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Review Article

Water Reuse: Extenuating Membrane Fouling in Membrane Processes

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Abstract: Membrane fouling has been recognized as a serious barrier in microfiltration and ultrafiltration of secondary effluent. Feed pre-treatment is a frequent use for fouling extenuation. Numerous techniques have been employed to monitor membrane fouling. These include: Pre-treatment of the feedwater, modification of membrane properties, optimization of module configuration and operating conditions, periodic membrane cleaning, evaluation of system performance using pilot plant, and use of predictive models. However, membrane fouling remains complicated task for both technico-economic reasons depending on water characteristics and pre-treatment processes and efficiencies. The large majority of the membranes employed in water and wastewater treatment are produced of polymeric materials. Nevertheless, it has been expected that ceramic membranes will be competitive options in the following years.

Keywords: Wastewater Treatment Plant (WWTP), Microfiltration (MF), Ultrafiltration (UF), Membrane Fouling, Feedwater (FW)

1. Introduction

Through the entire world, water officials are looking for substitutional water sources to satisfy the augmenting demand because of augmenting population [1]. It is established that reusing municipal wastewater will importantly elevate water availability. As an example, Australian water authorities have launched several water reuse and seawater desalination projects. One of these was the raise of the treatment techniques at a municipal wastewater treatment plant (WWTP) in Victoria. This WWTP treats sewage upon 4 steps: preliminary, primary, and secondary treatments followed by disinfection. A small quantity (< 5%) of the disinfected secondary effluent is employed as recycled water, mostly for irrigation and cleaning, and the remaining is discharged to the ocean. The target of this upgrade was to give the means the WWTP to produce "Class A" recycled water, which is appropriate for use in new housing estates, agriculture, and industry. It would as well assist to decrease flow to the ocean outfall and aid the WWTP to satisfy progressively more strict regulatory needs on the quality of discharged water [1].

Microfiltration (MF) and ultrafiltration (UF) of the secondary effluent to eliminate suspended solids (SS) and pathogens were viewed as tertiary treatment choices for the recycled water [2]. A main worry with this effluent was its brownish yellow color, which may restrict customer readiness to purchase and reuse the effluent. Thus, the WWTP as well pursued to decrease the true color (i.e., color after filtration through a 0.45 μm membrane) of the activated sludge (AS) effluent (which can vary across 65-120 Pt-Co units) by about 75-80%; for this reason, the final effluent would have a true color of 15-25 Pt-Co units, which looks almost colorless [1].

Membrane processes for the treatment of water and wastewater have been largely trusted because of their elevated quality treated water and inexpensiveness [1]. Nevertheless, for this technique to be employed efficaciously, membrane fouling requires to be reduced [3]. Fouling of filtration membranes conducts to a diminution of water treatability, requiring process stop, membrane cleaning [4, 5], and more usual membrane substitution [6].

The fouling process is complicate and affected by numerous parameters, like feedwater (FW), membrane features, and working situations [1]. Feed pre-treatment is frequently applied to decrease membrane fouling [7]. Nevertheless, the difficulty of the fouling process renders it hard to expect the efficiency of pre-treatment techniques on fouling diminution [8]. As an illustration, both useful and unfavorable impacts of coagulation on membrane fouling have been noticed [9-12]. Moreover, while secondary effluents at some WWTPs have a brownish yellow color (most probably because of the elevated content of humic substances (HSs) [13-16]), details concerning the efficiency of various pretreatment techniques for color elimination on fouling decrease in MF and UF of municipal secondary effluent is rare.

Up to now, the large majority of the membranes employed in water and wastewater treatment are produced of polymeric materials [1]. Nevertheless, it has been expected that ceramic membranes will be competitive options in the following ten years [1, 17, 18]. Former researches on MF and UF of water and municipal wastewater using ceramic membranes have been directed on the permeate flux and quality. The impacts of feed pre-treatments on membrane fouling have attracted little concern. With the expanding usage of ceramic membranes, it is helpful to have more developed comprehension of their fouling comportment in these usages.

2. Classical Municipal Wastewater Treatment Processes

The treatment of municipal wastewater is usually realized through four steps: Preliminary, primary, secondary, and tertiary [1].

