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Review

The Treatment of Endocrine-Disruptive Chemicals in Wastewater through Asymmetric Reverse Osmosis Membranes: A Review

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Abstract: Endocrine-disrupting chemicals (EDCs) present in aquatic environment have been regarded as detrimental organic pollutants that pose significant adverse impacts on human health and the aquatic ecosystem. The removal of EDCs is highly desired to mitigate their harmful effects. Physical treatment through membrane-based separation processes is an attractive approach, as it can effectively remove a wide range of recalcitrant organic and nonorganic EDCs. In particular, the reverse osmosis (RO) process has shown promise in removing EDCs of various concentrations and from different sources. Recently, the development of innovative asymmetric RO membranes has become the forefront in this field. Various membrane modification strategies have been commenced to address the limitations of commercial membranes. This review provides an overview of the recent advances in asymmetric RO membranes for EDC removal from water and wastewater system. The potential areas of improvement for RO processes and RO membranes are also highlighted. Based on the existing literature using RO for EDC removal from water, the most investigated EDCs are bisphenol A (BPA) and caffeine in the concentration range of 200 ppb to 100 ppm. Polyamide RO membranes have been shown to remove EDCs from water bodies with a removal efficiency of ~30 to 99%, largely depending on the type and concentration of the treated EDCs, as well as the properties of the RO membranes. It has been demonstrated that the performance can be further heightened by tailoring the properties of RO membranes and optimizing the operating conditions of the RO process.

Keywords: endocrine-disrupting chemicals; reverse osmosis; wastewater treatment; asymmetric thin-film composite membrane

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1. Introduction

The increase in various anthropogenic activities has introduced new pollutants into the environment through different routes. On the other hand, the advancement of industrialization has also led to the generation of various chemicals, including endocrine-disrupting chemicals (EDCs). EDCs are a class of emerging contaminants that has attracted attention from the public and scientific community as they have been increasingly detected in various water matrices. As an important component in the production of plastics, healthcare products, and pesticides, the widespread use of these commodities in modern society has resulted in increased human exposure to EDCs [1]. The most common types of EDCs found in aquatic environment are bisphenol A (BPA), phthalates, and perfluorinated compounds [2]. These compounds are produced through various industrial processes. These chemicals are produced on a large scale and are used in a wide range of applications, including the production of plastics and coatings. They can easily enter the environment through various pathways. EDCs have been classified as hazardous substances due to their ability to disrupt the endocrine system and cause adverse effects, such as reproductive dysfunction, cancer, and neurological abnormalities. Currently, EDC compounds are unregulated pollutants and are typically present in relatively low concentrations (typically in the mg/l range) [3]. Despite their negative impacts on humans and the environment, the use of EDCs in the manufacturing of various products is still inevitable. It has been well established that EDCs can enter the environment through wastewater plant discharge and runoff [4,5]. Owing to their significant negative impacts on human health and the environment, studies on EDCs have surged in the last 5 years, focusing on various aspects, including identification of their sources, detection, effects, and treatment approaches [6]. Due to the multiple transportation routes and complicated interactions with their surroundings, the severity of EDC contamination varies greatly among species, individuals, and localities [7]. It is crucial to evaluate the pollution levels of EDCs, identify possible risks, and enforce monitoring and treatment standards for safety.

The advancement of analytical tools has enabled the identification of various EDCs in terms of their structures and physicochemical characteristics [8,9]. This allows the proposition of suitable operating conditions and the selection or design of an appropriate membrane to maximize the treatment capacity. Treating EDC-containing wastewater is a straightforward approach to reduce the threats of EDCs to aquatic animals and the environment. EDCs in water and wastewater systems can be remediated via various biological, physical, and chemical treatment methods [10]. Among the potential EDC treatment technologies, membrane technology has shown great potential for the treatment of EDC compounds. Membrane technology is a physical separation process that uses a semipermeable membrane to remove unwanted substances from a fluid stream [11]. The membranes can be made of various materials, including polymeric, ceramic, or metallic materials or composites thereof. Membrane processes can remove EDCs effectively and produce high-quality treated water that is suitable for reuse. Such processes represent a flexible technology that can be tailored and retrofitted to meet specific treatment requirements. Various membrane-based processes, ranging from ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) to membrane bioreactors (MBRs) and electrocatalytic membranes [12–15], have shown great promise in effectively treating micropollutants including EDCs and pharmaceutically active compounds.

