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Review Research

APPLICATIONS AND CHALLENGES OF THE REVERSE OSMOSIS MEMBRANE PROCESS: A REVIEW

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Abstract: Reverse osmosis is one of the most prevalent methods of generating potable water owing to its low power usage, excellent rates of contaminant removal, simple design, large output capacity, and much cheaper initial and maintenance costs than comparable alternatives. In this review, the most important published research related to the reverse osmosis process was reviewed. It was found that the majority of reported studies were related to using the reverse osmosis process for water desalination and wastewater treatment. Research has proven that the reverse osmosis process is a very effective method for desalinating water and treating industrial effluent containing heavy metals, organics, and other pollutants. Fouling was found to be one of the greatest obstacles encountered by the reverse osmosis method in water treatment, which raises operating costs due to the need for frequent cleaning, reduces the membrane's lifespan, and reduces the permeate flux. In general, microfiltration/ultrafiltration pretreatment and backwashing were among the most effective strategies suggested by researchers to reduce fouling and ensure the longevity and proper operation of the system.

Keywords: *Backwashing; fouling; membranes; pretreatment*

1. Introduction

Water scarcity has become one of the greatest concerns. Ineffective water policies, water body pollution, unsustainable population increase, and climatic changes are the main contributors to water scarcity [1]. Water processing methods and wastewater treatment processes can help get rid of a wide range of contaminants, which is part of the solution to the growing amount of pollution in water [2]. Membrane is one of the most broadly implemented techniques for water treatment [3]. Membrane processes include microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) [4]. The RO method is presently regarded as the most trustworthy technology for desalinating water and wastewater treatment owing to its high energy efficiency, simple design, great production capacity, and high rate of contamination removal [5]. The RO system usually has four main parts: the intake system, the pretreatment system, the RO system, and the post-treatment system [6]. Conventional RO membranes are made of thin film composite polyamide (TFC-PA), which is made of three layers: a polyester non-woven layer, a layer that provides support, and a thin polyamide surface layer [7]. Due to these membranes' superior performance, which includes their extremely high permeability and salt-rejection

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characteristics, desalination frequently employs them [8]. Nonetheless, fouling and concentration polarization remain key problems for RO applications [9]. Fouling has a negative impact on membrane performance because it decreases filtrate flux, boosts operating pressure, shortens the lifespan of the RO membrane, and thus raises the cost of producing water [10]. Generally, fouling may be divided into four types: particulate, organic, inorganic, and biofouling [11]. Methods for fouling reduction include pretreatment of feedwater, membrane modification, membrane cleaning, and the adoption of fouling-resistant alternative processes [12]. Globally, there is a growing commercial interest in RO technology as a result of ongoing process advancements, which relate to membrane characteristics, module development, feedwater pretreatment, and energy recovery technologies [13].

This paper aims to summarize recent advances in the RO process and highlight areas in which more research and innovation are required. This review also addresses the RO applications, outlines the problems of RO, and presents cutting-edge solutions for fouling control, such as pretreatment and membrane cleaning.

2. Literature Review

2.1. Previous Research on Using the RO Process to Remove Pollutants from Wastewater

The use of RO technology to remove contaminants from water, primarily from industrial wastewater, has been the subject of recent investigations. Examples of employing RO process to remove various pollutants are shown in Table 1.

2.2. Prevention of Fouling Studies

Fouling is a significant challenge to the effective performance of RO systems [20]. Considerable attempts have been made to reduce RO process fouling, which is mentioned in Table 2.

2.3. Effect of Pretreatment on RO Performance

The effectiveness of water pretreatment has a direct impact on RO performance. The performance and lifespan of a membrane are closely related to the quality of the feedwater. Fortunately, prior treatment of the feedwater could be able to resolve these problems and keep the RO process sustainable [25].

2.4. Effect of Backwashing on RO Performance

Due to the RO backwash cleaning method's effectiveness and environmental friendliness, it has recently grown in popularity [29]. Table 3 depicts the RO process's pretreatment and backwashing research studies.