2.1. Preliminary Treatment

The goal of this stage is to eliminate large solid particles and grit from the wastewater to avoid deterioration to the remaining of the unit operations. This is frequently performed upon screening [1]. Coarse screens with openings of 6 mm or bigger are employed to eliminate big solid particles and rags, while fine screens can be employed to eliminate smaller particles [19, 20].

2.2. Primary Treatment

Primary treatment is designed to decrease the SS content of the wastewater and to eliminate floating matters like fat, oil, and grease [1]. It is frequently performed employing settling basins (or clarifiers) in which suspended particles heavier than water settle by gravity upon calm situations and floating materials are eliminated by skimming. The settling of particulates may be improved under pre-aeration or chemical coagulation [20-22].

2.3. Secondary Treatment

This implicates a biological treatment technique in which microorganisms consume dissolved organic matter (DOM) in wastewater to grow and reproduce; thus, decreasing the biological oxygen demand of the wastewater [20]. Secondary treatment may be performed employing fixed film, suspended, or lagoon systems [1].

In fixed film systems, microbes grow on fixed objects (such as rock, sand, or plastic) and are presented continuously to the wastewater for adsorption of organic material and to the atmosphere for oxygen [20]. In suspended systems (e.g. AS), microbes are suspended in wastewater by mixing the wastewater for many hours after which the biomass is settled out as sludge in a secondary clarifier [1]. Lagoons are shallow basins which carry the wastewater for many months to let natural decomposition of sewage [20].

2.4. Tertiary Treatment

Secondary effluent may hold pollutants (like nitrogen and phosphorus species, disinfection by-products, color, pathogens, metals and salts) at degrees higher than regulatory needs and thus necessitate more treatment before being discharged to local waters or recycled [1]. Such treatment techniques may be physical (such as membrane filtration and granular media filtration), biological (like oxidation ponds), or chemical (such as precipitation of phosphorus, iron and manganese) [19, 20].

3. Membrane Filtration in Water and Wastewater Treatment

At the present days, a set of membrane processes (MF, UF, nanofiltration (NF), and reverse osmosis (RO) (Figure 1)) have been employed to treat water and wastewater at several facilities throughout the world [3]. Illustrations of municipal WWTPs employing membrane filtration to treat secondary effluent comprise West Basin Water Recycling Plant in Los Angeles (California), Chandler Wastewater Reclamation Plant in Chandler (Arizona), Scottsdale Water Campus in Scottsdale (Arizona), the NEWater plants in Singapore, and the three advanced WWTPs at Bundamba (Luggage Point), and Gibson Island of the Western Corridor recycled water project in Queensland, Australia. In these treatment plants, MF or UF is employed as a pre-treatment for NF or RO [1].

There has been increasing attention in the incorporation of membrane techniques into present water and WWTPs for different causes [1], like to satisfy more strict regulatory needs for reuse and discharge and/or elevate plant capacity [23]. The benefits of membrane filtration upon classical filtration employing granular media comprise superior quality of treated water, small size, low energy consumption, easier maintenance and capacity extension, and the capacity of manipulating large variations in FW quality [24].