Touted as one of the most mature technologies for wastewater treatment and desalination, studies have shown that RO is also efficient in removing EDCs that are normally present in low concentrations in the aquatic environment. RO can remove up to 99% of EDCs and other contaminants, producing treated water of a potable standard. The structural and surface characteristics of an RO membrane are very important in determining its performance. While conventional asymmetric thin-film composite (TFC) membranes have been widely used in industry, tremendous efforts have been undertaken to develop novel membranes to enhance performance, especially in treating challenging wastewater such as EDC-containing wastewater. For instance, state-of-the-art RO membranes have been developed using nanostructured additives such as graphene derivatives to enhance membrane properties specific applications [16]. Another area of development in the RO process is in the design and engineering of the system, including the use of advanced controls and monitoring, energy consumption reduction, and performance optimization [17–19]. Although the RO process has shown promise in removing EDCs from water, an overview of the recent advancements of RO for EDC removal from the aqueous environment has not been performed. With the increasing concerns about the negative impacts of EDCs and the urgent need to address this issue, the aim of this review is to provide an overview of studies related to the use of the RO process for EDC removal. With this review, we seek to compare the effectiveness of various RO membranes in removing different types of common EDCs under different operating conditions based on existing literature. By assessing the performance and removal efficiency of state-of-the-art membranes, with this review, we intend to provide guidance to expand the application of RO for the removal of EDCs in actual settings and to identify potential areas for improvement and future research directions. The discussion presented herein is expected to help in the design and operation of RO systems for EDC removal by selecting the appropriate membrane and operating conditions.

2. Endocrine-Disruptive Chemicals: Occurrence, Impacts, and Treatment Technologies

EDCs are present in various forms in many everyday products, such as natural and synthetic hormones and their metabolites, pharmaceutical products, pesticides, personal care products, cosmetics, and food packaging. EDCs have been detected in different locations, as they enter the aquatic medium through different routes, including point or non-point sources, such as industrial wastewater, landfills, municipal sewage, and stormwater runoff. EDCs are normally classified based on their sources, functions, and effects and can inhibit or mimic the effects of the natural hormones found in humans and animals, in addition to acting as a substitute for these natural hormones, thereby deregulating their levels and imposing negative impacts on the health of affected organisms. Although an absolute cause–effect relation has not been established, research findings to date have indicated a strong correlation between EDC exposure and resultant long-lasting health issues of contaminated humans and wildlife [20]. Despite their extremely low concentrations, often in the range of ng/L, long-term exposure to EDC can disrupt the normal functions of the endocrine, growth, and reproduction system [21,22]. EDCs have also been regarded as a main contributor to gender shifts or cancerous growth in biota [23].

Several studies have examined methods for treating water and wastewater systems contaminated with EDCs. Treatments can be broadly divided into three categories, i.e., physical, biological, and chemical approaches. The application of these treatment strategies has also been reviewed based on their ability to remove and degrade EDC compounds [7,24,25]. EDCs can be removed through conventional methods including flocculation, precipitation, and adsorption [26–28]. In particular, the protection of water bodies that receive effluents can be guaranteed through the elimination of EDC compounds via wastewater treatment plants. Nevertheless, conventional wastewater treatment plants are not intended for EDC removal; hence, most existing treatment plants cannot effectively remove EDCs from wastewater. Due to their incomplete removal in wastewater treatment plants, a wide range of EDCs may be released into the environment through the effluent of these plants, potentially resulting in adverse effects on biota and ecosystems. Investigations on the treatability of EDCs in conventional wastewater treatment plants indicated that the removal capability is highly dependent on the process and the respective operating parameters [29]. Post-treatment processes such as advanced chemical oxidation processes are required to further eliminate EDCs [30,31]. Photocatalysis is a promising chemical method for the degradation of EDCs [32,33]. However, the formation of EDC byproduct residuals during photocatalytic reactions is often a major concern. Biological methods have been established to treat EDCs, such as the use of hormones [34]. Biodegradation through bacteria and algae is also capable of degrading a considerable proportion of EDCs, but the process is less effective in eliminating nonorganic EDCs [35]. In terms of physical approaches, the use of membrane filtration processes as a physical treatment method for EDC removal is particularly effective and does not require chemical disinfection. Membrane processes, especially NF and RO, have been evidenced as a highly efficient technology for EDC removal when the appropriate membrane materials are used and the operational conditions are carefully optimized [36]. Adsorption is another important physical method to remove EDC compounds from aqueous media, with growing interest in the development of biodegradable polymers and their nanocomposites to serve as effective adsorbents for the elimination of EDCs from wastewater [26].