2.5. Autopsy Studies for Fouled RO Membranes

Membrane autopsy can reveal the type and causes of fouling, assisting in the development of the most efficient cleaning techniques to prevent it in the future [31]. The most commonly used tools in fouling layer investigations are scanning electron microscope (SEM) image, which is performed to study the morphology of fouling, and the atomic force microscope (AFM) spectra, which are employed to determine membrane surface roughness and changes in fouling layers. An energy-dispersive X-ray spectroscope (EDXS) and SEM picture are used together to determine the chemical composition of fouling [32]. Another spectroscopic tool is Fourier transforms infrared spectroscopy (FTIR). Table 4 provides a summary of several papers on fouled membrane autopsy that have been published.

Table 1. Examples of the removal of various pollutants by the RO process.

Pollutant	Study Results	Ref.
Heavy metals (Cd^{+2})	The membrane's negative charge gradually neutralized due to the ionic strength of the feed solution, which decreased the membrane's capacity to extract cadmium. At pH equal to 4 or higher, with a low Cd concentration in the feedwater, higher rejection rates were observed.	[14]
Heavy metals (Fe, Zn, Mn)	Whenever the pH and pressure were ideal, RO membranes were able to efficiently remove a significant amount of Fe, Zn, and Mn from industrial effluent. Additionally, the RO process performed worse when the feedwater had additional heavy metals and components.	[15]
Heavy metals (Ni^{+2}, Pb^{+2}, Cu^{+2})	Heavy metal rejection and permeate flux rejection demonstrated linear correlations with induced pressure, pH, solution temperature, and feed flow rate when it comes to removing heavy metal ions, but inverse relationships with feed concentration.	[16]
Emulsified oil	When the emulsifier oil concentration in the feed was raised, it was discovered that the permeate flow and water content in permeate were decreased. The response was temperature-dependent, and the permeate flux was decreased as pressure was raised.	[17]
Ammonia	Separating ammonium from wastewater using the RO was successful. With a 96.9% recovery rate, the portion of ammonium in the feed decreased to 0.2 mg/l.	[18]
Fluoride and phosphate	For synthetic wastewater and real wastewater, RO membranes were able to reject over 80% and over 96% of fluoride, respectively. Phosphates, on the other hand, were rejected in amounts more than 95% for synthetic wastewater and 97% for actual wastewater.	[19]

Table 2. Research on reducing RO membrane fouling.

Methods	Study Results	Ref.
Development of a novel anti-scalant	Calcium phosphate scaling was effectively inhibited in RO units for wastewater reuse using the anti-scalant.	[21]
Surface modification	Exterior amine functions were deposited over a polyamide TFC membrane using a low-pressure plasma method, and silver nanoparticles were subsequently bonded to this membrane, which led to increased antibacterial performance.	[22]
Surface coating	The coated RO membrane's surface was given a more hydrophilic appearance and was neutrally charged by a cationic phosphorylcholine polymer anti-adhesive coating.	[23]
Development of a new RO membrane	Irradiating metal organic framework (MOF) nanocrystals with rays of gamma generated silver nanoparticles, which were then integrated into layers of polyamide. The fabricated membrane has excellent antimicrobial properties.	[24]

3. Reverse Osmosis Process

A common membrane technology for treating water is reverse osmosis. It has been extensively employed in a variety of operations, including the treatment of brackish and seawater, the treatment of sewage, and the creation of ultra-pure water. It is employed for the separation of undesirable ions, salts, microbiological components, organic materials, and inorganic materials from water [37]. The RO process involves forcing water from the area with a high concentration of feed solution through the semipermeable membrane to the region with a low concentration of solution by exerting pressure to the area with a high concentration of solution that is greater than the osmotic pressure (Fig. 1). Because of this, water that passes through the membrane into one compartment is mostly pure, while dissolved solids are rejected in the other compartment [39]. For RO, the nominal range of pore sizes is 0.0001-0.001 µm (0.1-1 nm) [40]. The majority of the time, RO has been used to remove pollutants with a molecular weight in the range of 150–250 Dalton, such as soluble organics, color, nitrate, and low-concentration dissolved solids [41,42]. In industry, dissolved contaminants can be removed using the RO process, particularly inorganic salts [43]. The applied pressure for RO is higher, ranging from 10-150 bar, compared to other filtering processes. The most effective pressure-driven desalination technology is RO because it uses NF membranes that can reject monovalent salts like sodium chloride (NaCl) [7].

