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Recent Advances in Measuring and Controlling Biofouling of Seawater Reverse Osmosis SWRO: A Review

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Abstract

This study presents recent literature that sheds light on the SWRO membrane biofouling, Inventory of causes, consequences, measurement, and possible solutions. In particular, biofouling of SWRO is considered as one of the challenges faced by seawater desalination today. For seawater desalination, mitigating membrane biofouling is essentially required and yet to be overcome. Specific shortcomings and prospective solutions are reviewed towards understanding the biofouling mechanism, pretreatment impacts, level of assimilable nutrients, and real-time monitoring. Accordingly, this review aims to address recent advances in biological fouling measurements and control to better understand biofouling and the best ways of dealing with such a challenging issue.

Keywords: biofouling, membrane, pretreatment, reverse osmosis, seawater

1. Introduction

Beyond doubts, Seawater desalination is commonly considered as a significant method towards producing and supplying potable water across the globe, especially in areas like the Middle East and North Africa (MENA) region characterized by a dry climate, low precipitation, and insufficiency of surface water. Despite the availability of various desalination technologies, membrane technology presented by Reverse Osmosis (RO) witnessed significant growth dominating about 60% of the desalination industry worldwide. The newly developed RO membranes characterized by high rejection and high flow membranes were allowed to operate at high pressures (up to 80–90 bar), thereby making conversions to 55–60% economically feasible. Such advancements towards simplifying RO processes from a two-stage treatment change to a single-stage array which in turn reduced capital and operational costs [1–3].

The high demand and global climate change have contributed to water scarcity in a significant way. As such, 71% of the world's population live under conditions of moderate to extreme water shortage, and about 66% (4.0 billion people) live in severe water deficiency. This well-felt scarcity could be a binding limitation on the socio-economic development of many countries according to Goal #6 [SDG6] of the Sustainable Development Goals cover all aspects of managing water for fair access, sustainability, and environmental protection. Having said so, seawater desalination is reliably seen compared to other sources, especially with the

long-term satisfaction tends to be achieved fully or partially for the demand in areas around the globe where water scarcity is felt, such as Australia, Southern Carolina, the Middle East, and Northern Africa [4].

Seawater desalination technology by RO is proven to be an extreme energy-efficient compared to other conventional thermal distillation methods and therefore is economically feasible. Membrane technologies application in the desalination industry has witnessed some rapid development and growth over the past 20 years. However, SWRO membranes are highly sensitive to the feedwater characteristics and to the concentration of certain organic compounds that potentially lead to membrane fouling phenomena [1, 5–7].

2. Desalination pretreatment

Pretreatment is crucial to SWRO, as it influences membrane efficiency and life expectancy by fouling reduction. Practically, it is essential to enhance the raw water quality before passing through RO vessels to promote high and effective performance. Yet, Membrane fouling and scaling remain challenging even though the perfect design and operating conditions can be significantly helpful. Both source and quality of feed water influence the pretreatment choice towards better fouling control. Technically, the silt density index (SDI) and turbidity are the two main parameters determining pretreatment performance [8–10]. In addition, microbial foulants characterization can be found in [11]. Pretreatment techniques are designed to eliminate the microbial loads on high-pressure membranes but may scavenge nutrients and potentially provide a suitable environment for microbial growth. A comparison of the bacterial community composition can, therefore, answer whether pretreatment compartments serve as inoculum for high-pressure membranes. Physical and chemical water treatment processing feed water in desalination industry is referred to usually as pretreatment, as shown in **Figure 1**, usually proceed by a series of methods: coagulation and flocculation, followed by granular media filtration (e.g., anthracite coal, silica sand, or garnet) and cartridge filtration. Biocides such as chlorine and Peracetic acid, in addition to ozone or ultraviolet (UV), can be used when biofouling is a problem [2, 11].

Furthermore, membrane biofouling cannot be removed by conventional pretreatment methods such as coagulation, flocculation, ultrafiltration, and cartridge filters (CF), as they are unable to remove all passing microorganisms tending to colonize the membrane. Sand filtration combined with chemical disinfection is more efficient in reducing microbial contaminants, including viruses, to acceptable levels meeting drinking water standards. Technically, the pressure-driven process presented by membrane filtration can provide high-quality drinking water. However, it could be faced with vital challenges including system demanding, relatively high cost, clogging, scale formation, and biofouling. Moreover, membranes have a limited lifetime regardless of how good they are and so they may not reject all pollutants of concern for drinking water after a certain time of operation even if microorganisms are successfully removed. One consideration in large-scale applications is that membrane filtration systems produce considerable amounts of more concentrated wastewater per unit of purified water. Having said so, membrane selection must take into consideration the nature of the contaminants associated or extracted [10, 12, 13].