Among the abovementioned technologies, membrane-based processes are a promising option for the removal of EDCs due to their several advantages. Compared to chemical approaches, membrane processes require minimal chemical addition, which reduces the environmental impacts of the treatment processes and the formation of oxidation byproducts. Compared to physical processes such as adsorption, membrane-based processes have a smaller footprint and can be designed in a modular fashion, making them suitable for both centralized and decentralized treatment applications. Despite the efforts undertaken for the treatment EDC-containing wastewater, it is important to point out that none of the treatment methods can completely remove emerging contaminants [37]. For example, the incomplete removal of EDCs by biodegradation in wastewater treatment plants indicates that surface waters still pose a risk of receiving variable amounts of these pollutants [38]. In addition, the characteristics of EDCs in terms of solubility, hydrophilicity, and polarity are also crucial to establish a better understanding of the interactions and the possible formation of byproducts. The integration of physical, chemical, and biological treatments is becoming more important to intensify the removal efficiency for a wide range of EDCs while keeping the treatment economically and environmentally friendly. Figure 1 summarizes the effects of EDCs on human health, common sources of EDCs, and EDC removal techniques.

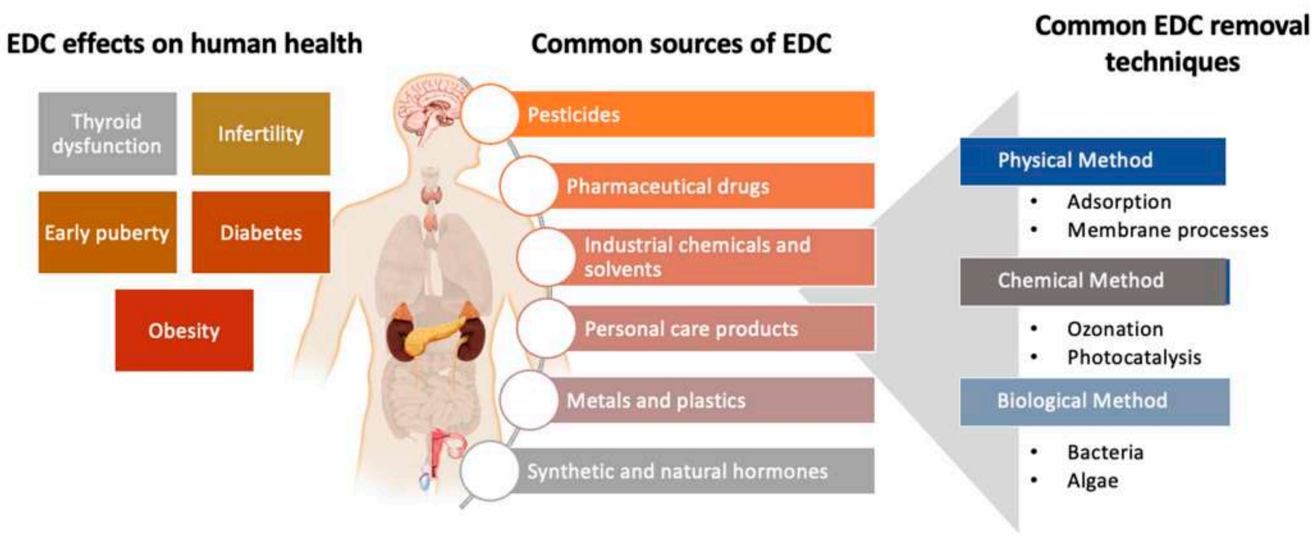

Figure 1. Summary of the effects of EDCs on human health, common sources of EDCs, and EDC removal techniques.