Table 3. Pretreatment and backwashing of the RO process studies.

Method	Finding	Ref.
UF pretreatment	The UF pretreatment delivered excellent quality permeate water. For example, the SDI was lowered by 96.8% using UF.	[26]
UF pretreatment	The UF membrane system functioned effectively to remove COD, and RO had the ability to get rid of the phenol in the UF permeate.	[27]
MF/UF pretreatment	A two-phase membrane system could polish treated wastewater to be used in the District's feedwater pipeline.	[28]
The effectiveness of backwashing	The system was operated at various NaCl solution concentrations (6900, 14200, 27600, 50300, and 59700 mg/L) until it reached a stable state, at which point the operating pressure was shut off and backwashing was carried out. Up to the prescribed NaCl concentration, the collected volume rose; however, above the prescribed concentration, the volume decreased due to concentration polarization (CP) occurring on the permeate portion.	[30]
The effect of backwashing water concentrations	Different circulating water concentrations (20000, 35000, and 50000 mg/L) were used to investigate the effectiveness of backwashing. When the concentration of the circulating water was higher, the concentration polarization took place more quickly on the permeate side.	[29]

Numerous models can be used to explain how mass moves through RO membranes. The most accurate way to explain how RO membrane performance works is with the solution-diffusion model [44]. Water flows over an RO membrane in three steps according to the solution-diffusion model, often known as the "non-porous" model: absorption over the membrane surface, diffusion through the membrane thickness, and desorption from the membrane permeating the surface. Once a water molecule has been caught up by the membrane's surface, the difference in the concentration of water across the membrane causes the water molecule to move to the permeate side of the membrane. The water molecule is consequently freed from the membrane and contributes to the bulk permeate [45].

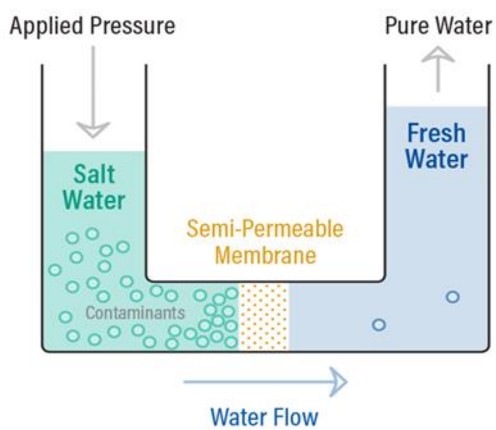

Figure 1. The principle of reverse osmosis process [38].

4. RO Process Challenges

Water produced by the reverse osmosis method is practically devoid of dissolved ions. There are some negative aspects, like short membrane lifetimes, limited selectivity, significant capital and operational costs, the requirement for extensive pretreatment, and handling the brine solution and its potential issues. Concentration polarization and fouling are two issues that RO membrane water filtering systems encounter [46].

4.1. Fouling

Filtered particles that precipitate on the membrane's surface and build up as foulants over time cause membrane fouling [7,47]. Fouling of RO membranes is commonly considered to be the most critical problem in the design and operation of RO membrane systems. Water flux across the RO membrane is reduced if the membrane becomes fouled because of increased mass transfer resistance [48]. In order to provide the greatest possible membrane performance and reduce costs, accurate forecasting and the total eradication of fouling are essential [37]. The problem can be resolved by changing the operating parameters, using anti-scalants, and washing the membrane to remove the fouling layer. Surface modification and material selection can lessen fouling tendencies [49].