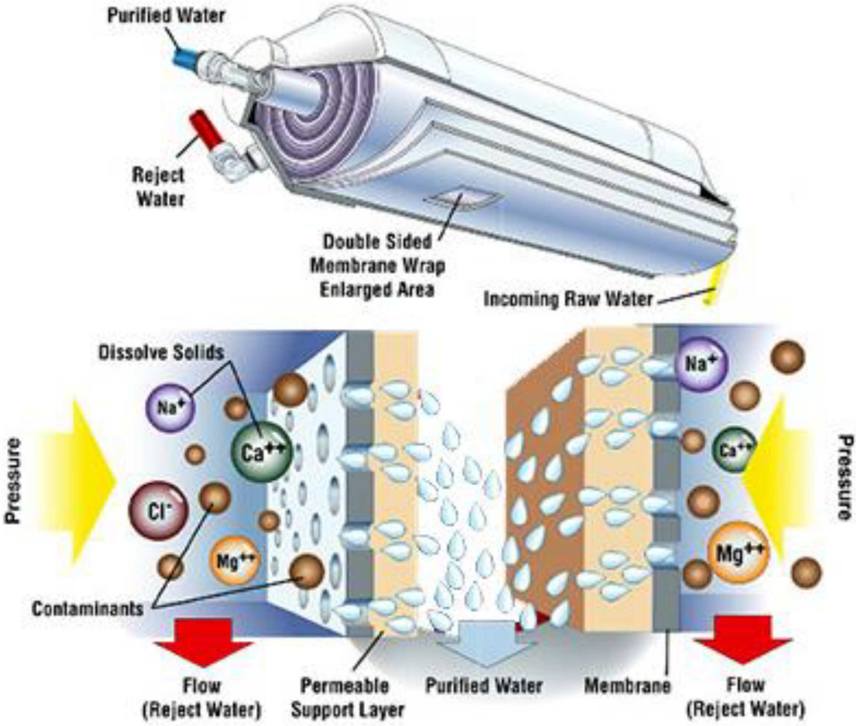

Figure 1. *RO membranes for drinking water purification [3].*

MF and UF membranes have also been largely employed in membrane bioreactors (MBRs) [25, 26]. In MBRs, the AS process and membrane filtration are employed in incorporation to attain biological treatment and solids/liquid separation [27]. Since the attention of this survey is on membrane fouling in MF and UF of secondary effluent, membrane fouling in MBRs will be shortly examined in this literature review [1].

3.1. Membrane Categorization

Membranes are frequently classified following their pore size, the molecular weight (MW) of the rejected material, the applied pressure, and their water affinity [1]. The pore size, MW cut-off (MWCO), and operating pressure of the four various types of membranes are listed in Table 1.

Table 1. *Some features of various membrane types [23].*

	MF	UF	NF	RO
MWCO (Da)	> 100,000	> 2,000-100,000	300-1000	100-200
Pore size (μm)	0.1-10	0.01-0.1	0.001-0.01	< 0.001
Operating pressure (psi)	1-30	3-80	70-220	800-1200
Operating pressure (kPa)	(7-207)	(20-550)	(480-1500)	(5500-8250)

MF membranes are efficient to eliminate SS, certain protozoan cysts (such as the pathogens *Giardia* and *Cryptosporidium*), and bacteria (3-6 log removal) [1]. UF may eliminate certain colloidal particles, dissolved macromolecules, and certain viruses. NF and RO membranes are able to eliminate dissolved solids (comprising ions) [28]; the separation capacity of NF membranes is comprised between that of UF and RO membranes [29-32]. MF and UF are performed at much lower transmembrane pressure (TMP) than NF and RO and thus are frequently named *low pressure membrane filtration* [33].

According to separation mechanism, filtration membranes may be classified as either dense (NF and RO membranes) or microporous (MF and UF membranes) [1, 8, 34]. The separation mechanism of MF and UF membranes is size exclusion (or sieving), i.e., components larger than the pore size are blocked from penetrating across the membrane [35, 36]. For NF and RO membranes, in addition to size exclusion, separation as well depends on the big gaps in the solubility and diffusion rates of water and solutes [37]. The much slower diffusion rate of solutes than water through the membranes lets the generation of a solute-free permeate stream [23, 38]. Following water affinity, membranes can be classified into two groups: to be specific hydrophobic membranes and hydrophilic membranes [10, 34, 39].

3.2. Membrane Matters and Constructions

Membranes may possess symmetric or asymmetric constructions [1]. Symmetric microporous membranes are cast from one matter and their pore size may be either uniform (isotropic) or diverse (anisotropic). For anisotropic membranes, the surface possessing the smaller pore size is employed as the filtering surface. Integral asymmetric membranes (or "skinned" membranes) are composed of a very thin (< 1 μm) layer (skin) and a thicker (up to 100 μm) porous layer that provides support and is capable of elevated water flux. A more modern advance is thin-film composite membranes, produced by bonding a thin layer of cellulose acetate, polyamide or other acetate-containing constituents to a thicker porous substrate [23].

Filtration membranes obtainable on the market are formed from a various collection of matters, which may be organic or inorganic. The most largely employed organic materials comprise polyvinylidene fluoride (PVDF), polysulfone (PS), polyethersulfone (PES), polyacrylonitrile, polypropylene, cellulose acetate, polyamide, and polytetrafluoroethylene [1]. PS and PES have been largely employed as the fundamental matter for the great number of trade membranes employed in water treatment plants in some countries like the United States [9]. Each membrane matter possesses its benefits and drawbacks in term of costs, thermal stability, chemical resistance, and biodegradability [23, 29].