3. Advances in Reverse Osmosis and Asymmetric Reverse Osmosis Membranes

Pressure-driven membrane processes, which are classified as MF, UF, NF, and RO, are a promising solution for water and wastewater treatment [39–42]. During the filtration process, hydraulic pressure is applied to force water to permeate through the semipermeable membrane while rejecting the unwanted solutes as retentate. Among the membrane processes, RO plays a vital role in desalination and wastewater treatment processes due to its capability and reliability in rejecting almost all types of pollutants that are present in the feed water, generating fresh water that can be utilized for various purposes [15]. UF and microfiltration (MF) are widely useful in the treatment process but have limited capacity to remove EDCs. Nevertheless, when used as a pretreatment unit, UF can treat wastewater containing larger molecules and particles, whereas MF can remove bacteria and other microorganisms from the feed water. Some removal of steroidal-type compounds have been observed in association with these loose membranes [43]. Asymmetric polyamide TFC membranes dominate the current RO membrane market. Figure 2 shows a schematic diagram of an asymmetric polyamide TFC membrane and the typical thickness of the substrate and polyamide layer. TFC consists of a porous substrate that acts as a support and a selective layer that is responsible for separation. The polyamide-selective layer is typically fabricated through interfacial polymerization of two monomers, namely m-phenylenediamine in the organic phase and trimesoyl chloride in the aqueous phase. New monomers have also been explored for polyamide formation to customize the properties of the selective layer [44]. Over the last decade, tremendous efforts have been made in this field; approaches and modifying agents have been introduced to heighten the performance of modified membranes [45–47]. The primary goal of membrane modification is to address the inherent limitations of current commercial membranes in terms of the water permeability–solute rejection tradeoff, high fouling propensity, and poor resistance to chemicals such as chlorine and the oxidizing agents commonly used in conventional wastewater treatment plants.

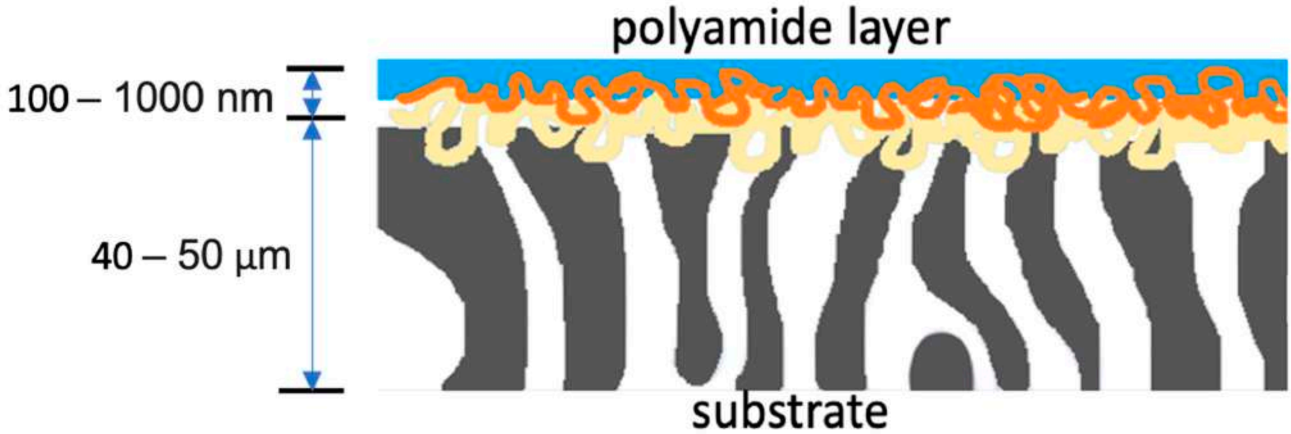

Figure 2. Illustration of asymmetric polyamide TFC RO membranes.

