that there was a relationship between organic fouling and intermolecular adhesion, thus indicating that foulant-foulant interaction is an important aspect that can determine the rate and level of fouling, therefore emphasising that the main factors that control membrane fouling differ from foulant to foulant [8].

Studies on the fouling in ODMs have revealed that fouling propensity within the ODMs is lower as compared to PDMs [2, 3, 9, 10]. The lower fouling propensity is said to be so in the case, whereby the active layer of the membrane is arranged to face the feed solution containing the foulant. In addition, the low flux conditions and lack of applied pressure in the FO process have been highlighted as some of the reasons for this occurrence. However, internal concentration polarisation (ICP) could still occur within the membrane [10]. Therefore, ICP is one of the major drawbacks of ODMs especially in FO [3].

Factors such as draw solutions, hydrodynamics and operating conditions and feed water characteristics could impact fouling in different ways. The effect of these factors, if properly

managed, will help mitigate fouling propensity on the membrane. The configuration of the membranes can also affect membrane performance significantly. Tang et al. [3] studied the coupled effects of internal concentration polarisation and fouling on flux behaviour of FO membranes during humic acid filtration. They found that the membrane orientation plays an important role. In their observation, ICP occurred more when the active layer faced the draw solution (AL-facing-DS) as compared to when the membrane active layer faced the feed water (AL-facing-FW). This leads to a dilutive ICP in the FO support layer [3]. However, a more substantial flux stability is said to be achieved by the AL-facing FW as against the dilutions of the bulk draw solution and membrane fouling.

Thus, understanding the phenomenon of fouling in ODMs will provide more information that could lead to the development of new FO membranes with reduced ICP and high water permeability. The aim of this review is to evaluate the impact of fouling on the ODMs performance and to explore the factors and mechanisms governing the fouling behaviour. Further, it aims to develop approaches for mitigating fouling and to further elucidate the effect of membrane fouling and mitigation strategies. The causes of fouling in ODMs will also be described. The performance of FO membranes is defined by three parameters; the pure water permeability coefficient, solute permeability coefficient and the structural parameter. The solute permeability describes mass transport across the membrane active layer while the structural parameter governs the transport phenomena across the membrane support layer. The aforementioned parameters are used to describe the permeate water and solute fluxes of FO processes [11].

2. Fouling in membranes

The fouling phenomenon in PDMs and ODMS differs in some ways. In PDMs, factors that affect membrane fouling can be classified into three categories: membrane properties, operating parameters and the nature of the waste water to be treated. In ODMs, there could be additional factors to the aforementioned, such as the membrane orientation and the type of draw solutions [12–14]. The driving force for PDM systems is pressure. Hence, the relationship between pressure and flux is positive. A rise in pressure causes a rise in flux; however, for a feed mixture there is a point where a further increase in pressure results in a minimal increase in flux. This is because the particles of the component being rejected by the membrane accumulates on the membrane surface and obstructs the passage of the solvent through the membrane. If the process is allowed to continue to run, the rejected layer on the membrane surface grows thicker and becomes more and more resistant to solvent flow and this results in the flux dropping. At this point, it is said that the membrane is fouled and it is no longer economically justifiable to continue to run because the added energy to the system does not recover or even maintain flux [15, 16].

On the other hand, ODM systems use the osmotic pressure gradient, which is the chemical potential difference between the feed water and the concentrated draw solution as its driving force. With this application, the use of external pressure is not needed [3, 10, 17, 18]. As a result of this, the system is said to be more economically viable due to its significantly low

energy consumption [19]. This advantage has attracted the application of ODMs in seawater desalination, wastewater reclamation and in liquid food processing. However, like PDMs, a decline in flux always results, due to the severe internal concentration polarisation that always occurs in the porous membrane support [9, 17, 20, 21].

Fouling in membranes could occur internally or externally on the membrane. The extent of fouling in membranes depends on the type of separation and the type of membrane used to carry out the separation. Fouling leads to an overall increase in membrane resistance for mass transport, and hence affects the performance of membranes by a gradual decrease in flux and a decrease in rejection. The effect of this is seen in the deterioration of the membrane properties and as such results in high costs of operation and cleaning of the membranes to restore its initial flux [22].

The orientation of ODMs could be in two ways; active layer-feed solution (AL-FS) and the active layer-draw (AL-DS) solution. Hence, the nature of fouling differs with orientation [17]. The AL-FS mode is reported to be the FO mode (normal), while the AL-DS is the (PRO) reversed AF [23]. AL-FS orientation is when the active layer of the membrane faces the feed solution; and the AL-DS is when the active layer of the membrane faces the draw solution [14]. The type of fouling that will occur in the membrane will depend on the orientation of the membrane. The AL-DS could also be referred to as external fouling because solutes from the feed solution accumulate on the membrane surface thus forming a cake layer with time. This is similar to that formed in PDMs. On the other hand, in the AL-DS orientation, complications arise because other fouling mechanisms, such as pore blocking, could occur in addition to the cake layer formation. The occurrence of this is however dependent on the type and nature of foulants. Smaller sized particles will find their way into the pores of the membranes, thereby causing the membrane pores to be become blocked and therefore, internal fouling occurs. However, if it contains larger particles, these foulants will remain on the surface of the membrane and are thus deposited on the membrane surface hence blocking the pores leading to external fouling. If the feed solution contains a mixture of both sizes of foulants, both types of fouling could be occurring within the membrane [7, 23].

Both orientations affect the performance of the membrane in different ways. The AL-DS orientation has shown to have a lower initial flux, however, a higher fouling resistance, while the AL-FS has a higher initial flux but is less prone to fouling. However, it can be immensely affected by dilutive ICP. Therefore, ODM membranes are faced either with a more severe dilutive ICP in AL-FS or having much greater fouling tendencies in AL-DS, and therefore a balance must be reached in order to obtain optimum performance carrying out mitigating measures [17]. However, Chen et al. [23] reported in their study that the effect of fouling is more enhanced in PRO membranes. The purpose for this is the fact that PRO membranes are composed of a denser or thicker structure than the FO membranes to enable them to withstand the high pressure loading. Therefore, the denser structure contributes to the fouling tendencies.

Mi and Elimelech [6] studied the organic fouling of forward osmosis membranes. The main aim of that study was to examine organic fouling and the cleaning methods that will follow in the FO. Two types of membranes were used; polyamide and cellulose acetate (PA and CA) with alginate as the model foulant. Again, they used atomic force measurement (AFM) to detect the role of membrane materials in determining membrane fouling and cleaning behaviour.

They found that the PA was prone to more fouling propensity. The PA membrane surface were said to contain some adhesive sites even though lower as compared to those from the CA. The higher fouling in the PA membranes were due to the fact that the PA membranes caused more adsorption, thereby leading to a more severe fouling at an early stage [6].