Polymeric MF membranes may be formed from polytetrafluoroethylene, PVDF, polypropylene, polyethylene, cellulose esters, polycarbonate, PS, PES, polyimide, poly (ether imide), aliphatic polyamide, and polyetheretherketone [40]. The first four polymers are hydrophobic while the others are hydrophilic [34]. Various from MF membranes, which may be symmetric or asymmetric, UF, NF and RO membranes usually possess an asymmetric construction with a much denser top layer and thus need a bigger applied pressure to prevail over their higher membrane hydraulic resistance [1]. UF membranes are mostly produced from PS, PES, sulfonated PS, PVDF, PAN (and linked block-copolymers), cellulosics (e.g., cellulose acetate), aliphatic polyamide, poly (ether imide), and polyetheretherketone. Exemplary matters employed in the generation of RO membranes comprise cellulose esters (nearly frequently cellulose diacetate and cellulose triacetate), aromatic polyamide, and polybenzimidazoles [34].

Ceramic membranes are as well obtainable. The great number of ceramic membranes are produced from aluminum oxide (alumina, Al_2O_3), titanium oxide (titania, TiO_2), and zirconium oxide (zirconia, ZrO_2) [1]. Ceramic membranes usually possess better thermal, chemical, and mechanical resistances, and longer service life than their polymeric counterparts (up to 15 years in comparison with 3-5 years) [41, 42]. Nevertheless, they need cautious working since the matter is breakable. Different from the polymeric membranes, the elevated thermal and chemical resistances of ceramic membranes render it easy to clean the fouled membranes at elevated temperatures [43] and with elevated contents of cleaning agents; as a consequence, total flux recuperation may be attained with easy chemical cleaning [44-46] with a lower hazard of membrane deterioration. The elevated chemical resistance as well lets ceramic membranes to treat ozonated water without being deteriorated by elevated residual ozone contents [47]. An additional benefit of ceramic membranes comparatively with polymeric membranes is their higher operating fluxes [42]. Moreover, with ceramic membranes it is easy to integrate oxidation processes, like UV irradiation, with filtration to eliminate pollutants in water and wastewater. In such uses, titanium oxide plays the role of a photocatalyst which launches the oxidation of pollutants [48]. Ceramic membranes have been largely employed in the food, beverage, and dairy industries and in the treatment of industrial wastewater [49, 50]. Nevertheless, since they are more costly than polymeric membranes, their application in water and municipal wastewater treatment is until now rather restricted. It is important to note here that they have been largely employed in Japan for the treatment of drinking water. Lately, reducing price has conducted to a rising attentiveness in the usage of ceramic membranes in the water industry [1, 42, 51, 52].

3.3. Membrane Arrangements

Membrane organization (or design) and the manner IN which the single membranes are accommodated to form modules are extremely crucial parameters influencing the global process efficiency [1]. Frequent membrane arrangements in wastewater treatment comprise plate-and-frame, spiral-wound cylinder, hollow-fiber, tubular, and rotating flat-plate [29] (Table 2).

Table 2. *Usual membrane arrangements in WWTPs [29].*

Membrane organizations in WWTPs	
Plate-and-frame configuration	This configuration is composed of a series of flat membrane sheets and support plates. Several membrane sheets are attached to a support plate on both sides, constituting a membrane cartridge. These cartridges are usually hold in a container (cassette) in which they are slid into grooves for support. The cartridges are usually arranged 10 mm away from each other. FW is filtered as it flows between and parallel to the cartridges [23].
Spiral-wound configuration	This configuration is composed of numerous flat membrane sheets, each of which is closed on three sides and the open side is glued to a perforated plastic collection tube. A flexible permeate spacer is placed between two successive membrane sheets [53, 54]. Flow through the spiral-wound configuration is outside-in [29].
Hollow-fiber configuration	In this geometry, millions of fibers are coiled into a U-shape and the extremities are potted into a special epoxy resin which acts as a tube sheet [20]. The prioritized direction of water flow in hollow-fiber systems is "outside in" (the FW enters the fibers from the fiber external wall and the permeate flows inside the fiber lumen and is collected at the fiber extremity. This geometry may be either immersed (as in MBRs) or contained in pressure vessels, which isolate the FW and the permeate. With its elevated packing densities and low pressure needs, which tend to conduct to low life-cycle cost, this geometry has the capacity to become the most frequent membrane configuration for big municipal wastewater treatment facilities [23].
Tubular configuration	In this geometry, the membranes are cast on a support tube which is hold in a pressure vessel. Membranes of this configuration are frequently ceramic run in cross-flow mode where the FW flows axially within the tube, while the permeate flows radially through the porous structure of the tube wall. The permeate is collected outside the tube while the concentrate continues to flow through it [23].