A wide range of modifying agents, including polymeric additives and nanostructured materials, has been used to achieve these purposes [16,48,49]. In general, hydrophilic modifying materials are highly desired, as the improved membrane surface hydrophilicity can effectively contribute to water flux enhancement and antifouling properties. As electrostatic repulsion is also an important solute rejection mechanism, the membrane surface can be modified with charged modifying materials to render the modified surface with the desired surface charge. Among the modifying agents used for the modification of RO TFC membranes, the incorporation of nanostructured materials of different dimensions to form so-called thin-film nanocomposite (TFN) membranes is a current focus of RO research [50]. From zero-dimensional metal and metal oxide nanoparticles to one-dimensional tubular structures, two-dimensional nanosheets, and three-dimensional framework structures, these nanostructured modifying agents demonstrate structural and chemical functionalities that can heighten the membrane performance. Various membrane surface and in situ modification techniques have been established for membrane modification to introduce modifying agents onto the surface of preformed RO TFC membranes or to incorporate them within the polymeric matrix during fabrication [51]. Physical techniques such as layer-by-layer coating and ontology doping involve physical interactions based on electrostatic force or hydrogen bonding between the modifying agents and the polymer [52]. On the other hand, chemical grafting can be performed on the surface of RO TFC membranes through the formation of covalent bonding between the reactive functional groups present on the membrane surface and on the modifying agents [53].

4. Removal of Endocrine-Disruptive Chemicals through Reverse Osmosis

Early studies on EDC removal through RO have been largely focused on evaluating the capability of commercial RO membranes to selectively reject EDC compounds such as bisphenol A (BPA) [54,55] and caffeine [56]; promising rejections of 75–90% and >95% have been reported for BPA and caffeine, respectively. Yuksel et al. compared the effectiveness of various commercially available NF and RO membranes for BPA removal from model solutions [57]. The polyamide-based dense NF and RO membranes investigated in the study, including NF 90, AD SWRO, BW30, and XLE BWRO, showed excellent performance, with a BPA rejection rate > 98%. Nevertheless, the NF membranes generally exhibited lower rejection compared to their RO counterparts. The results suggest that polyamide-based RO membranes are effective for removing BPA from water, but cellulose acetate-based membranes were not found to be as effective as the polyamide RO membranes. Similar findings were reported by Comerton et al., who observed that compared to commercial NF membranes, commercial RO membranes effectively removed over 90% of EDCs, including

BPA, equilin, estradiol, and oxybenzone [58]. The presence of organic matter and fouling may cause higher rejection rates, but a higher concentration of divalent compounds can lead to lower rejection rates of EDCs by the membranes.

Pilot-scale studies using commercial RO membranes provide a clear indication of the feasibility of RO membranes for EDC removal. Fujioka reported that the rejection of several types of trace organic compounds, including EDC estradiol, differed significantly among three tested RO membranes, i.e., ESPA2, TFC-HR, and TMG [59]. While there was a clear correlation between membrane permeability and conductivity rejection, this relationship did not extend to the rejection of most trace organic compounds. However, it is evident that the ESPA2 membrane, which has the lowest water permeability among the three analyzed membranes, exhibited consistently high rejection for a wide range of compounds. A more recent pilot study further confirmed the potential of commercial RO membranes (DOW-FILMTEC BW30-2540) in achieving high removal efficiency of pharmaceutically active EDCs, including caffein [60]. Mechanisms involved in the selective removal of EDCs by RO membranes were revealed in these studies. It is generally agreed that the rejection of EDCs is governed by many factors, especially the interactions between the membrane surface and EDC molecules. Important parameters include the molecular size of EDCs, which enables size exclusion effects and steric effects rendered by the membrane surface, which allows for repulsion of EDC molecules from the membrane. The log of the octanol water ($\log K_{ow}$) and dipolar interaction of the EDC compounds also play important roles in EDC rejection [61,62].

With evidence showing the potential of RO for EDC removal, efforts have been focused on tailoring the properties of RO TFC membranes to address the limitations of commercial RO membranes. In particular, high water flux has been achieved using TFN membranes incorporated with various hydrophilic modifying agents [63]. As shown in Figure 3a, Ahmad et al. developed a polyamide TFC membrane incorporated with one-dimensional titania nanotubes (TNTs) for EDC removal [64]. At a low BPA concentration of 10 ppm, rejection rates of 89% and 97% were reported for BPA and caffeine, respectively. The water flux was improved by more than 40% compared to commercial RO TFC membranes, indicating that the TFN membrane mitigated the water permeability and EDC solute rejection tradeoff. Figure 3b illustrates the role of tubular TNTs in facilitating water transport and EDC rejection. Improved water permeability and EDC rejection ability have also been reported for TFC membranes modified with silver nanoparticles (AgNPs) [65] and graphene oxide (GO) [66] for the removal of propylparaben and N-nitrosodimethylamine, respectively. Based on the incorporated AgNPs [65], Yang et al. reported a novel discovery of the formation of nanochannels that were roughly 2.5 nm in size around the AgNPs. The nanochannels resulted from the hydrolysis of trimesoyl chloride monomers and the subsequent termination of interfacial polymerization by the surrounding water layer. These nanochannels increased the water permeability of the TFN membranes by nearly three times compared to that of the neat membrane. Moreover, this membrane exhibited enhanced rejection against NaCl, boron, and the EDC compounds (propylparaben, norfloxacin, and ofloxacin) due to its concerted effects of size exclusion, Donnan exclusion, and hydrophilic interaction.