Furthermore, Mi and Elimelech [6], in the same study, considered the flux behaviour in RO and FO and found that similar flux patterns were obtained in membrane types; however, the flux recovery was different. A higher flux was recovered from FO than the RO. The reason for this occurrence was attributed to the fact that the fouling layer formed on the FO membrane was less compact due to a lack of hydraulic pressure application [6].

Xie et al. [24], in their study on the role of pressure in organic fouling in FO and RO, used alginate as the foulant, while varying the contribution pressure in terms of osmotic and hydraulic. From that study, two possible mechanisms of fouling were identified which were permeation drag force and compression of foulants. The fouling thickness that was observed by them was in the decreasing order of FO < PFO < R O. They arrived at the same conclusion that hydraulic pressure plays a significant part in the compression of the fouling layer to a great extent [24]. The drag force was the only applied force in FO; however, this did not necessarily mean that fouling will not occur in the FO membranes.

As stated earlier, different factors are responsible for fouling in membranes. One dominant factor is the nature of contaminants that can be found in the wastewater, for example, colloidal particles or particulate matter, dissolved organics, chemical reactants, micro-organisms and other microbial substances [17]. Foulants are colloidal materials with different properties, which interact with the membrane thereby causing fouling. They can be grouped into four categories: organic precipitates, inorganic precipitates, biological and particulates [13, 25]. Hence, the type of fouling can be grouped based on the foulant type, e.g., inorganic (scaling), organic and biofouling [22].

2.1. Inorganic fouling

Inorganic fouling normally results from the deposition and accumulation of inorganic matter and other precipitates such as metal hydroxides and silica on the surface of the membrane. Inorganic fouling will foul the membrane both on the surface and internally. The precipitates are formed when the concentration of the chemical species is more than their saturation concentrations. This tends to happen on the membrane surface where accumulations of particles occur due to retention on the membranes. The result of this will be a decline in flux [17, 26].

Mi and Elimelech [27], in their study on the gypsum scaling and cleaning in FO, reported a decline in flux in both RO and FO modes. About 96% of the flux was recovered in the FO mode following a water rinse only without the use of any chemical cleaning agent. In the RO mode, however, the flux recovered was 10% lower than that of FO. Similarly, the same authors, Mi and Elimelech [26], reported in their study for silica scaling and scaling reversibility in FO, a decline in flux both in the FO and RO mode. However, 100% flux was recovered in the FO and only 80% in the RO modes. They concluded, after characterising the fouled membrane, that scaling on the membrane originated from the monosilicic acid deposition on the membrane

surface, which was followed by polymerisation (the formation of a soft amorphous silica gel layer that hardened with time by a continuous dehydration). Again, on the use of the AFM force measurement, it was revealed that the membrane surface roughness played a crucial part by increasing the adhesion force between the membrane and the silica gel layer, thereby considerably reducing the cleaning efficiency of the membrane [26].

The combination of alginate, which is the main component of polysaccharides with calcium ions in water, could lead to a more pronounced decline in flux due to the formation of a cake layer or gel layer. Chun et al. [28] reported that inorganic scaling, which was caused by calcium and phosphate and the interactions with other organic constituents in the feed solutions used, were the main cause of the reduction in flux of the membrane [28]. The cleaning of the inorganic scaling was, however, poor after using both physical and chemical methods. On further characterisation of the membrane, it was confirmed that gypsum and organic components that were present in the feed solution might have formed a gel layer (calcium bridging), thereby enhancing the fouling layer rigidity [17, 28]. Silica scaling is said to be difficult to be removed physically, while other types of the NOM foulants can be easily removed.

2.2. Organic fouling

The adsorption of organic matter such as humic substances, protein, and grease onto the membrane surfaces is referred to as organic fouling. These organic substances can be hydrophobic, hydrophilic or transphilic in nature. The mechanisms of organic fouling are complicated due to the wide variety of organic foulants existing in natural waters. These organic matters, commonly known as natural organic matter (NOM), are prevalent in most natural water sources such as run-offs, rivers, seawater and ground water [17].

NOM which are terrestrially derived are known as autochthonous NOM. There are also the microbially derived and wastewater NOM. Each of these organic fractions foul membranes differently because of different hydrophobicity, molecular weight size and charge density. However, microbially derived NOM are found to be the worst foulants. Fouling from these fractions is found to be most problematic and severe [29]. A study by Bessiere et al. [30] on the effect of NOM on fouling shows that hydrophilic components of NOM are responsible for the rapid but reversible fouling on the membrane. **Figure 2** elaborates concentration polarisation that could occur in FO membranes. The hydrophobic components were found to be responsible for the slow but irreversible fouling on the membrane. The hydrophilic components were small compared to the hydrophobic components. Both of these components are adsorbed on the membrane material.

The size of NOM plays a great role on the fouling of the membrane. Because NOM adsorbs onto the membrane, small NOM enter the pore of the membrane and get adsorbed on the wall of the pore channel resulting in pore narrowing. Larger NOM components get trapped at the entrance of the membrane pores and block the entrance to the pore channel resulting in cake layer formation as filtration progresses [31]. Fan et al. [32] found that the fouling order of hydrophobic membranes by NOM material is as follows; hydrophilic neutrals > hydrophobic acids > transphilic acids. Again, Chun et al. [17], in their study, noted that hydrophilic, H-bond acceptor, non-H-bond-donor and neutrally charged membranes are said to be resistant to organic fouling; however, hydrophobic and rougher membranes are more prone to fouling by NOM [17].

For ODM systems, a strong correlation has been established between organic fouling and intermolecular adhesion forces. For example, Mi and Elimelech [8] studied the chemical and physical aspects of organic fouling of FO membranes and found a strong correlation between organic fouling and intermolecular adhesion forces, which indicated that foulant-foulant interaction played an important role in determining the extent of the fouling [8]. They used the AFM. Adhesion force measurement was used to elucidate the impact of membrane material fouling. They found that the small adhesive sites on the membrane played a significant role in organic fouling formation [8]. They concluded that permeation drag, hydrodynamic shear force and calcium binding were the main contributing factors that govern organic fouling development [8, 17].

Colloidal matter in a suspension can be charged and depending on the charge of both the membrane and the particle, adhesion or repulsion will occur. The charge of the particles can be altered by adjusting the pH of the suspension. pH adjustment changes the electrostatic interaction between the membrane and particle from attractive to repulsive or from repulsive to attractive [33]. The effect of the ionic strength of colloidal particles on fouling was also studied by Singh and Song [34]. The study found that increasing the ionic strength of colloidal matter and its concentration in the feed solution increases the fouling potential of the water linearly.

2.3. Biofouling

Biofouling in simple terms can be defined as biological fouling. It is a net resultant of microbial attachment to the membranes and the consequent growth and discharge of biopolymers that are connected with this microbial activity. The foulants in biofouling include proteins, organics, organic acids, polysaccharide fats, etc. [14]. Biofoulants in this section will be divided into humic materials and micro-organisms (bacteria) [35]. The attached communities of bacteria in aquatic systems are encased in a glycocalyx matrix that is polysaccharide in nature. This matrix material mediates adhesion. The biofilm is made up of single cells and micro colonies that are enclosed in a hydrated, predominantly anionic exopolymer matrix. The attachment of bacteria to surfaces is irreversible and it results from a secretion by the bacteria itself which is a matrix of extracellular polymeric substances in which the bacteria cells are embedded upon [36].