Membrane fouling is affected by the feedwater characteristics, membrane properties, and operational conditions [50]. However, fouling is highly influenced by the quality of the pretreated feedwater (Fig. 2). As a result, a good pretreatment approach may greatly lower the membrane's fouling proclivity [39]. Fouling is categorized by the prevalent mechanism, involving complete pore blockage, standard blockage, intermediate blockage, and cake layer development (Fig. 3), as well as whether it can be cleaned (reversible or irreversible), and by the substance generating it. Cleaning can get rid of reversible fouling, but irreversible fouling caused by organic fouling and biofouling is not affected by physical cleaning and is only eliminated by chemical cleaning [48].

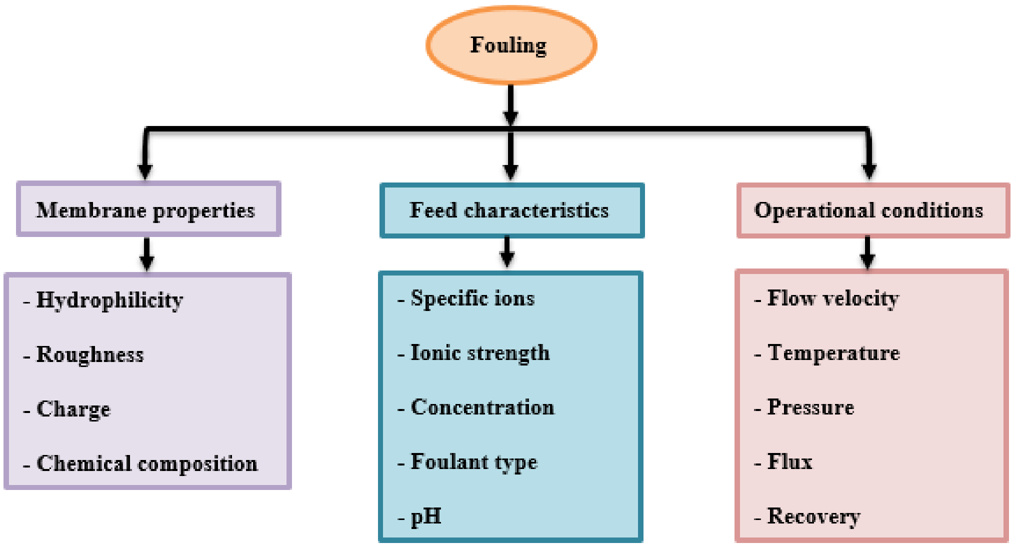

Figure 2. Factors influencing RO membrane fouling [50].

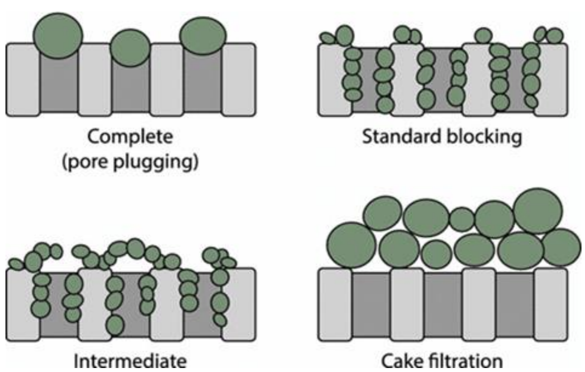

Figure 3. An illustration of the mechanisms of fouling [51].