Microbial colonization at the membrane surface is traditionally overcome by overall applying disinfection to the feed water. Ideally, any disinfectant should not be expensive or hazardous. However, it must be highly toxic to microbes with zero

Figure 1.
Stages of an RO membrane system.

effect on the desalination plant productivity. Traditionally, there are many disinfection processes applied in water treatment including but not limited to chlorination, ozonation, and UV radiation. Although ozonation is found to be an effective disinfection technique using oxidative effects in removing microorganisms, it is a bit costly and unstable in addition to producing carcinogenic bromates as by-products in the treated water occasionally. Chlorine on the other hand is the most commonly used disinfectant characterized by easiness use and low cost. During the chlorination process, the biomass on the RO membrane is effectively destroyed. Besides and due to molecular analysis, some bacterial groups appear to tolerate this biocide. Well-known bacterial classes potentially resisting chlorination, such as *Bacillus* and *Clostridia* due to their ability to sporulate, are very much identified on fouled membranes [2, 14].

For many reasons, biofouling is challengingly difficult to manage in RO systems. Some membranes like polyamide-based membranes tend to be sensitive to oxidizing agents such as chlorine leading to significant limitations for such use. Generally, Commercial plants are not observably in sterile environments. Therefore, any microorganism that enters the system can rapidly multiply. Surprisingly, it takes only 30 minutes for some bacteria to duplicate their population, showing exponential growth. The free chlorine presented during the chlorination process may potentially lead to membrane damage and salt rejection deterioration. Another downside of applying chlorine as a disinfectant is its capacity of breaking down the organic and humic material to Assimilable organic carbon (AOC), resulting in the rapid growth of biofilm which in-turn leads to accelerated incremental of feed channel pressure drop. In some treatment plants, Mono-chloramine is usually applied to achieve biofouling control. Nevertheless, mono-chloramine can be used to produce N-Nitrosodimethylamine (NDMA), which is a human carcinogenic material that can result in public health issues. Furthermore, contaminated water with mono-chloramine may potentially result in the damage of membrane in the iron and manganese presentation [8, 12, 15].

Surprisingly, various bacterial types and groups were found to be succeeding and thriving when membranes are cleaned intermittently with various cleaning agents. One thing to think of is the inclusion of citric acid leading to several community compositions compared to when chlorine was used alone. *Acinetobacter*, *Ralstonia*, *Comamonadaceae*, and *Diaphorobacter*, *Stenotrophomonas*, and *Enterobacteriaceae* are dominantly shown on cleaned membranes via chlorination. When chlorination combined with citric acid cleaning *Silicibacter*, *Rhodobacteraceae*, *Pseudomonas*, *Pedobacter*, and *Janthinobacterium*, they became abundant. This is confirmed based on physiological features assigned to taxonomically related bacteria and Adenosine Triphosphate (ATP) concentrations. It is, therefore, suggested that spore-formers, Gram-positive bacteria, and Acidophiles are better resisted citric acid treatment. These suggestions should be taken into consideration with caution because simply, there is no evidence provided that bacteria are recalcitrant against citric acid [16].

3. SWRO membrane fouling

Membrane fouling is practically seen as a chronic drawback hindering the development and operation of SWRO desalination processes. Fouling results in overall membrane performance deterioration with operational pressure drop and more frequent cleaning leading to operational costs increase and eventually full loss of membrane. From hydrodynamics perspectives, fouling development mainly in space-filled channels of the membrane is influenced by water quality, operational conditions, and spacer and membrane design. Technically, membrane fouling issues vary from organic and inorganic fouling to colloidal and biofouling contributing to increase cost of operation as well as affecting the quality of water produced. Amongst, biofouling seems to be way too complicated and hard to be controlled due to the excessively increase of biofilm formation on the surface of membrane surface, consequently leading to deteriorated performance. Additionally, the capability of lived bacteria inside biofilms in terms of high tolerance to antibiotics and other antimicrobials than planktonic cultures is problematic. As such, various techniques including pretreatment, membrane surface alteration or modification, disinfecting of feed water via chlorination, and cleaning are developed to overcome and/or control biofouling simply by treating biofilm formation on membrane surfaces [2, 17, 18].