This adhesion of microbial cells to the membrane surface is the beginning of membrane biofouling. Subsequent to attachment of microbial, a biofilm layer is formed, which has a composition that is vast in diversity of different micro-organisms which could be bacteria, algae, protozoa, fungi, etc. [36]. Basically, three steps are involved in the formation of the biofilm; adsorption of the organic species and other suspended species on the wet membrane, transportation of microbial cells to the formed film and finally, the microbial cells then attach themselves on the membrane surface. The growth and metabolism as well as the biofilm of the attached organisms are then developed [37].

Extracellular polymeric substances (EPS) are high molecular weight secretions of microorganisms that are made up of organic substances such as polysaccharide, protein, nucleic acids and lipids. EPS offer a binding base for biofilm to the membrane surface. They contribute to the mechanical stability of the biofilm and to the organisation of the biofilm community. Once the biofouling has been established, other organic and inorganic materials contribute to

the building of the fouling mass [38]. EPS promotes the adhesion of microbial to surfaces by changing the physicochemical characteristics of the biofilm fouled membrane surface such as its charge, hydrophobicity and roughness. The EPS offers building blocks between the membrane pore and microbial cells. High concentration of EPS contributes greater binding capacity. EPS aggregates are comprised of charged groups, and they therefore have both wetting and cross-linking characteristics which contains both hydrophobic and hydrophilic sites on their structure. This enables them to be able to adhere to both hydrophilic and hydrophobic surfaces. The factor that makes biofouling very complex to understand and plan against is the fact that EPS have flexibility and rearrangement characteristics. This means EPS structure will rearrange themselves so that they are able to stick to any surface [37].

Biofouling is one of the most difficult fouling to control as there is a large range of biofoulants that could be present in a particular aqueous system at a particular time for a particular feed solution [17]. Other types of fouling are easily mitigated by the use of chemical and physical pre-treatment. Like other fouling mechanisms, it causes significant losses in flux it is reported that it can cause a 10–15% decline in the membrane performance of the start-up values under the applied operational conditions [17]. Further impacts of biofouling are observed in membrane biodegradation which can lead to an increased salt passage as well as raising energy requirements. Consequently, a higher operating and maintenance cost and possibly shortening of membrane lifetime will be the overall impact [17].

Bogler et al. [14] reported that biofouling in FO has a lower influence on permeate water flux than that in PDM membranes. The same hydrodynamic conditions, feed concentration, membrane type and bacterial concentration were used to test for biofouling in RO and FO membranes, and it was found that there was a 10% decrease in flux as compared to the 30% in RO membranes after 24 h. However, the influence of biofilm in FO has been considered to be more complicated than in RO. This is due to the fact that the additional phenomenon that occurs is unique to membrane systems, which are driven by osmotic force [14]. According to Bogler et al. [14], there is an interaction between the reverse solute and the biofilm by the draw solution especially when it contains divalent cations as calcium [14]. Again, the biofilm formed on the FO membrane is more loosed and thicker than that formed in RO membrane. This was said to enhance CP instead of the additional hydraulic resistance as the main reason for permeate water flux reduction [14].

3. Concentration polarisation in ODMs

The major challenge in bringing about a deep knowledge that will aid to understand membrane fouling is the difficulties in the identification of the actual foulants, and distinction between the indicators of fouling and effect of CP. CP is the occurrence in membrane processes, whereby the concentration of solute near the membrane surface is very different from that of the bulk solution [7, 39, 40]. In membrane systems, using hydraulic pressure, the liquid is passed through the membrane and the particles accumulates near the membrane surface thereby forming a thin layer. In the layer, the particles get stuck in the transverse direction which is close to the membrane surface such that retained particles on the stationary layer provides an added resistance to the permeate flow. The resistance therefore depends on the

total number of particles formed on the layer and on as well as the spatial distribution. The stationary layer containing retained particles is called concentration polarisation (CP) and is inherent to all cross flow filtration processes [41]. The retained solutes/particles diffuse back to the bulk solution. However, the rate of permeation in membrane systems is higher than the rate at which the rejected solutes diffuse back to the bulk solution. This results in a higher solute concentration at the membrane surface than in the bulk solution. As filtration progresses, the concentration of the particles on the membrane surface becomes so high that a gel layer is formed which acts as a secondary barrier to permeate flux [42].

The effect of the CP is noticeable during membrane operation by the reduction of permeate flux as well as decline in the effective driving force across the membrane, leading to further fouling of the membrane. This influence occurs both in PDMs and ODMs. A similar scenario is observed with the ODM membranes; however, because the driving force here is osmotic pressure, a difference in CP mechanism is noticed. It has been emphasised that in ODMs, CP could occur as internal concentration polarisation (ICP) or external concentration polarisation (ECP) of the membrane (see **Figure 1**) [7, 17, 21, 39]. **Figure 1** shows that the solutes on the draw side decreases while those on the feed side increases, as a result a concentration gradient is formed and as such, a reduction in the osmotic pressure difference between the two solutions is enriched as shown in **Figure 1B**. The result of this is seen in the build-up of CP, which thus reduces flux flow.

ICP occurs within the membrane porous support layer, while ECP occurs on both sides of the membrane surfaces [17, 39]. The orientation of the membranes plays a vital role with regards to the type of CP that will occur on the membrane and it should be noted that CP is contributed by both convective and reverse solute diffusion (RSD) [21, 39]. The effect of ICP is more pronounced on the membranes than that of ECP. The reason is attributed to the fact that there is an axial flow of salt solution within the asymmetric FO membrane, which is the solute that enters and exits the porous support layer. To further validate and understand the nature of CP, both ECP and ICP have been elucidated and categorised as concentrative external concentration polarisation (CECP) and diluted external concentration polarisation (DECP) for ECP and diluted ICP (DCIP) (**Figure 2**).