Membrane fouling is classified into four types: organic; inorganic; colloidal; and biological [52]. When organic compounds gather on the membrane surface, organic fouling occurs [49]. Organic materials include humic, proteins, lipids, organic acids, and natural organic matter, which is produced by the breakdown of plants, microbes, and viruses [52,53]. Organic fouling was shown to be the most detrimental fouling and should be minimized as much as possible because the dissolved organic components in the feedwater serve as nutrition to the organisms whose development might contribute to significant biofouling [54]. Inorganic fouling, also known as scaling, is the deposition of soluble salts on membrane surfaces, which is one of the key challenges encountered throughout the desalination process [49]. Scaling occurs when the concentration of inorganic salts in the retentate exceeds their solubility limitations. These salts precipitate and form a scale on the RO membrane surface when the water becomes supersaturated [48]. The principal inorganics responsible for scaling are sulfates, fluorides, iron, carbonates, calcium, magnesium, and silica [10,49]. Furthermore, the membrane may become fouled by colloidal particles that are present in the feedwater and are deposited there. Colloidal foulants include inorganic pollutants and organic molecules [53]. Silt, clay, silica, and metal oxides make up the majority of the inorganic colloids in natural water, whereas proteins, oils, and humic acids make up the majority of the organic colloids [10]. Biofouling, or the attachment and growth of microorganisms on a membrane surface, is another hindrance resulting in a loss in membrane performance. This process raises the pressure drop across the membrane and reduces its permeability [12,53,48]. Images of four distinct types of fouling from a SEM analysis are shown in Fig. 4.

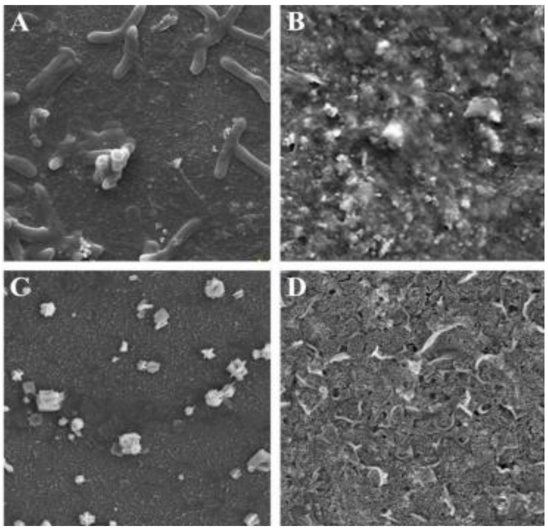

Figure 4. SEM images for (a) Biofouling; (b) Organic fouling; (c) Inorganic scaling; (d) Colloidal fouling [53].

4.2. Concentration Polarization (CP)

On the membrane surface, a buildup of salt ions is known as concentration polarization. As water passes across a membrane and salts are rejected, the retained salts might accumulate near the membrane surface, where their concentration progressively rises. The concentration buildup at the membrane will cause a diffusive flow of salts back into the feed (Fig. 5). Concentration polarization reduces the efficiency of the RO process by increasing osmotic pressure at the surface, increasing salt passage, decreasing water transport over the membrane, and promoting fouling [8]. It can be reduced by modifying the fluid's parameters (such as viscosity and temperature) and increasing the feed velocity. This lowers the solutes' osmotic pressure on the membrane, which necessitates applying less pressure [56].

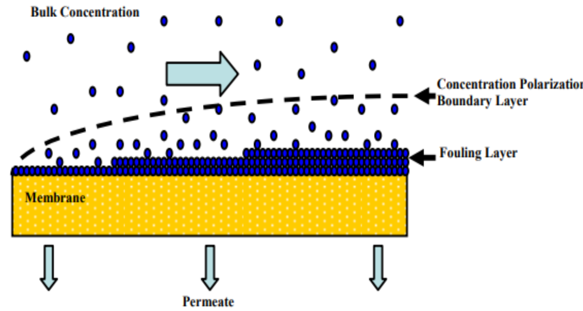

Figure 5. Diagram of membrane fouling and concentration polarization layer [55].

The permeate flux (J_W) may be expressed as (1) if it is assumed that CP occurs only on the feed side [57].

$$J_W = K_{OV}\,(C_f - C_p) \qquad (1)$$

where C_p and C_f are the concentrations of the permeate and feed solution, and k_{ov} is the total mass transfer coefficient.