Dead-end filtration using monolith type tubular membranes has also been practiced [42, 52].

3.4. Working Ways of Membrane Processes

Membrane filters may be used in either dead-end or cross-flow mode, as shown in Figure 2 [34]. In the “dead-end” way, the pressure pushing the liquid flow is exercised perpendicularly to the membrane surface. In cross-flow filtration, the FW is pushed to flow at fairly elevated velocity in the direction tangential to the membrane surface [1]. A thin cake layer may generate because of the deposition of the solutes in the FW on the membrane. Elevated liquid velocity is employed to clean away some of the rejected materials from the cake layer, avoiding it from building up and thus decreasing fouling [34].

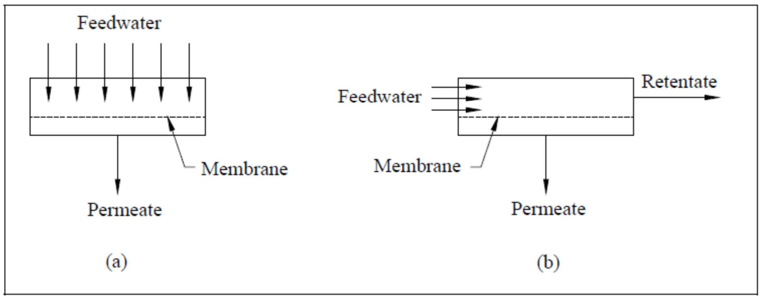

Figure 2. *Schematic presentations of (a) dead-end mode and (b) cross-flow mode [34].*

Filtration may be worked in either constant-pressure way or constant-flux way [55]. Constant-flux mode needs varying the applied pressure to keep a fixed permeate flux [1].

3.5. FW for Membrane Processes for Water Reuse

In WWTPs, the FW for membrane processes is frequently secondary effluent. The organic tenor of this effluent is usually called *effluent organic matter* (EfOM), which holds different complicate and heterogeneous constituents [1]. EfOM may be categorized into three various groups following their origins [56] (Table 3).

Table 3. *Three groups of EfOM according to their origin [56].*

EfOM’s groups following their origins	
Refractory natural organic matter (NOM)	This group originates from potable water [57].
Synthetic organic compounds	This group is produced through domestic usage and disinfection by-products generated upon water and wastewater treatment.
Soluble microbial products (SMP)	This group is extracted from the biological processes of wastewater treatment. Constituents in SMP comprise polysaccharides, proteins, aminosugars, nucleic acids, extracellular enzymes, antibiotics, steroids, and structural components of cells [58].

To decrease membrane fouling, the secondary effluent is frequently pre-treated to eliminate the foulants. The most efficient pre-treatment technique depends on the features of the secondary effluent [1].

Distinct from MF and UF of secondary effluent, in which the FW holds EfOM and a relatively small tenor of SS (usually < 25 mg/L), the feed to the filtration process in MBRs is a mixed liquor containing [27, 59, 60]:

1) The AS (mixed liquor SSs) with elevated degrees of SS (3000-31000 mg/L [61]),
2) Bound extracellular polymeric substances (EPS) (composed of polysaccharides, proteins, nucleic acids, lipids and humic acids (HAs) [62] which adhere to the surface of microbial cells in the sludge), and
3) Colloidal and soluble organic matter, including soluble EPS (SMP, originating from substrate metabolism of micro-organisms) [1, 63].

4. Membrane Fouling and Parameters Influencing Fouling

Membrane fouling may be described as the build-up of pollutants on the membrane which results in an augmentation in the TMP need (in constant-flux filtration) or a decrease in the permeate flux across the membrane (in constant-pressure operation) [1]. It may happen at the surface (macro-fouling) or inside the pore (pore fouling or micro-fouling) [64].