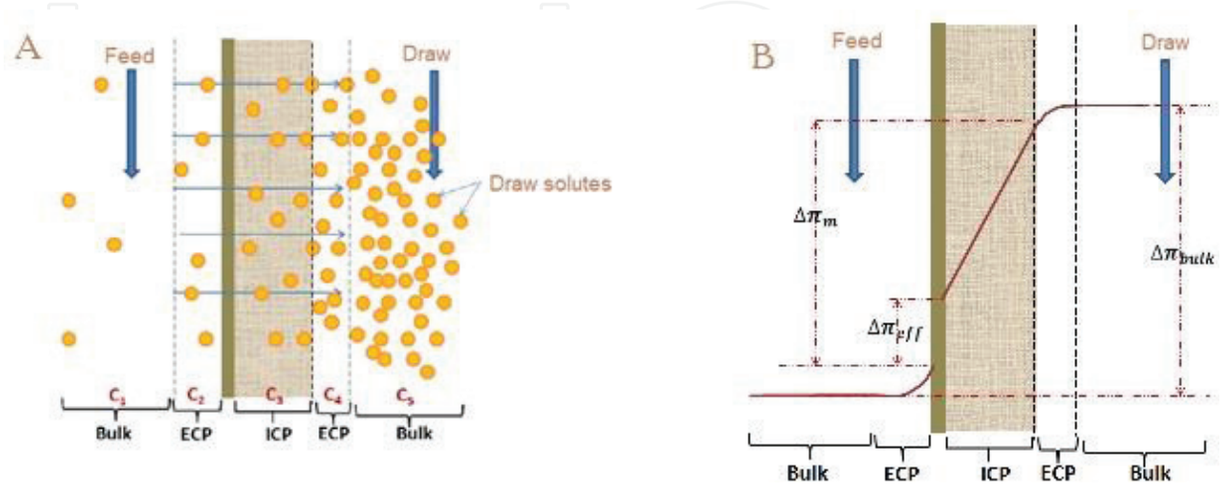


Figure 1. Schematic representation of (A) concentration polarisation on FO membranes (B) osmotic pressure difference due to effects of CP [43].

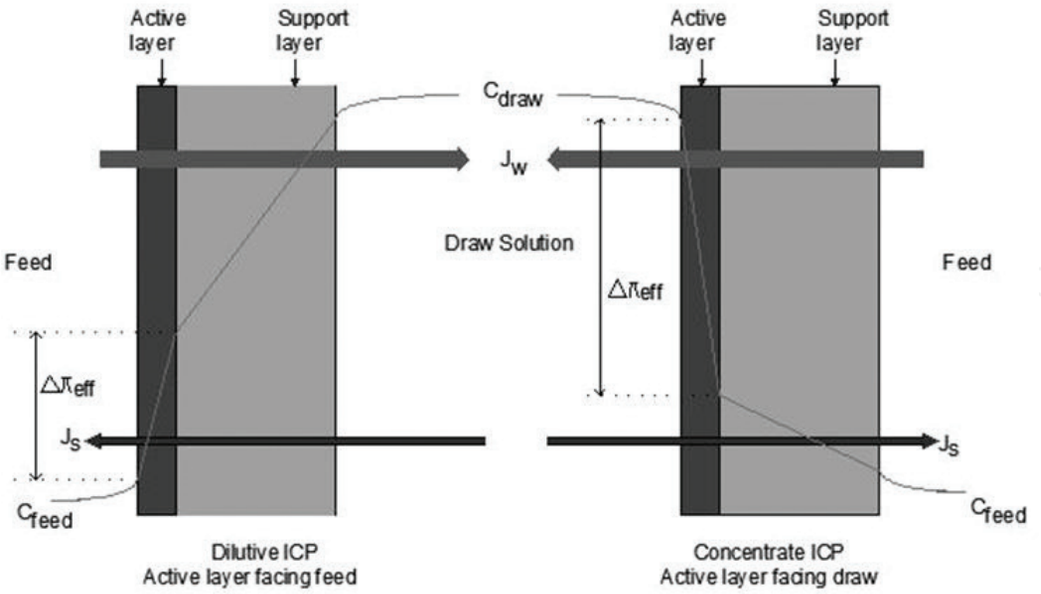


Figure 2. Schematic representation of DECP and DICP on a porous support layer [17].

The logical explanation for this is the fact that the drawn solution is greatly diluted by the permeate water within the porous support of the membrane [39]. Therefore, CECP occurs when the active layer of the membrane faces the feed solution and as such, there is accumulation of the solutes thereby increasing the feed concentration while DECP occurs when the active layer of the membrane faces the draw solution, hence dilution. The outcome of this is seen in the effective osmotic pressure of the feed solution increasing from the bulk solution to the membrane surface and that of the draw solution decreasing from the draw bulk solution to the to the membrane surface. This can be seen in the equation of FO which describes the permeate flux as seen in (Eq. (1)).

$$Jw = A * \Delta\pi = (\pi_{D,m} - \pi_{F,m}) \tag{1}$$

where Jw is the permeate flux; A is the pure water permeability coefficient; $\pi_{F,m}$ is the osmotic pressure of feed solution on the membrane surface; $\pi_{D,m}$ is the osmotic pressure of draw solution on the membrane surface.

Equation (1), above which describes the flux in FO, was first modified by McCutcheon and Elimelech [44].

$$\frac{\pi f, m}{\pi f, b} = \exp\frac{Jw}{K} \tag{2}$$

$$\frac{\pi D, m}{\pi D, b} = \exp\frac{Jw}{K} \tag{3}$$

Where Jw is the permeate flux and k is the mass transfer coefficient. k is related to the Sherwood number (Sh), solute diffusion coefficient and hydraulic diameter of the flow channel

$$k = Sh * \frac{D}{d_h} \tag{4}$$

Depending on the flow regime, *Sh* is calculated using either Eqs. (5) and (6).

$$sh = 1.85 * \left(Re * Sc * \frac{d}{L}\right)^{0.33} \text{ (laminar flow } Re \leq 2100) \tag{5}$$

$$sh = 0.04 * Re^{0.75} Sc^{0.33} \text{ (turbulent flow } Re > 2100) \tag{6}$$

However, if the salt back diffusion across the membrane does not take place, then the permeate flux [Eq. (1)] is modified by taking CECP and DECP into consideration the equation can be transformed to Eq. (7).

$$Jw = A * \left(\pi D, b * \exp\left(-\frac{Jw}{Kd}\right) - \pi F, b * \exp\left(\frac{Jw}{Kf}\right)\right) \tag{7}$$

Equation (7) describes ECP in FO; however, ECP effect on flux decline is not as pronounced as that of ICP. The impact of ICP on the membrane is more prominent on the membrane. Therefore, to account for ICP that occurs in the membrane, the equation is modified [1].

Apparently, due to the nature of most membranes being asymmetric and comprising of a thin selective layer and a thick, non-elective layer, Eq. (7) cannot be used to describe ICP porous support layer. This being due to the fact that the osmotic pressure of a solution can be established only at the interface with the selective layer. Noted also is the fact that asymmetric structure of the membrane.

The asymmetric structure of the membrane is made such that one of the boundary layers is within the support layer which then results in ICP [1]. Therefore, to justify for the porous layer, an effective mass transfer coefficient (K_{eff}) is defined as shown in Eq. (8) [1].

$$K_{eff} = \frac{D_s \epsilon}{\tau \delta} = \frac{D_s \epsilon}{\tau t} \tag{8}$$

Where D_s is the diffusivity of the solute, δ is the thickness of the boundary layer ε, τ, and t are the porosity, tortuosity, and thickness of the porous support layer of the membrane.