4. Biofouling

4.1 Definition

Presently, several foulants considered or categorized as microbial ones including various microorganisms and organic compounds, known also to be aquatic, such as polysaccharides, proteins, and lipids, called extracellular polymeric substances (EPS). Identically, the biofouling process involves in adhesion of organisms that are aquatic along with their metabolic products presented on membrane surface or feed spacers. As shown in **Figure 2**, strong biofilm growth can be observed and found on the feed spacer strands. More than 45% of all membrane fouling is biofouling originated mainly by unicellular or multicellular microorganisms and therefore seen as one of the major issues of concern to reverse osmosis membrane filtration processes. Although membrane biofilm majority is formed by bacteria, other organisms such as fungi, algae, and protozoa may potentially be attracted by the membrane surface and add up to the formation of biofilm in a significant manner. Various studies confirm that *Pseudomonas*, *Bacillus*, *Arthrobacter*, *Corynebacterium*, *Flavobacterium*, and *Aeromonas* are the most predominant bacteria identified in fouled RO membranes [9, 11, 12, 19–22].

Membrane biofouling takes place gradually in sequential steps, as shown in **Figure 3**. Firstly, the microbial cells get to membrane surface attachment, causing the forming of the biofilm as layer, involving communities of different microorganisms' types (e.g., bacteria, algae, protozoa, and fungi). Initially and acting as mediator for the attachment of microbial substances, electrokinetic and hydrophobic interaction, the growth and multiplication of cell usually follows at the expenses of nutrients being soluble in water feed or membrane surface adsorbing organics. The roughness and charge of the membrane surface are considered as key factors contributing to the enhancement of the microorganisms attached to the membrane surface [9].

Several environmental factors raising bacterial growth such as nutrients amount and types which strongly affect the microbial composition and biofilms density. Also, membrane characteristics such as type, roughness, charge, and hydrophobic/hydrophilic characters very much influence the biofouling microbial film establishment. Producing RO membranes highly resistant to biofouling as well as other fouling types remains challenging. Typically and from operational point of view, biofouling poses itself as a challenge, especially for saline waters having natural organics at high levels. Seasonally, biofouling tends to be problematic during extreme algal blooms or in time of having accident entrance to the open intake of the plant in rainy season with highly organic water [2, 11].

Figure 2.
Biofouling in RO sample (left: top view, right: cross-section) [12].

Figure 3.
Steps of the biofilm [20].

Commonly, biofouling attributes to the increased probability of bacteria producing polysaccharides and natural adhesives. It occurs at all open-ocean desalination plants such as the Jeddah SWRO desalination station in KSA. Mature biofilms exhibit anti-bactericidal properties and are also resistant to detachment. Biofilm formation results in biofouling when exacerbated in desalination systems by water production efficiency deterioration of membrane degradation, leading to a significant increase in operational costs associated with cleaning regiment and shortened membrane lifespan [23, 24].

4.2 Factors affecting biofouling

Generally, the saline feed water biofouling potential is influenced by several interrelated factors including microorganisms' concentration; content of readily biodegradable compounds; nutrients concentration and composition in the source water; temperature; the salinity of the feed water as well as operating parameters such as cross-flow velocity [11, 25, 26].

The study of [25] elucidated Algal organic matter (AOM) impact on biofouling affecting various membranes modules (capillary and spiral wound) by algal blooms. They found that measuring Adhesion force illustrate that AOM has the propensities towards adhering to a membrane surface and would need massive force to be removed from the membrane. Also, the seawater capacity supporting bacterial growth illustrated a correlated positive linear with AOM concentration levels in the water. It was linked to the tending of AOM, especially, transparent exopolymer particles (TEP), to nutrients concentration absorption from the feed water feeding attached bacteria. Also, fastened experiments of biofouling made with spiral wound and capillary membranes evidently show that when biodegradable nutrients presented in the feed water unlimitedly, a high level of AOM concentration in water feeds or as membrane attachment may significantly speedup biofouling. Further observation is that lower biofouling rates occurred once membranes are exposed to feed spikes with AOM or nutrients [25].

4.3 Microbial communities in RO systems

The bacteria can tolerate a wide range of pH (0.5–13) and temperature (–12–110 °C) while being able to colonize on all membrane surfaces in RO plants

under different conditions. Various studies were carried out to investigate frequently observed microorganisms on membranes in RO plants. As concluded by [28] some bacterial groups are presented with some potential finger print significantly related to biofouling. Their study mostly opened some future window towards focusing on having already-cleaned membranes treated prior to installation. Also, paying more attention to primarily target troubling colonizers, or developing pre-treatment designs considering biofouling measures through the bacterial load minimization attempting to access membrane unit feed. While, a pilot-scale study of [29] was implemented to compare bacterial populations (membrane biofilm) in seawater, CF, and from Carlsbad plant at California, USA.