There are several manners in which a membrane is fouled, comprising [65, 66]:

1) Deposition of particulates and SSs on the membrane (particulate fouling). This kind of fouling may be minimized upon membrane backwashing and/or air scrubbing;
2) Precipitation of DOM on the membrane surface or in membrane pores (organic fouling);
3) Aggregation of biological growth in the system and/or its fixation to the membrane (biofouling) [67]. EPS formed by the fixed microorganisms may constitute a viscous slimy gel, which delay the permeate flow;
4) Physical or chemical reactions between certain constituents of the FW and the membrane surface [1].

The principal source of fouling of MF and UF membranes is organic fouling [68], following from the aggregation of DOM in the FW in the membrane pores or on the membrane surface

[69]. Biofouling can happen in long-term working. Membrane fouling in MBRs is more difficult than that in MF and UF of secondary effluent, because of the existence of AS and linked EPS in the mixed liquor [1, 27].

Fouling is ordinarily categorized as reversible and irreversible fouling [70]. Foulants in hydraulically reversible fouling usually appear as a cake layer on the membrane surface and can be eliminated by hydraulic cleaning like backwashing the membrane with the permeate. Irreversible fouling is likely generated by the adsorption or pore plugging of solutes in and within the membrane pores [71]. Chemically irreversible fouling is the proportion of fouling that cannot be eliminated by chemical cleaning of the membrane [1].

The quality and level of fouling are influenced by reciprocal actions of numerous parameters, comprising the features of the FW and the membranes, membrane geometry, and working situations [1].

4.1. Effect of FW Content

DOM, inorganic matters (e.g., silica, alumino-silicates, iron, and aluminium), SS, and microorganisms (bacteria and fungi) are possible foulants in membrane filtration of surface water and wastewater [1, 72].

The fouling capacity of DOM is determined by solution chemistry, membrane features, and working situations [73]. FWs with higher DOM levels do not every time produce more serious fouling, showing that several organic portions have a more elevated fouling capacity than others [23, 74]. Nevertheless, there have been differences of opinion concerning which constituent is mostly important for membrane fouling (Table 4) [1].

Table 4. *Three fractions of EfOM following their interaction with water [1].*

EfOM's portions following their interaction with water	
Hydrophobic	HSs, the main constituent of NOM, are mostly hydrophobic and usually classified into three portions: HA, fulvic acid (FA), and humin. HA and FA are anionic polyelectrolytes with negatively charged carboxyl ($COOH^-$), methoxyl carbonyl (C=O), and phenolic hydroxyl and alcoholic hydroxyl (OH) functional groups. HA is not soluble in water at pH under 2 but begins to be soluble at more elevated pH. FA is water soluble while humin is water insoluble at all pH values [75]. HA carries fewer carboxylic and hydroxyl functional groups and is more hydrophobic than FA. The MW of aquatic HA is between 2000 Da and 5000 Da while MW of FA is usually less than 2000 Da. HA is thus considered to be colloidal. There are more color centers on HA molecules than on FA molecules [76, 77].
Hydrophilic	Several scientists studied the fouling capacities of the portions derived from bulk NOM and EfOM solutions (employing resin fractionation) and observed that the hydrophilic (non-humic) constituents, which carried polysaccharide-like and protein-like constituents, were the main foulants in membrane filtration [78-80]. Researchers [81] proposed that these foulants have their origin from SMP produced through the biological processes of wastewater treatment.
Transphilic	Fan et al. [82] classified the fouling capacity of NOM portions on hydrophobic PVDF MF membranes as hydrophilic neutral > hydrophobic acids > transphilic acids > hydrophilic charged. These results were confirmed by more recent investigations which analyzed the feeds and the permeates in dead-end UF of EfOM with size exclusion chromatography with organic carbon detection and observed that the constituents kept by the membranes were protein-like and polysaccharide-like constituents [83-85].