The flux across the fluid layer close to the surface can be expressed as (2) [57]:

$$J_W = K_f\,(C_f - C_m) \qquad (2)$$

where C_m is the fluid boundary layer concentration and k_f is the fluid boundary layer's mass transfer coefficient.

Additionally, the flux across the membrane may be represented as (3) [57]:

$$J_W = K_m\,(C_m - C_p) \qquad (3)$$

where k_m is the membrane's mass transfer coefficient [57].

5. Ro Process Applications

There are numerous uses for the RO technique [39,44,58]. Below is a discussion of the two RO process applications that are most popular.

5.1. Desalination

The RO desalination market has quickly developed into the preeminent choice for new plant deployments. Seawater and brackish water are the two primary media for RO desalination [45]. The most energy-efficient method was thought to be RO. As a result, when energy efficiency is the main concern, RO is the preferred desalination technique. Additionally, RO is characterized by its exceptional productivity, high salt rejection, high water permeability, and inexpensive membranes [59]. RO is the most cost-effective process to desalinate water, which has contributed to a decline in desalination expenses over the last decade. Currently, RO makes up about 45% of the world's desalting capacity and 80% of all desalination plants around the world. One promising method of utilizing RO for water desalination is the use of closed-circuit RO (CCRO). Compared to conventional RO systems, CCRO reduces the required feed pressure, enhances membrane performance, and reduces the need for power recovery equipment [60].

5.2. Industrial Wastewater Treatment

RO was initially used to desalinate seawater and brackish water. Due to the increasing industrial need to recover valuable components from waste streams, reduce energy use, conserve water, and limit contamination, new uses of RO have become economically desirable [61]. Industrial operations release wastewater into waterways, which raises the most significant worries about contamination. Consequently, these wastewater must be treated before they can be disposed of [62]. Because heavy metals are toxic, poorly biodegradable, and readily incorporated into the food chain, heavy metal pollution of water from industrial operations is a global concern. Zinc, copper, nickel, mercury, cadmium, and chromium are toxic metals that are frequently released. Wastewater from refineries, coal-fired power plants, mining, tanneries, electroplating, and pesticides are the main sources of these minerals [63]. Oil is a different contaminant that is released by industrial operations and poses a significant concern [64]. Numerous sources produce oily wastewater, including offshore oil extraction, refining, and oil drilling [52]. It has been determined that using RO to remove salts, heavy metals, and organics from water is an efficient way to improve water quality. In light of this, it is appropriate for the treatment and recycling of wastewater streams [58,65].

6. Fouling Mitigation Methods

6.1. Pretreatment Methods

The water used to feed the RO system must be free of any impurities in order to prevent fouling [39]. Pretreatment lessens the need for frequent membrane cleaning, lowers the frequency of membrane replacement, and lessens the possibility that constituents in feedwater will damage membranes [45]. There are three methods of pretreatment: physical, chemical, and biological. Physical pretreatment can be accomplished by a variety of methods, including mechanical and thermal pretreatment [66]. Fig. 6 illustrates the conventional pretreatment methods that can be utilized before the membrane processes.