Observably, population of biofilm for seawater and membrane tend to have some similarity, but the CF harbored other biofilm community type. It was a relatively firm study because it concluded the findings of different communities of biofilm in five fouled SWRO membranes than those of other found around the globe. Apparently, such unique occurrence was due to differences observed in operational conditions and sampling across the year. Various mutually and dominantly existence of bacterial group could be observed in all samples. As such, strong suggestion was made about certain group being conformed to the membrane surfaces growing under chemolithoheterotrophic conditions oligotrophically [27–29].

Similarly, [30] results found that members of the *Ruegeria*, *Pseudoruegeria*, *Parvularcula*, *Legionella*, and *Shigella* were the only bacterial groups shared between the CF and RO membranes. *Phaeobacter*, *Leisingera*, *Kangiella*, and *Bacillales* are abundant in the CF, while *Haliangium* and *Limnobacter* are abundant on the RO membrane. The presence of bacteria belonging to taxa harboring facultative and obligate chemolithotrophs, such as *Geobacter*, *Desulfuromusa*, and *Thioalkalivibrio*, on the CF potentially indicate the effective removal made by the pre-treatment compartments for certain nutritional compounds, such as ferrous iron or sulfur. Consequently, published studies do not uniformly present the composition of the bacterial community at the same taxonomic level, hardening the comparison of bacterial diversity. For instance, a review of [14] compared 33 studies investigating bacterial communities on fouled high-pressure membranes. They classified the identified bacteria at the order level. A total of 35 bacterial orders from those fouled high-pressure membranes have been recorded. These orders were used as a benchmark to compare the microbial diversity of feed water, pre-treatment compartments, and fouled membranes, and to detect the role of specific selection pressures on the microbial composition [14, 30].

A review of [14] found that the most commonly detected bacteria on fouled membranes are *Burkholderiales*, *Pseudomonadales*, *Rhizobiales*, and *Sphingomonadales*, and *Xanthomonadales*. Whereas *Burkholderiales* and *Xanthomonadales* have not been identified in earlier studies, but studies of next-generation sequencing (NGS) have frequently identified these orders of bacteria on fouled membranes. Due to its ability to study bacterial community compositions in a culture-independent and high-performance way [31]. In [32] they compared the bacterial diversity of the surface water and the membrane population. They concluded that the biofilm actively produced on the membrane surface, rather than being a concentration effect of bacteria. In general, the composition of the bacterial population on the membrane varies from the feed water because only a fraction of the bacterial feed water diversity accumulates at the membrane surface, indicating that the membrane surface provides bacterial selection pressures. However, [33] found that the bacterial composition of a mature fouling layer was similar to the feed water composition [14, 31–33].

In the experiment of [34], a lab-bench cross-flow RO system was used to explore the impact of chlorine disinfection on reverse osmosis membrane biofouling.

No significant distinctively chlorine-resistant bacteria were detected in the sample without chlorine dosage and with 1 mg-Cl₂/L chlorine dosage. However, in the samples with 5 and 15 mg-Cl₂/L chlorine, kinds of significantly distinctive chlorine-resistant bacteria were presented included *Methylobacterium*, *Pseudomonas*, *Sphingomonas*, and *Acinetobacter*. These results indicated the significant selection effect of chlorine on the chlorine-resistant bacteria. Results of [35] found *Proteobacteria*, *Bacteroidetes*, *Firmicutes*, and *Planctomycetes* are the most abundant phyla with the application of high throughput sequencing. Microbial community succession was revealed during biofilm formation, in which *Proteobacteria*, *Planctomycetes*, and *Bacteroidetes* played significant roles [34, 35].

The research of [28] analyzed the biochemical properties by selecting a good-model bacteria include *Paracoccus*, *Burkholderia*, *Pseudomonas*, *Acinetobacter*, *Pseudoalteromonas*, *Cytophaga*, *Microbacterium*, *Bacillus*, *Marinomonas*, *Rhodococcus*, *Exiguobacterium*, and *Staphylococcus* which may influence its ability in terms of forming insurgent biofilms cumulatively at membrane surfaces. In this study, bacteria was isolated across stages of all plant. Predominant organisms were detected and seem to be significantly involved in biofouling as well as including almost all isolated cultures by culturing and next-generation sequencing (NGS) through applying 16S rRNA meta-barcoding. Researchers have also found that as biofilm community influenced by bacterial community on seawater reverse osmosis membranes, it is compulsory to have customized/designed controlling measures targeting the invading microbial elements related to the plant's geographical spot [28].