However, different scientists detected that the hydrophobic portion of DOM (mainly HS) was the most significant constituent playing a part in fouling [86, 87]. The elevated aromaticity, adsorptive capacity, hydrophobicity, and elevated MW of HA were suggested to be in charge of its more increased trend to deposit on membrane surface [71, 88]. Researchers [89] examined the fouling of UF membranes and established that the HA portion was in charge of irreversible pore adsorption and plugging, while FA and the hydrophilic NOM produced a smaller and mainly reversible flux decline. Other scientists [90] as well mentioned that HA was a crucial foulant in MF and UF. Kim and Dempsey [91] observed that organic acids (which possibly carried HA, as shown by their elevated UVA_{254}), fouled MF and UF membranes more seriously than any other constituents (comprising colloidal organic matter and hydrophilic bases/neutrals) in a municipal wastewater [1]. The paradoxical conclusions shown previously may be affected to gaps in water sources and membrane features. They as well establish the necessity for distinguishing the foulants for a specified wastewater and membrane type [92, 93].

The existence of inorganic solids in the FW was observed to influence the fouling comportments of organic matters [94]. Inorganic particles like clay minerals participated with organic constituents to adsorb onto the membrane surface or in the pores [1]. Moreover, the elevated surface area of clay minerals might favor the adsorption of DOM on the inorganic layer. This process may possess fundamental impact on fouling features. It may conduct to improved deposition of inorganic solids on the membrane and a decrease in the sorption of DOM onto the membrane, which augments membrane permeability [71].

Until now, the most important part of the researches into the characterization of the foulants has been performed in dead-end filtration mode employing polymeric membranes. Obviously, it may be concluded that the constituents of the DOM in charge of fouling in dead-end filtration would as well be the membrane foulants in cross-flow filtration with ceramic membranes. Earlier researches, nevertheless, have not tried to confirm this conclusion, specifically with municipal secondary effluents. Data concerning the performance of feed pre-treatments on fouling decrease in cross-flow MF and UF of municipal wastewater with ceramic membranes is as well rare [1].

4.2. Effect of Solution Chemistry

Solution chemistry (pH, ionic strength, content of multivalent cations, and water hardness) was established to participate importantly to the nature and extent of fouling [95, 96]. It significantly influences the construction and hydraulic resistance of the foulant layer through monitoring the charge and arrangement of organic macromolecules [97]. It was detected that HS are inclined to assemble more at low pH and elevated multivalent cation (specifically Ca^{2+}) levels [1]. At neutral pH and low ionic strength, the molecules are inclined to dilate to more linear forms [98].

Numerous researches observed that membrane fouling by NOM was augmented in solutions of low pH, elevated ionic strength and elevated divalent cation content [99]. This process may be interpreted by variations in intra- and inter-molecular electrostatic mutual actions between organic molecules; specifically those carrying negatively charged functional groups like carboxylic, phenolic and carbonyl [1]. It is suggested that augmenting ionic content shielded the charges on solute molecules and assisted their coiling and agglomeration, which conducted to the aggregation of these molecules on the membrane surface [71].

4.3. Effect of Membrane Features

Membrane features like MWCO, pore size, surface charge and hydrophobicity/hydrophilicity are crucial parameters influencing the rejection, types of kept solutes, rate of flux decline, and fouling stages [1].

Electrostatic repulsion and hydrophobic attraction are the two main forces monitoring the mutual action between NOM/EfOM and membranes in MF and UF [1]. Electrostatic repulsion between DOM and the membrane surface is the consequence of the likeness in the surface charge of these two constituents. In the pH interval of typical natural water and wastewater (pH 5-8), most membranes and DOM constituents hold net negative surface charges, and thus DOM and membranes are inclined to electrostatically repel each other [100]. For this explanation, researchers [101] proposed that membranes with negatively charged surfaces must be chosen to decrease fouling provoked by DOM.

4.4. Effect of Membrane Geometry

Membrane geometry is an important parameter influencing the efficiency of the filtration process [1]. Geometries that are simple to clean and generate elevated turbulence in the water flow are better in reducing fouling. Elevated turbulence enhances mass transfer on the feed side and thus diminishes the aggregation of matter near the membrane surface. Additional selection criteria for good membrane geometry comprise [29]: (1) High membrane area to module bulk volume ratio, (2) Easy to modularize, (3) Low cost per unit membrane area, and (4) Low energy consumption per unit volume of treated water.