In normal mode of FO, Eq. (7) is modified to:

$$Jw = A * \left[\pi D, b * \exp\left(-\frac{Jw}{Kdeff}\right) - \pi F, b * \exp\left(\frac{Jw}{Kf}\right)\right] \tag{9}$$

According to Chun et al. [17], the effect of ECP is suffered on all membrane processes. The effect of CP is experienced more on the interface because it is more in contact with the bulk solution. This is due to the fact that the layer interface becomes polarised. Transport of water and other solutes within this interface is merely on advection and molecular diffusion [17]. Because, it is only a minimal amount of the solute that is able to penetrate through the dense selective layer, back diffusion occurs with an accumulation of solute within the porous layer which leads to the formation of ICP effect [17]. Like PDMs, enhanced cake layer concentration

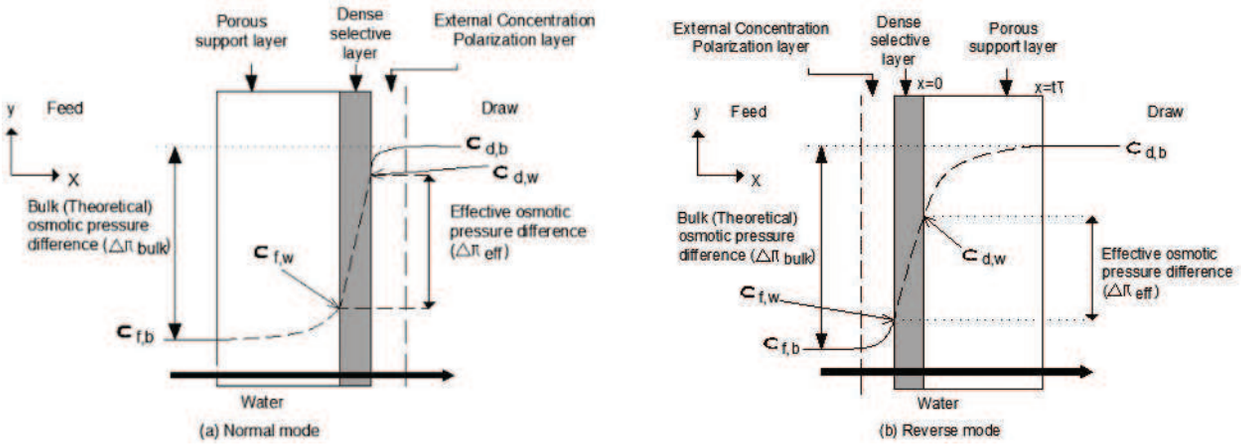


Figure 3. Schematic representation of (a) and (b) shows the different membrane orientation. (a) The normal mode and (b) reverse mode adapted from [24].

polarisation could be formed on the membrane surface. This can happen when the flux is significantly high and thus leads to the formation of a porous fouling layer on the membrane surface such that solute diffusion inside this layer becomes seriously hindered [21, 45]. The effects of Enhanced CP can be expressed through a mass transfer coefficient as shown in Eq. (10) [21].

$$KECP = \frac{Dml.\varepsilon la}{\delta la.\tau la} \tag{10}$$

where D_{ml} is diffusion coefficient of the solutes inside the fouling layer; εla is porosity and δla the thickness and τla is the tortuosity of the fouling layer, respectively.

She et al. [39], in his review, outlined the main equations that described both ICP and ECP in ODMs. He noted that the actual solute concentration at the support-active layer interface and that on the active layer surface were not the same with that of the bulk solution.

Xie et al. [24] modified the film models to predict flux behaviour in FO considering its external and internal concentration polarisation. They tested the membranes in two modes; the normal and the reverse. In the normal mode, the dense selective layer faced the DS while the porous layer faced the feed solution; while in the reverse mode, the dense selective layer faced the feed solution while the porous layer faced the draw solution [24]. This is illustrated in **Figure 3**. From their study, they expected the FO to have a greater flux, considering the fact that the influence of ICP in the FS was lesser than in the DS. According to them, the FO process should be preferably operated in the normal mode, this is also the mode implemented which is obtainable commercially as FO membrane for FO processes [24].

4. Membrane materials

One factor that is now increasingly being considered in membrane materials is the material's susceptibility to fouling. Some of the properties of the membrane that affect fouling are charge, roughness and pore size. Membrane material and its properties play an important role in the

type of fouling that will occur in ODMs [8]. Knowledge of the nature of the membrane helps in the identification and understanding the fouling mechanism occurring in the membrane.

The development of membranes that can be used for FO has remained a challenge till date. ODMs can be made either by modifying an existing NF or RO membranes or by the development of new membranes with specific design for FO applications [22]. The latter is said to be simple, effective to some extent and cost efficient. Membranes used in RO or NF are made up of a non-porous active layer and a porous support layer and are made from thin-film polymerisation on a polysulfone layer supported by nonwoven fabrics However, they suffer from ICP and thus reduces the effective driving force [7, 22, 46].

The phase inversion and membrane process formation is one way to modify the membranes to improve its properties. These membranes are fabricated with a thin and porous support layer that can reduce ICP effect, while at the same time maintaining a thin and dense selective layer for adequate water flux and salt rejection [46]. Loeb and Sourirajan [47] were the first to use the phase inversion method to fabricate asymmetric polymeric membranes viz. cellulose triacetate (CTA). Ever since, cellulose acetate (CA) has become a popular material for different separation applications [46]. Relatively high hydrophilicity that favours flux and low fouling propensity has been associated with the use of CA. In addition, CA has shown high mechanical strength and availability. The other commonly available membrane type is the polyamide (PA). This is also referred to as the thin film composite (TFC) membrane. This membrane has an asymmetric structure with a dense thin film as well a thick porous support layer. This membrane is said to offer a higher flux and salt rejection and can be operated over a wide range of temperature. Early attempts in using the RO membrane as FO, however, failed due to CP that occurred in the membranes hence reducing flux. Wang et al. [48] further defined asymmetric membranes as consisting of a 0.1–1 μm thick dense layer supported by a highly porous, 100–200 μm thick support layer. The dense layer provides the selectivity of membrane. Hence, the separation properties chemical nature, thickness of the skin layer and pore sizes that are normally between 0.4 and 1 nm [48].

To attain optimum performance of ODM membranes, their selection and fabrication should be based on the following characteristics:

1. The membrane should be dense, ultrathin, have uniform active surface layers, high solute rejection and high permeate flux rate.
2. It should have a thin, porous supporting layer as well as be strong enough to provide mechanical strength to the membrane. The thin layer should help curb ICP and hence increase the membrane flux.
3. Finally, the membrane material should have high hydrophilicity tendency to enhance water flux and reduced membrane fouling [49].