4.4 Biofouling potential indicators and measurements

A biofilm has a high content of water and organic matter (70–95%), high numbers of colony-forming units and cells, high contents of carbohydrates and proteins, high content of ATP, and low content of inorganic matter. Indicating biofouling potential can be proposed by multiple parameters as ATP, AOC, and biodegradable dissolved organic carbon (BDOC). Generally, the previously mentioned parameters are generally applicable for fresh waters and yet to be extended to be applied for desalination plants [25, 36]. Meanwhile, the study of [37] suggested some testing sets to allow for the determination of the water samples capacity of microbial support. In addition to using fluorescence intensity microplate analysis to determine biofouling potential on RO membranes [35, 37, 38].

Measurement of RO feed water biofouling tendency is not an easy task. To do so, several in-practice parameters are indicatively considered like: Silt density index SDI, turbidity, and total suspended solids (TSS). Having said so, biologically-based data is yet to be obtainable supporting such measurements. The RO feed water microbial support capacity (MSC) is practically determined by factors associated with the algal activity, such as TOC, the ratio of TOC:TN:TP, the increase in RO train DP, Chlorophyll a, TEP, bacterial activity (e.g., ATP), total bacterial count, microscopic observation, and nutrients concentration (Total N, Total P). Biological-based factors such as AOC and BDOC are used in waters with no salinity. Also, many consistent monitoring systems like monitoring of biofilm and the MFS had been developed to determine formation rate of biofilm. These monitoring systems cannot predict the feed water potentiality for biofouling but simulate overall plant operation [11, 19].

The concentration of TOC is widely applied to indicate the potentiality of saline water to biofouling whereas the rate of DP increase is indicatively used for the rate of biofouling. From operational point of view, potentiality to biofouling tends to be significantly increased when TOC concentration raises to 2 mg L⁻¹.

Practically, the weekly measurements made for ratio of TOC:TN: TP to indicate biofouling increasing. Consequently, ratios above 20% of 1:1:1 indicates an elevation requires bacterial EPS generation leading to have the bacteria encouraged to cause membrane fouling [11, 39].

The concentration of Chlorophyll *a* for the feed water can be indicatively seen as a sign related to the green pigmentation algae content in the water [11]. The total count of algae is potentially determined via online methods or through lab experiments. Technically, there are three KPIs (key-performance-indicators) determining the algal high content impact in feed water including: efficiency of solid removals deterioration at pre-treatment stage due to filtration overload, fouling acceleration of CF, and finally RO train productivity deterioration [11].

4.5 Membrane biofouling impact

In SWRO systems, biofouling has many adverse effects, as increases in differential driving pressure and feed channel pressure drop. These are required to maintain the same production rate due to biofilm resistance. In addition to increased energy consumption associated with high pressure to achieve the biofilm resistance and flux decline. Biofouling eventually leads to the biodegradation of cellulose acetate membranes caused by acidic by-products concentrated at the membrane surface. Also, it leads to reducing the active membrane area, and therefore decreased flux of permeate due to the formation of a low-permeability biofilm on the membrane surface. Other main consequences of biofouling decreased membrane permeability, increased the frequency of chemical cleaning, and the possible increase in replacement frequency of membrane [9, 19, 24, 40].

Research conducted by [41] investigated the biofouling effect on the sequentially declining in reverse osmosis membranes in terms of membrane operational parameters like membrane permeability, pressure drop in feed, salt rejection. Also, the consumption of temporal organic carbon (DOC) is being measured. It could be illustrated that all indicators were influenced by biofouling formation. Observed increase in the pressure drop in the feed channel (FCP) affected permeability and decline salt rejection, consequently leading to prove the FCP sensitivity to biofouling. Besides, [35] found that biofouling can accelerate the formation of scaling, and the mixed foulants can block the membrane pores, leading to a significant flux drop [35, 41]. In brief, biofouling has a potential effect on the following: differential driving pressure, feed channel pressure, energy consumption, the flux of permeate, membrane area, membrane permeability, the frequency of chemical cleaning, and salt rejection.