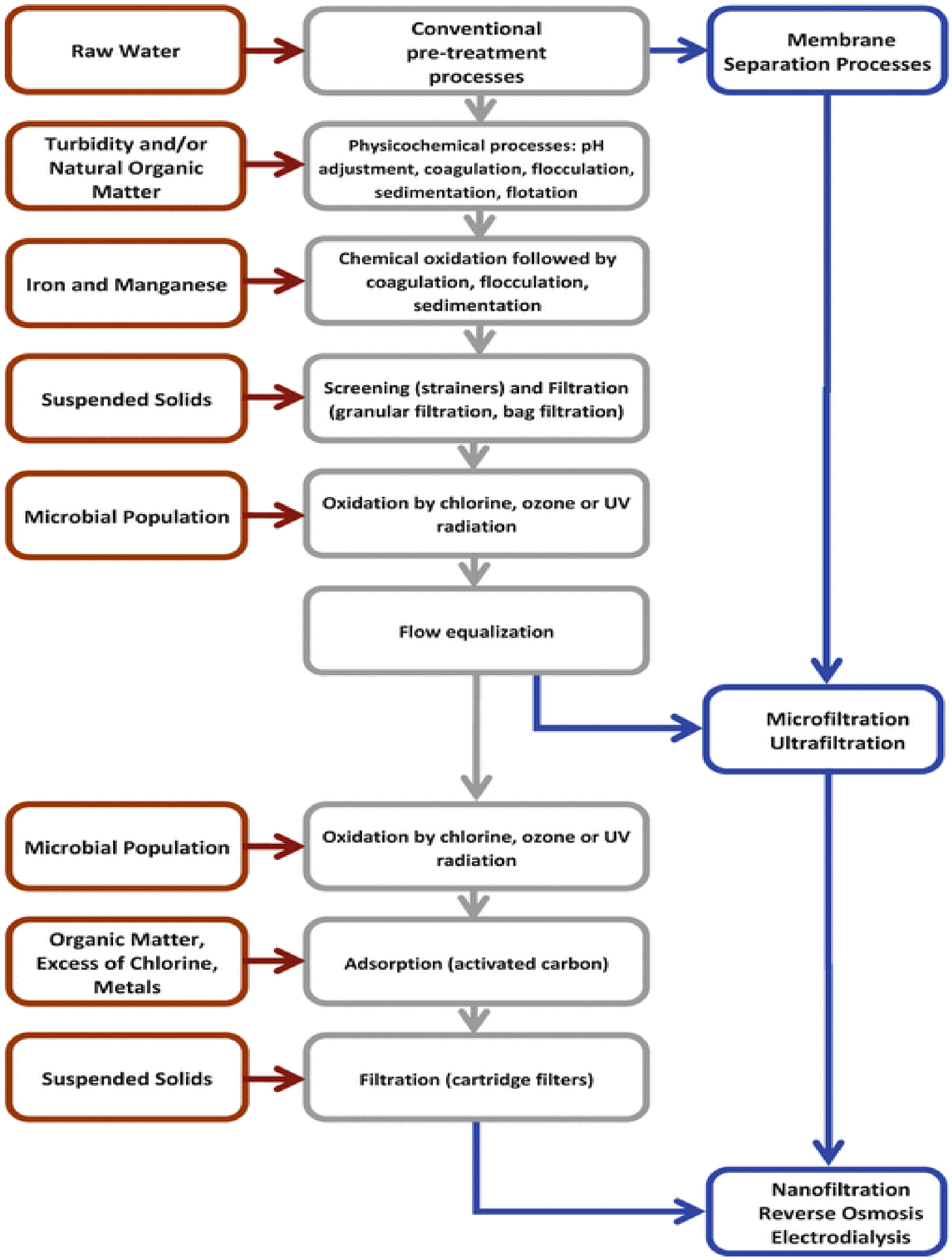

Figure 6. Conventional pretreatment prior to the membrane process [67].

However, slight alterations in a conventional treatment might have a detrimental influence on the RO process. For instance, chemical overdosing and incorrect use of chemicals can lead to permanent fouling and additional cleaning processes. According to these constraints, membrane filtration is frequently used as a pretreatment technique in RO facilities [39,52]. At the industrial scale, both MF and UF are employed as pretreatment techniques before the RO membrane, but UF currently dominates among the membrane pretreatment strategies in many research investigations, notably at the pilot scale [48]. In terms of filtration effectiveness, UF outperforms MF. This is primarily because UF has extremely small pores (0.01-0.1 µm), which facilitate the separation of colloidal particles and organic and inorganic compounds [52,60]. However, both MF and UF are effective membrane processes for the pretreatment of the RO system to reduce the concentration of suspended solids, decrease the capital and operating expenses of the downstream RO process in terms of size reduction, and enhance production capacity. Another economic advantage includes reduced chemical usage, less waste disposal, and a smaller footprint [60].