The hydrophobicity of the membrane material plays a major role in membrane fouling. Hydrophobic interaction can be described as "like attracts like." The similar chemical structures owned by both the membranes and the solutes tend to have a natural tendency to be attracted to each other. Hydrophobic attraction is a result of the van der Waals forces, which

occur between molecules [50]. Hydrophobic adhesion is a crucial mechanism for fouling which dominated by NOM due to the fact that high molecular weight NOM offers a higher potential for hydrophobic adhesion because of their charge density. Other factors that affect the strength of the adhesion to membrane surfaces are membrane surface roughness and membrane pore size [51]. A study by Bendinger et al. [52] showed that most foulants that are hydrophobic and slightly hydrophilic adhere better on hydrophobic surfaces than on hydrophilic surfaces. Only highly hydrophilic foulants attach stronger on hydrophilic material. Extremely hydrophobic materials do not adhere too well on the hydrophobic and hydrophilic material.

Hydrophilic membranes have higher fouling resistance than hydrophobic membranes. This means that hydrophobic membranes can be impregnated with water-soluble materials such as poly-vinyl pyrrolidone or poly-vinyl methyl ether. However, this is mostly at the polymer formulation stage [53]. The FO membrane surface roughness does not vary significantly from those of a typical RO and nanofiltration membrane (NF) [6]. The rough and large pore size membranes are shown to be more prone to fouling than the smooth, small pore membranes. This is because the bigger pores are more accessible to foulants. The nature and the extent of the fouling are determined by the specific physical and chemical characteristics of the each component as well as the membrane [6].

In RO membranes, it is expected that the porous support layer material should be thick enough to be able to withstand the high pressures involved, but for FO membranes, which uses osmotic pressures, the thickness of the support layer could be reduced since mechanical strength is not an issue here. Therefore, modifications can be made to reduce the thickness and adjust the structure of the support layer to mitigate the CP phenomenon [19]. The modification of membranes is potentially one of the suitable ways to mitigate and prevent fouling. Therefore, attempts have been made to modify the singly skinned asymmetric FO membranes into a double-skinned membrane structure. This is made such that it contains a porous support, which can be sandwiched between the two rejection skins [10, 46]. The single skinned asymmetric FO membranes face a dilemma of either experiencing more severe dilutive ICP in AL-FS or having much higher fouling propensity in AL-DS [10].

Also, some FO membranes are modified from RO/NF membranes. Hence, they are composed of asymmetric structures which are characterised by a dense active layer on top of a porous support layer. This main separation and structural properties of the active support layer governs both the water and solute transportation. This further enhances the membrane fouling behaviour.

Membranes made up of superior separation properties and structural properties such as the higher water permeability, selectivity and smaller structural parameter could provide much higher water flux [49]. However, an increase in the membrane fouling could be observed due to the enhanced hydrodynamic drag force. Therefore, a balance between mechanical strength and porosity of the membrane is needed. The mechanical strength of the membranes should be reduced so as to increase the porosity and tortuosity [22]. McCutcheon and Elimelech [49], in their study, removed the backing fabric support layer (thickness of 80–120 μm) of commercial RO membranes (overall thickness of 200 μm) and the FO water flux of the modified membranes was improved by a factor of 5.

Pore wettability of the membrane is tied to its ease to wet easily with water. Therefore, for FO membranes, it is important that the pore wettability is improved because the presence of un-wetted pore regions may block the water flux and significantly intensify ICP [22]. The use of a highly hydrophilic polymer, like polydopamine (PDA), to coat the membranes has been demonstrated to be an effective technique in the improvement of the wettability. It has been reported that the wettability can be increased ten folds after coating with FDA [22, 54, 55].

5. Fouling mitigation

Membrane fouling mitigation deals mainly with the management or minimization of the effect of membrane fouling since fouling itself cannot be completely avoided in membrane filtration [56]. Membrane fouling can be controlled and managed at different stages. These include feed pre-treatment to reduce the fouling tendencies, and improve on its antifouling properties. Others such as membrane cleaning and optimisation of operating conditions could further be of benefit also [50].

5.1. Hydrodynamic/operating conditions

Hydrodynamic condition controls the rate of particle deposition on the membrane. According to She et al. [7], most of the conclusions drawn regarding fouling mechanisms in PDMs can also be drawn on ODMs. The operating conditions and properties of the membrane play an important role in the mass transport of the ODMs. Cath et al. [1], in their study, supported the fact that the effect of operating conditions is more noticeable in ODMs than in PDMs. They reiterated that newly developed ODMs are tested under varying temperatures, draw solution compositions and as well the concentrations, flow rates and pressure [1, 48]. Hence, optimum operating conditions should be established to serve as a basis of comparison. Like in PDMs, severe fouling could occur at a higher water flux and lower cross flow velocity. Cross flow velocity has been the most common and widely used method to control fouling at the membrane surface; however, it cannot certainly prevent internal fouling. High cross flow velocity influences membrane fouling through CP and mass transfer near the membrane surface [7, 50].

High cross-flow velocity creates mixing on the membrane surface thereby improving the mass transfer coefficient, but the increase in mass transfer coefficient is different for different feed solutions [57]. At the membrane surface for any filtration system, rejected particles accumulate in a boundary layer. According to Fick's law, particles in the boundary layer collide with each other more frequently thereby improving particle diffusion from the boundary layer to the bulk solution. This diffusion can be improved by what is called shear-induced diffusion. This is achieved by causing movement of the liquid close to the boundary layer. When the movement of the liquid is increased, the particle collision becomes vigorous and the particle diffusivity is increased. Shear-induced diffusion of particles is highest at the membrane surface or at the boundary layer because of the high particle density in that region [57]. The membrane orientation should also be considered, because AL-FS is preferred due to low fouling propensity, however, the ICP is more prone in this orientation.

Hydrodynamic conditions in PDMs mostly refers to initial permeate flux, transmembrane pressure and turbulence at the membrane surface. Initial flux is the flux at the beginning of filtration and is usually high because at this stage the membrane is clean. Due to high initial flux, particles in a suspension are dragged towards the membrane surface faster than they are diffused/dispersed back into the bulk solution. Therefore, more particles are deposited on the membrane during high initial flux [58].

The study by Hwang et al. [59] showed that high initial flux, results in a large number of particles being simultaneously transported towards the membrane surface. The simultaneous arrival of these particles on the membrane surface was found to be the factor that benefits flux because entry to the membrane pore is hindered and particles only deposit on the membrane surface rather than the membrane internals. The opposite was found for a low initial flux. The finding of Hwang et al. [59] was also confirmed by Wang and Tarabara [60].

For most PDM systems, the effect of aeration as a means to mitigate fouling has been extensively studied especially for membrane bioreactors [61]. The introduction of aeration to cross flow velocity helps to reduce fouling on the membrane surface. This concept has not been widely researched on ODMs. Therefore, there is the need to investigate the effect of aeration on fouling in ODMs.