4.6 Biofouling alleviation and control

The control of biofilm formation is a complicated and controversial process involving the reduction of microorganisms within the RO water, monitoring strategies, and controlling factors such as nutrient concentrations and physicochemical interactions between microorganisms and membrane surface. Gulf Sea at the Saudi Arabia is known to be having biofouling major challenge uneasy to be controlled. It still the main challenge in membrane filtration installations. Curative or preventive measures are not always efficient. Flocculants provide a suitable habitat for microbial growth, whereas conditioning agents are potential sources of microorganisms and nutrients for the biofilm. Another source of microbial contamination is the piping, storage tanks, and treatment systems before RO, such as ion exchangers and active carbon filters. Biofilm can grow in very low-nutrient habitats with TOC levels as low as 5–100 µg/L. In practice, several methods for biofouling control have been

investigated, such as the application of the pretreatment before SWRO to remove bacteria and biodegradable organic matter, dosing of biocides, and limiting essential nutrients such as carbon and phosphate [9, 40, 42–44].

Membrane cleaning as a method of biofouling control typically done when there is a significant decrease in differential pressure drop or permeability. Principally, cleaning process involves removing and/or destroying of the biomass accumulating on membrane surface to reserve membrane permeability. Cleaning process can be applied physically or chemically. Physical cleaning was usually performed before chemical cleaning, involving flushing of air and water. It requires applying pressure mechanically, attributing to the removal of all non-adhesive fouling-based. Membrane manufacturers suggest different chemical agents' forms for cleaning purposes (e.g. alkaline, acids, biocides, enzymes, and detergents). Such process is efficiently eliminating or deactivating non-accumulating microorganisms. Therefore, the residual inactive biomass can be consumed as food by survived bacteria leading to bacteria regrowth acceleration. Base/acid cleaning removes organic foulants on membranes and destroys the microbial cell walls. Metal chelating agents and surfactants were used to disintegrate EPS layers by removal of divalent cations and solubilization of macromolecules, respectively. The efficiency of cleaning agents to remove biofouling is limited because the EPS layer is recalcitrant against cleaning agents. Improvement of cleaning efficiency difficult, particularly for aged biofilms. Membrane cleaning frequently removes only part of the fouling layer and cleaned membranes, therefore, provide a suitable environment for swift microbial colonization. Thus, cleaning processes (physically and chemically based) may partially result in biofouling reduction on the short run without sustainably controlling biofouling on the long run [8, 45–47].

Control of bacterial growth by chemical disinfectants depends on many factors, such as chemical concentration, its mode of action, contact time, the density of organisms, and TSS of feed water. These factors make it extremely difficult to attain absolute disinfection. Besides, chemical disinfectants like chlorine and its derivatives may be hazardous to health. Chlorine is known to oxidize and degrade the humic substances in seawater, thus, resulting in smaller molecules, which are AOC. The AOC is a good nutrient source for marine bacteria, and under such status could also lead to rapid biofilm formation in SWRO plants. Chlorination may foster the formation of trihalomethanes and other chlorinated by-products, which are carcinogenic [48].

Many researchers have concluded that biofouling is inevitable and tend to be difficult to prevent with having the focus shifted towards control strategies aiming to achieve: biofilm formation delay, biofilm accumulation impact reduction or delay on performance, and finally removing biofilm via advanced strategies of cleaning. For many reasons, biofouling control tends to be challenging. As such, various methods were developed towards treating biofilm formation on membrane surface and/or mitigating biofouling effect in general. Instantly, some strategies were applied including: membrane flushing or cleaning, application of chemical additives to target bacterial cell or extra-cellular matrices, membrane surface modification, limiting nutrient content, and the quenching of quorum. All previously mentioned methods have limitations and may result in unwanted membrane degradation [14, 18, 21, 49, 50]. As part of chemical treatments with biocides in addition to anti-microbes were applied mutually as part of industry practices. Chemically-based cleaning are known to be affecting exclusively the top layer of biofilm by colonizers. The effect of nutrient levels and possible manners to control membrane biofouling poses another potential solution for many membrane installations and should be further investigated. Biofouling impact on membrane efficiency is potentially minimized through a combination of strategies involving early identification,

preventive cleaning, substrate limitation for delaying biofouling built-up, and cleaning procedures optimization towards effective biofilm removal [14, 41, 50].

Based on the current knowledge, membrane surface modifications tend to be incompatible for control biofilm formation in full-scale membrane operations because of the drag force that transfers bacteria and nutrients to the membrane surface. As various components are moved to the membrane surface by the drag force, they are easily covered, and membrane surface modifications are rendered less efficient. By applying comprehensive pretreatment, therefore, biofouling can be limited but not eliminated. Practically, membrane biofouling prevention tends to be fully or partially achievable by better pretreatment in new desalination systems. Yet, it might be essential to have old, insurgent biofilms and prolonged membrane operating plants dispersed sufficiently. Most existing techniques in efficiently use an enormous spectrum of biocides and chemicals attacking bacteria to maturely disperse biofilms [14, 26, 28].