4.5. Effect of Working Situations

Working in “dead-end” mode is disposed to conduct to quick fouling because of the speedy formation of a cake layer of kept matters. In cross-flow procedure, the generation of the cake layer is decelerated by the high-velocity liquid flow [1]. Working parameters like applied pressure, cross-flow velocity, and backwash frequency as well importantly influence the ratio and size of fouling [102-104]. The starting flux in MF and UF as well influences the significance of flux decrease. It has been observed that working at more elevated fluxes conducted to quicker fouling [105].

5. Resistances in Membrane Filtration and Fouling Models

The global hydraulic resistance in membrane filtration comprises resistances applied by the membrane, pore blocking, pore adsorption, the cake layer, and by concentration polarization [106]. The membrane hydraulic resistance is a membrane constant and is independent of the feed composition and applied pressure. Pore blocking may happen in porous membranes, when solutes of the same size as the membrane pore block the pore entrance [1]. Adsorption of solute molecules on the membrane surface or within membrane pores, if it happens, as well participates to the total resistance [34]. Cake formation happens when the feed holds particles bigger than the membrane pores. Pore blocking, pore adsorption, and cake formation are seen as the three mechanisms of membrane fouling formed by DOM, while concentration polarization, even if generating flux decrease, is not viewed as a fouling mechanism [107].

6. Fouling Extenuation

Numerous techniques have been employed to monitor membrane fouling [1]. These include [1]:

1) Pre-treatment of the FW,
2) Modification of membrane properties [108],
3) Optimization of module configuration and operating conditions,
4) Periodic membrane cleaning,
5) Evaluation of system performance using pilot plant, and
6) Use of predictive models [109].

Secondary effluent is frequently pre-treated to decrease membrane fouling and/or enhance the permeate quality before being passed to MF or UF processes [1]. Convenient pre-treatment techniques are chosen following the constituents to be eliminated and the level of their elimination. Frequent pre-treatment techniques for MF and UF comprise [23, 110, 111]:

1) Coagulation (habitually with lime, alum, or ferric salts) and flocculation [112-120],
2) Adsorption (most frequently employed material is powdered activated carbon (PAC)),
3) Pre-oxidation (utilizing ozone) [121],
4) Pre-filtration (employing large pore size membranes, granular media, filter cloth, etc.).

Practically, these processes [1] may be used in integration, as an illustration, coagulation followed by pre-filtration, coagulation followed by adsorption with PAC [122, 123], and ozonation followed by coagulation [124].

7. Conclusions

The main points drawn from this review are listed as below:

Membrane processes for the treatment of water and wastewater have been largely trusted because of their elevated quality treated water and inexpensiveness. Nevertheless, for this technique to be employed efficaciously, membrane fouling requires to be reduced. Fouling of filtration membranes conducts to a diminution of water treatability, requiring process stop, membrane cleaning, and more usual membrane substitution.

The fouling process is complicate and affected by numerous parameters, like FW, membrane features, and working situations. Feed pre-treatment is frequently applied to decrease membrane fouling. Nevertheless, the difficulty of the fouling process renders it hard to expect the efficiency of pre-treatment techniques on fouling diminution. Both useful and unfavorable impacts of coagulation on membrane fouling have been noticed.

Up to now, the large majority of the membranes employed in water and wastewater treatment are produced of polymeric materials. Nevertheless, it has been expected that ceramic membranes will be competitive options in the following years.

Numerous techniques have been employed to monitor membrane fouling. These include: Pre-treatment of the FW, modification of membrane properties, optimization of module configuration and operating conditions, periodic membrane cleaning, evaluation of system performance using pilot plant, and use of predictive models. However, membrane fouling remains complicated task for both technico-economic reasons depending on water characteristics and pre-treatment processes and efficiencies.

List of Abbreviations

AS	Activated sludge
DOM	Dissolved organic matter
EfOM	Effluent organic matter
EPS	Extracellular polymeric substances
FA	Fulvic acid
FW	Feedwater
HA	Humic acid
HS	Humic substance
MBR	Membrane bioreactor
MF	Microfiltration
MW	Molecular weight
MWCO	MW cut-off
NF	Nanofiltration
NOM	Natural organic matter
PAC	Powdered activated carbon
PES	Polyethersulfone
PS	Polysulfone
PVDF	Polyvinylidene fluoride
RO	Reverse osmosis
SMP	Soluble microbial products
SS	Suspended solids
TMP	Transmembrane pressure
WWTP	Wastewater treatment plant
UF	Ultrafiltration

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