5.2. Temperature

Temperature of the solution is one of the parameters that can be altered to reduce the effects of fouling. However, this parameter is not often used for fouling control particularly in water treatment [62]. For FO processes, factors such as osmotic pressure, fluid viscosity, mass transfer and mineral solubility depends on temperature, hence it needs to be maintained so that the membrane performance is not altered [62]. Zhao and Zou [62] elaborated that at a higher temperature there is a higher initial permeate flux, higher water recovery and higher concentration factors, and since temperature effect can significantly impact on the membrane, it is important that this parameter is optimised.

Salahi et al. [63] found that when the temperature of the feed water (oily wastewater) used in their study was increased by 20°C, there was an increase in flux of about 60%. This was attributed to an increase in the diffusion rate as the temperature was raised. The flux increase was attributed to the combined effects as listed by She et al. [7] to be (1) a decrease in solution viscosity which can reduce the membrane resistance and as such can cause an increase in the water permeability, (2) an increment in the solute diffusivity which also can increase the mass transfer around the boundary layer and thus leading to a reduction in CP most importantly, ICP and (3) finally an increment in the osmotic pressure thereby increasing the effective driving force. The effect of temperature on ODM fouling was outlined to be through the influence of hydrodynamic conditions such as mass transfer of foulants and initial flux thermodynamic conditions such as osmotic pressure of the solution, solubility and stability of the foulant and finally the interaction of the foulants and the membrane [7].

Kim et al. [64], in the study of the fouling types and mechanisms in a FO membrane processes, under raised temperature, found that flux due to organic fouling was more pronounced when

the draw solution was increased. This increase was attributed to the increased permeation drag at increased initial flux level. However, on increasing the feed solution, less fouling was observed because of the organic back diffusion from membrane surface and the increase in the organic solubility [64]. The same authors, Kim et al. [64], in their study observed that membrane fouling became more enhanced when the initial flux was increased to a certain critical flux as temperature for both the feed and DS was increased. This was because organic convection by permeation drag dominated the fouling mechanism. At critical flux, only localised deposition on the membrane occurs, because the rate at which particles deposit on the membrane surface is almost equal to the rate at which they are diffused back into the solution [65]. However, if the process is operated above the critical flux, enhanced fouling is observed on the membrane.

5.3. Feed pretreatment

The feed water to be treated, in most cases, are made up of various components which might include divalent ions, humic substance, alginate, silica and a host of others. These particles could accumulate on the porous membrane structure thereby causing severe decline in membrane permeate flux [23]. The extent to which the feed water is pre-treated depends on the quality of the water; hence, this factor is also dependent on the sources of the water. Pretreatment of feed can be divided into two: physical and chemical. Physical pretreatment involves the use of mechanical filtration such screening, cartridge filters, sand filters or membrane filtration while chemical pretreatment involves the addition of scale inhibitors, coagulants, disinfectants and polyelectrolytes [26].

Extensive studies regarding feed pretreatment in PDMs especially for NF and RO membranes have been investigated extensively, basically for removal of particulate matter [27]. Ultrafiltration (UF) and microfiltration (MF) membranes are used as feed pretreatment to most NF and RO processes due to their porosity. At other times even NF membranes can be used as pretreatment method. The permeates from these membranes have been presented to have low turbidity and silt density index thus increasing recovery in the RO process. For instance, Mi and Elimelech [27] compared three pretreatment technologies; powdered activated carbon (PAC), addition of coagulants such ferric chloride and pretreatment using UF before RO desalination.

The use of NF as pre-treatment to ODM systems however has not been comprehensively studied and remains a crucial aspect for further investigations. Chen et al. [23] studied the first systematic investigation on the use of a loose NF to pretreat feed wastewater in practical PRO practice. They found that the low pressure NF was able to mitigate the fouling potential from multivalent ions and organic matters. Thus, they found the NF method of pretreatment as cost effective. However, the low-pressure NF was able to mitigate the fouling potential from multivalent ions and organic matters, but silica scaling was still predominant, hence, they recommended further investigation. This comparison was made based on a previous study of theirs. That study made use of retentate from a RO unit of a municipal water recycling plant as the main feed stream for an osmotic power generation. Two pre-treatment methods were used: anti-scaling and pH adjustment. The pH adjustment was accompanied by water flushing and 100% by air bubbling thereby resulting in an increased flux [43].

Chemical pre-treatment, on the other hand, involves the addition of chemicals to the feed water. The addition of chemicals for pH adjustment, prevention of scaling and fouling is also used for the pre-treatment of feed to RO processes. This however, in most cases still requires a physical method to be used alongside. For example, a membrane filtration process could be used to pre-treat the feed water and thereafter the chemicals could be added. The advantage presented in following this path is the reduction in chemical consumption. Chlorination, however, should be added to the feed water independent of the pre-treatment method that is being employed. This is to prevent biofouling of the membrane [26]. Nonetheless, after the chlorination, a dechlorination of the feed has to be considered since most of the membranes are susceptible to chlorine attacks.

The addition of coagulants and flocculants causes the dissolve matter to adsorb on the hydroxides and also to cause the agglomeration of colloidal matter. The use of the coagulants aids in reducing the fouling potential on the membrane and also provides a better quality feed water to the RO [26]. The addition of antiscaling agents is considered as one of the pre-treatment methods as well. The precipitation of salts on the membrane surface is referred to as scaling and it is caused by super saturation. It reduces membranes productivity and as well the recovering of water. Different scale inhibitors can be used as antiscalant. These inhibitors control the scaling caused by sulphates, carbonates and calcium fluoride [26].

5.4. Selection of draw solutes

One of the key factors in ODMs is the selection of the right draw solution (DS). The knowledge on the various types of DS used is needful to understand the crucial issues that are related with FO such as CP and mass transport [11]. The following factors should be considered in the selection of DS in ODMs; the solution should produce a substantial amount of osmotic pressure, it should not be expensive ant toxic to the environment and easily regenerated [5, 11, 17, 66]. The commonly used DS is NaCl, because of its high water solubility and it is relatively easy to reconcentrate using desalination processes [17, 66]. Other low molecular weight salts used as DS in recent times include; $MgCl_2$, $CaCl_2$, KCl, Mg_2SO_4. Others such as sucrose, glucose, 2-methylimidazole-based compounds have also been used. Further still, magnetic particles, thermolytic inorganic salts for example ammonia-carbon dioxide and hydrogels have all been tried as DS. It is expected that these solutions should provide a high osmotic pressure and at the same time be easily regenerated and recovered [17].

Cai and Hu [5] reviewed draw solutes used in FO, where they categorise DS into two, namely responsive and non-responsive. The non-responsive solutes were defined as those which when a stimuli such as temperature, pH and others were added to them, no significant change was observed in their water affinity. While on the contrary, the responsive DS were those that, upon exposure to a stimulus, underwent a significant change in their water affinity and thereby accompanied by phase transitions between two states with different water affinities [5].