Practices presented as clean-in-place (CIP) tend to be less efficient and that successful. This is related probably to various reasons including: wrong selection of chemical, improper pH control, temperature, time of contact, unsuitable recirculating flow rates, and partial biomass removing. The repetitive biocides usage potentially lead to bacterial resistance inducing via bacterial cell modification on membrane surface, permeability deterioration of biocide, and biocides degradation by enzymes development, or gaining more resistance for biocide genes [28].

Strategies for Biofilm control applying enzymes towards degrading of EPS matrix including glycosidases, proteases, and deoxyribonucleases. However, these enzymes targeting specific strains, and their sufficiency in complex multi-species biofilms is yet to be established. Also, enzymes are costly and may not be so practical when applied for membrane treatment or flushing. On the other hand, a bad need for more efficient and cost-effective methods to eliminate biofilms and alleviate biofouling in SWRO processes do exist. As such, it is highly recommended to conduct researches investigating novel chemical cleaning agents which may positively contribute to overcome or mitigate biofouling [26, 28].

A study of [18] investigated the *Pseudomonas* quinolone signal (PQS) pathway role in biofouling control in reverse osmosis membranes. They inoculated *Pseudomonas aeruginosa* inside water feed as a sort of biofouling simulation. Conversely, a novel-based method on quorum sensing (QS) biochemically, has triggered considerable interest in controlling biofouling. Several advantages could be concluded, as it is characterized by high efficiency low operational pressure, practically contribute to hindering development capacity of the bacteria. QS Identified as cell-to-cell signals whereby microorganisms applied it for the sake of cell density sensing; reaching to a critical threshold level in terms of signals will trigger responsive sets of genes. Many researchers have found that the interference with such cell density-dependent communication technique formulate a biofilm potential controlling strategy.

The application of bacteriophage in synergetic way combined with some other traditional methods, such as cleaning proven to be mitigating *P. aeruginosa* biofouling-based sufficiently. Some alternative options are presented by bacteriophages. *Pseudoalteromonas*, for example, presented in high amount on a marine-based biofilm layer is potentially isolatable and known to be having some lytic footprint, highly efficient. Lastly, it might be of interest to explore the bacteriophage treatment effectiveness in biofilm formation prevention instead of having the structure of biofilm removed. To this regard, bacteriophage activation may be limited by low cell density. Another bacterial hosts might be targeted by taxonomical families performing a more sufficient approach towards maximizing infection impact on the way to achieve biofouling mitigation [51].

In [51] research, the isolation of lytic bacteriophages was used to hinder *P. aeruginosa* growth in planktonic-based mode and varied pH, salinity level, and temperature. Accordingly, bacteriophages were found to be optimally infective with 10-times infection multiplication under salinity mode. It illustrated that the lytic has reasonable abilities over experimental testing temperatures (25, 30, 37, and 45 °C) and pH range of 6–9. When exposed to bacteriophages, Planktonic *P. aeruginosa* found to be significantly exhibiting a longer lag mode and low rates of specific growth, taking into account the application of bacteriophages to *P. made* in subsequent manner. The biofilm presented by *aeruginosa*-enriched was determinant to lowering the relative amount of *Pseudomonas*-related taxa from 0.17 to 5.58% in controlling to 0.01–0.61% in processed communities of microbes. The findings illustrated the potential application of bacteriophages as a biocidal agent to achieve the mitigation of unwanted *P. aeruginosa* associated with issues in seawater-based applications [51].

In [26] study, biofilm amount and characterization were analyzed concerning membrane performance applying acid/base cleaning. Generally, cell and tissue of the bacteria deactivate chemical agents used in cleaning process to remove mainly the biomass related to biofouling. Chemical-based reactions like dispersing, chelating, solubilization, suspension, peptisation, sequestration, and hydrolyzing are observed during cleaning process. Cleaning by Alkaline-based solutions like Sodium hydroxide was also applied in this study for three types of biofilm to explore biofilm removal efficiency as well as illustrating EPS matrix role. They concluded that with minimum biomass amount at low substrate concentration cleaning was not as efficient as with high substrate concentration, with same observed phenomena for membrane performance restore [26].

While [43] describes the biofouling monitoring technology of the “Megaton Water System” project and verifies the technology in the pilot and real plants in Al Jubail, Saudi Arabia. Biofouling monitoring technology refers to the community of bacteria composition change by chemical usage of the Membrane Biofilm Formation Rate (MBFR) was applied to this project was a positive indication of a reliably system design and operation. Such monitoring technology could be applied to achieve plant operational and reliability improvement throughout the overcome of biofouling issue. It could also assist in environmental impact reduction and lower plant production costs through chemical-free injection [43].