Table 1 summarizes the performances of RO membranes used for EDC removal from the aquatic environment. In general, most of investigations to date were performed at bench scale using small-surface-area flat-sheet membrane units tested using a dead-end filtration system in short-membrane operation times. For now, standardization in terms of feedwater characteristics and operating conditions is still impossible to enable direct comparative evaluation of different cases. Furthermore, bench-scale studies reported to date are largely based on the use of synthetic wastewater that does not reflect actual wastewater conditions. For instance, in a normal bench-scale setting, only selected EDCs are investigated, and the concentrations of EDC are significantly higher than those detected in actual wastewater or effluents. Based on the existing literature using RO for EDC removal from water, the most investigated EDCs are bisphenol A (BPA) and caffeine in the concentration range of 200 ppb to 100 ppm. Polyamide RO membranes have been demonstrated to effectively remove

EDCs, with a removal efficiency ranging from approximately 30 to >99%. The efficiency is largely dependent on the type and concentration of EDCs, as well as the properties of the RO membranes used in the process. It has also been evidenced that the development of new membrane materials and membrane surface functionalization have helped enhance the removal efficiency of RO membranes for EDC removal. Studies have also revealed the mechanisms underlying the removal of EDCs using RO membranes; several factors contribute to removal, including size exclusion and electrostatic repulsion. The relative importance of these mechanisms is likely to vary depending on the specific EDC being targeted and the properties of the RO membrane used in the system.