6.2. Cleaning the Membrane

Regular RO membrane cleaning is necessary, and the frequency will depend on the feedwater's quality. Cleaning assists in restoring permeate flux, which lowers salt passage [45]. Additionally, cleaning is an essential step in preventing the need for regular membrane replacement [48]. It may be either physical or chemical [68]. Physical cleaning entails exerting mechanical pressures that are larger than those required to hold foulants to the membrane in place, allowing for their removal from the surface [69]. Backwashing and forward or reverse flushing are the physical cleaning techniques. To eliminate contaminants from the membrane surface, forward flushing requires moving permeate water through the feed side at a high cross-flow velocity. In the operation of "reverse flushing," the permeate flush alternates for a brief period between forward (feed to brine) and backward (brine to feed) motion (Fig. 7). Colloidal particles can be effectively removed by forward flushing [70]. Conversely, the only methods of cleaning foulants that adhere to membrane pores are backwashing and chemical cleaning [48]. Backwashing involves flushing permeate from the permeate side to the feed side to remove the foulants from the surface and discharge them to the feed side, as shown in Fig. 8.

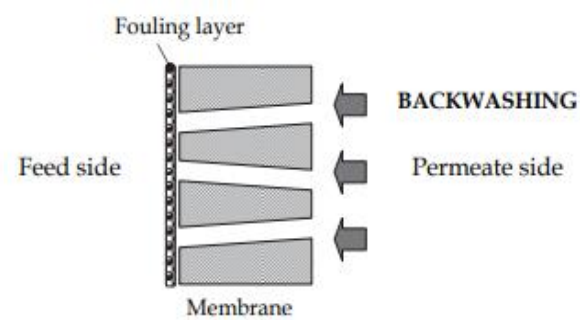

Figure 7. Flow direction for flushing both forward and reverse [70].

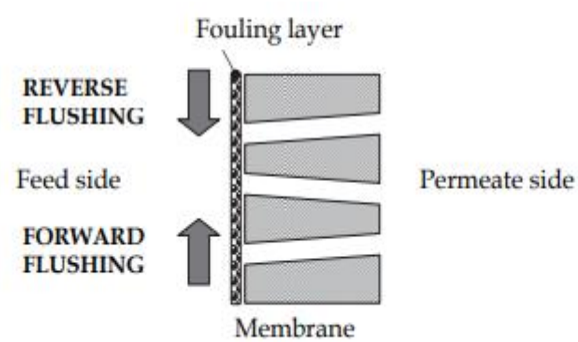

Figure 8. Flow direction during backwashing [70].

7. Concluding Remarks and Perspectives

Through our review, it was concluded that the RO process had the ability to desalinate water and treat industrial wastewater containing many pollutants with high efficiency. One of the main challenges faced by RO technology was fouling. Presently, a variety of fouling control strategies are in practice, and these approaches play a significant role in fouling reduction. Generally, pretreatment and backwashing were among the most successful solutions recommended by researchers to address the fouling issue that strikes RO membranes. Further studies on the behavior of fouling are required to get a clearer knowledge of fouling phenomena, which might give a stronger basis for the enhancement of fouling mitigation approaches. Reviewing the research also showed that the biggest challenge of the RO process was its energy consumption. Future research should therefore concentrate on finding techniques to utilize green or sustainable power, employing energy recovery techniques (for instance, using a pressure exchanger device), discovering the best solutions to the problem of brine handling to render the RO process far more achievable, and accomplishing the ideal situation, which is a zero liquid discharge In order to treat the brine water, another process (such as the crystallization process) is added to the RO system.

Conflict of interest

The authors guarantee that there is no conflict of interest with the publication of this review paper.

Author Contribution Statement

The first author wrote the paper. The second and third authors are the thesis supervisors.

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