According to [52] study, they developed a simple method where a combination of bubbling and cleaning-based on frequent addition of hydrogen peroxide (H_2O_2) at lower concentration level at feed water. The same approach was also explored with the use of CuO or PP spacers. The dosage of 0.3% (w/w) H_2O_2 being applied periodically at 12 h intervals resulting in having no increase in FCP in the tested system, also an indication referring to the tangible biofouling lacking with intermittent H_2O_2 dosing. For tested fouled membranes fouled over a period of eleven days, a single dose of 0.3% (w/w) H_2O_2 applied and successfully eliminated almost all spacers and membranes accumulated biofilm in few minutes demonstratively by a FCP of 69% (CuO spacer) and 54% (PP spacer). The biofouling reduction was primarily due to the high shear created by the generated oxygen bubbles in the system, combined with the disinfection effect of H_2O_2 . The reasonably low cost of \$0.009/m³ from intermittent H_2O_2 dosage was not more than 0.8% of overall assumed cost and 6.5% out of pre-treatment cost, allowing for economical accepted approach to overcome biofouling [52].

It seems that dechlorination water, activated carbon, cartridge filtration, UV irradiation, ozone treatment, hydrogen peroxide, detergents, alkaline, sodium bisulfite, and hot water sanitization are effective techniques and limitations to control biofouling.

5. Conclusion

Biofouling in SWRO membranes continues to be problematic for operation and maintenance quality. It plays an essential role in the fouling of the membrane parts in full-scale and pilot-scale plants, and it's significant to reduce its occurrence by prediction and prevention. The study demonstrates the RO membrane biofouling mechanisms and the effective fouling control strategies within seawater desalination, where biofouling is a critical drawback. The study aims to evaluate microbial fouling (biofouling) to understand its effect on RO membrane performance. The study highlighted the composition of the microbial community and the functional potential of the RO membrane biofilm. In general, biofouling has affected all performance indicators. The selection of pretreatment seems to be a factor affecting the microbial community composition and functional potential. Analysis of the biofilm bacterial community has shown that seasonal changes in water quality influenced the biofouling bacteria.

The results showed that the accumulation of biofilms on membrane surfaces remains the key obstacle for high-pressure membrane filtration. For future research, it is significant to describe the cleaning agent and cleaning frequency. Also, measuring feedwater temperature, determine the location of the membrane element, and the sampling location at the membrane. These comprehensive researches will use to establish an integrated strategy to control biofouling. Biofouling control should concentrate on improving low fouling feed spacers, and the hydrodynamic conditions reduce the effect of biomass accumulation.

We conclude that to maintain plant productivity and membrane recovery it is necessary to increase the membrane cleaning frequency. In the CF and RO membrane, the microbial regrowth rate is a significant factor that impacts the biofouling rate. We recommend further searches of the strategy of balancing the nutrient levels as a solution for several membrane installations to control membrane biofouling. To measure biofouling, it needs for real tool, sensitive pressure drop data, and systematic methodology. Therefore further studies related to avoiding adverse biofouling processes will be valuable to investigate specific microbial members in more detail using biofilm monitoring and control strategies. Finally, additional SWRO research and development are critical for the efficiency of this growing industry.

Abbreviations

AHL	N-acyl-homoserine lactone
AOC	Assimilable organic carbon
ATP	Adenosine Triphosphate
BDOC	Biodegradable Dissolved Organic Carbon
CF	Cartridge Filters
CIP	Current Clean-In-Place
DOC	Temporal Organic Carbon
DP	Differential Pressure
EPS	Extracellular Polymeric Substances
FCP	Feed Channel Pressure
H ₂ O ₂	Hydrogen Peroxide
MENA	Middle East and North Africa
MFS	Membrane-Fouling Simulator
µg L ⁻¹	Micrograms Per Liter

mg L ⁻¹	Milligrams Per Liter
MSC	Microbial Support Capacity
NDMA	Nitrosodimethylamine
PQS	<i>Pseudomonas</i> Quinolone Signal
PX	Pressure Exchangers
QS	Quorum Sensing
RO	Reverse Osmosis
SDI	Silt Density Index
SWRO	Seawater Reverse Osmosis
TEP	Transparent Exopolymer Particles
TOC	Total Organic Carbon
TSS	Total Suspended Solids
UF	Ultrafiltration
UV	Ultraviolet

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