There is a general perspective regarding the increase in the concentration of the draw solution. Increasing the DS concentration leads to an increase in initial water flux and as such an increase in membrane fouling. The occurrence has been attributed to the effect of increase in hydraulic drag force which is a result of the higher flux that promotes foulant deposition on the membrane [3, 8, 11]. The effect of increasing the DS concentration also influences the RSD

by elevating it from the FS to the DS thereby increasing fouling also [67]. She et al. [68] reiterated in their study how RSD influences the deposition of solutes on the membrane surface. The result of this is a change in the feed water chemistry and thus may cause more severe fouling. In that study, they observed that greater alginate fouling occurred on the FO membrane when the DS contained higher concentration of divalent ions of Ca^{2+} and Mg^{2+}. They attributed that the RSD enhanced organic fouling relates to the nature of the DS and to the rate of its diffusion into the feed solution and its ability to interact with the foulant [68]. Therefore, the type and nature of the DS can affect the membrane fouling and the water chemistry too. It was observed that divalent ions in DS, as mentioned above, could influence an additional fouling which is more than the DS even without the specific ions at the same initial water flux level. This occurs as a result of the strong attraction between the ions (foulants) in the solution and the specific ions after they reversely diffuse from DS into FS.

She et al. [39] studied the relationship between reverse and forward solute diffusion to membrane fouling in ODMs. The types of DS used were; NaCl, $MgCl_2$, $CaCl_2$ and $Ca(NO_3)_2$ to reiterate the connection that exists between RSD and forward solute diffusion (FSD). They found that the extent of fouling for the chosen DS was in the order of $Ca(NO_3)_2 > CaCl_2 > MgCl_2 > NaCl$. They concluded that NaCl DS had the highest RSD, this was followed by $Ca(NO_3)_2$ DS, then $CaCl_2$ and finally the least was $MgCl_2$ DS. According to them, the order of the RSD was consistent with the order of their solute permeability. Therefore, the RSD of divalent ions impacted more on the feed solution thus leading to an alginate membrane fouling. Fouling propensity was in the order $Ca(NO_3)_2 > CaCl_2 >> MgCl_2 > NaCl$. Even though a greater amount of NaCl was reversing, the effect of fouling was limited using the NaCl, reason been that the Na^+ did not interact with the alginate. This was related to the cation and anion of the DS and rate of its reverse diffusion.

6. Membrane cleaning

Membrane cleaning is an integral and an important part of membrane processes [16]. Cleaning could be done either hydraulically or chemically. Membrane cleaning becomes necessary when avoiding irreversible fouling of the membrane. The longer the membrane is allowed to operate in its fouled state, the harder it becomes to remove the foulants from the membrane. It, therefore, becomes necessary to use chemicals or greater force to recover a highly fouled membrane.

Physical and chemical methods of cleaning can be employed for fouled membranes. Physical method is also referred to as the hydraulic method. It employs the use of mechanical forces to displace and remove the fouling agents from the membrane surface [69]. These methods of cleaning are typically used in the cleaning in place (CIP) situations. Series of studies have been carried out for the cleaning of ODM membranes using physical methods such as membrane surface flushing and membrane backwashing [7, 16]. The surface washing (forward washing) is achieved when the cross flow velocity is increased on the membrane surface to remove the deposited foulants [13]. Backwashing involves pumping permeate water at a high cross-flow velocity in the opposite direction from which the feed comes in. It is a reversed filtration process in which the permeate of backwashing solution is flushed through the

membrane back to the concentrate side. These methods have both shown to be effective against the membrane fouling under different of conditions.

Mi and Elimelech [6] determined the efficiency of surface flushing to investigate the reversibility of FO and RO membranes fouled with organic foulants. Their findings indicate that fouling in FO was more easily reversible than in RO. The reason was due to the hydraulic compaction imposed on the RO membrane which was absent in the FO membranes. It is recommended that for higher recovery of flux, backwashing should be combined with surface flushing. Both surface flushing and backwashing are limited to the fact that only the surface foulants are removed. The internal foulants within the membrane remains after the whole procedure; however, backwashing is moderately successful in removing internal clogging material from the membrane internals.

For FO and PRO membranes, osmotic backwashing has been developed for these processes. The process employs the use of high salinity water to replace the feed solution while a lower salinity water is used to replace the draw solution. Just like in PDMs, the water permeation direction is in the reverse form, thereby creating a negative water flux. The action of this results in the breaking of the foulants away from the membrane [7]. Even though success of osmotic backwashing has been reported by many researchers on recovering of flux, a few others have contrary views where efficiency of osmotic backwashing for water flux recovery was low [7].

When a fouled membrane can no longer be completely removed by physical cleaning, the membrane is irreversibly fouled and therefore, chemical cleaning is required. Caution is however to be employed when cleaning the membranes chemically because the membranes can also be damaged by the chemicals used for membrane cleaning [26, 70]. The choice of chemicals for membrane cleaning must be able to completely dissolve the foulants on the membrane but not damage the membrane itself [69].

Chemical cleaning is a reaction between the chemicals and the foulants on the membrane surface. The process involves mass transfer of the chemicals to the fouling layer and the products of the reaction are dispensed back to the bulk liquid phase. Effectiveness of the chemical cleaning is improved by hydrodynamic conditions that promote contact between the cleaning chemicals and the fouling layer on the membrane surface [50].

The recovery of flux through cleaning has been enumerated to be more in FO than RO membranes. The reason is due to the fact that most fouling in FO is more reversible than that in PDMs [28]. This has extensively been studied by Mi and Elimelech [6], Mi and Elimelech [27] where they carried out chemical and physical cleaning on alginate, bovine serum albumin (BSA) and Aldrich humic acid (AHA) as model organic foulants. They reported a fouling reversibility in the FO and attributed that to the less compacted organic fouling layer formed due to the absence of hydraulic pressure. Another study on the efficiency of physical cleaning in inorganic scaling experiments was also carried out by Zhao and Zou [62] under different temperatures of 25, 35 and 45°C. Membranes were cleaned by the use of water at a cross flow velocity of 33.3 cm/s for 20 min, thus no chemicals were used. Their findings revealed that the higher temperature resulted in higher initial permeate fluxes, higher water recoveries and higher concentration factors. However, more compressed solutes were deposited on the membrane surface and thus the membrane cleaning efficiency was affected [62].

Air scouring induces shear force at the membrane surface as the air bubbles rise travelling adjacent to the membrane surface. The mechanisms responsible for the shear force in the membrane surface are fall film effect and wake effect. These are a net result of the quick rise of air bubbles and the feed solution. Air scouring generates localised cross-flow conditions along the membrane surface thereby reducing the deposition of particles and the development of a cake layer on the membrane surface [61].

7. Conclusion

Fouling in ODM membranes was the main objective of this book chapter. Despite the recognition that ODMs have received in applications in various industries, the use of this this technology is still limited by fouling, thus hindering its overall performance. The information on the fouling mechanisms is still limited and thus needs to be examined critically. This book chapter provides vital information on the impact of fouling on ODMs performance and it explored the factors and mechanisms governing fouling in ODMs. Further still, the effects of membrane fouling were expounded and approaches on the mitigation and cleaning of the membranes were outlined.

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