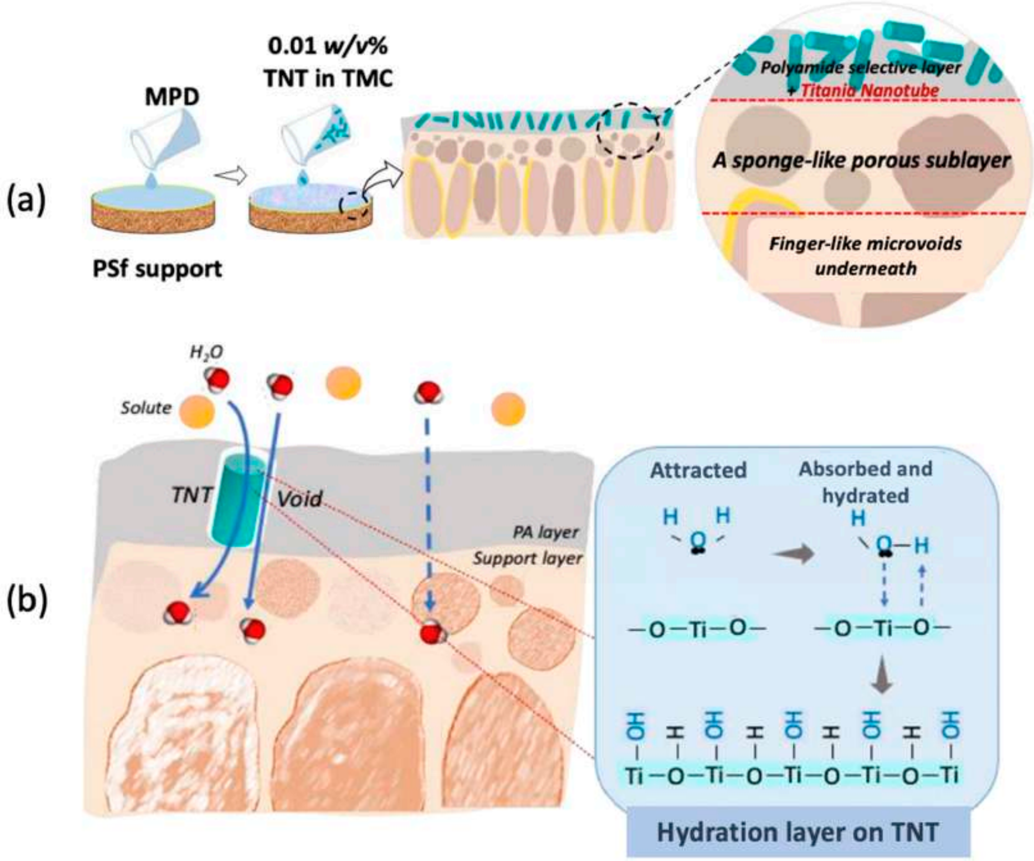

Figure 3. (**a**) Asymmetric polyamide TFC membrane incorporated with one-dimensional TNTs. (**b**) Schematic illustration of the role of tubular TNTs in facilitating water transport and EDC rejection [64].

Table 1. Summary of exemplary work using RO for EDC removal.

Membrane	EDC	EDC Concentration	Rejection (%)	Reference
BW30	BPA	50 ppm	>98	[57]
ESPA2	17α-estradiol	50 ppm	>98	[59]
BW30-2540	caffein	<1 ppm	~100	[60]
ESPA2	diuron	1 ppb	34	[62]
PA/TiO_2 TFC	BPA	100 ppm	90	[63]
PA/TNT TFC	BPA	10 ppm	89	[64]
PA/TNT TFC	caffein	10 ppm	97	[64]
PA/AgNP TFC	propylparaben	200 ppb	98	[65]
PA/GO TFC	N-nitrosodimethylamine	890 ppb	83	[66]

5. Challenges and the Way Forward

The results and findings reported to date have provided sufficient evidence of the capability of RO in treating EDC-containing wastewater. Although RO is a mature and commercially available technology for desalination and wastewater treatment, it is still confronted with several limitations and challenges, particularly for the treatment of emerging pollutants such as EDCs. Several strategies can be implemented to enhance the sustainability of the treatment process. The development of high-flux and antifouling TFC RO membranes is a crucial effort in achieving sustainability in this area. By maintaining the EDC rejection capability, the development of high-flux TFC RO membranes can address the permeability–rejection tradeoff and increase water productivity. Through the modification of TFC RO membrane surfaces, the fouling tendency of the membrane can be reduced, contributing to the reduction in the cost required for cleaning and membrane replacement. In addition, a considerable number of studies have been conducted with respect to the design of the RO process. Innovative RO processes such as pulse flow RO and semi-batch/batch hybrid RO have been established to enable high-recovery, high-flux, energy-saving, and zero-waste discharge. These concerted efforts are expected to promote the acceptance of RO as an alternative to existing wastewater treatment technologies for more effective EDC removal.

The transformation of laboratory findings to commercial implementation is a challenging process. Discrepancies have been observed due to the different experimental settings in RO membrane fabrications or the RO filtration set up. In some studies, only feed water spiked with target solutes and commercial membranes were investigated, whereas water matrix effects and membrane fouling were neglected. As a result, some important details such as the interactions of pollutants in the water matrix and the capability of the RO membrane to treat EDCs in ultra-low concentrations have been overlooked. Furthermore, the commonly observed issues in full-scale applications such as fouling and performance stability have not been considered in these studies. Therefore, the implementation and evaluation of the bench-scale optimized RO process at pilot scale are required to practically increase the reliability and accuracy of the treatment process.

Although RO is a mature and widely used wastewater treatment technology, the removal mechanisms of micropollutants such as EDC compounds through RO are complex and still not fully understood. Factors that can influence the rejection of EDC in RO include the dipole moment, hydrophobicity, and molecular size of the compounds. Furthermore, it is challenging to identify the underlying mechanisms of EDC rejection in real-world conditions due to the interactions between solutes and between solutes and the membrane. In this regard, the use of computational tools to provide in-depth understanding of the interactions among EDC molecules, the membrane surface, and surrounding aqueous media can be useful in predicting the performance of RO in treating EDCs. Several models such as rigorous mathematical models and artificial neural network models have been developed to simulate the rejection of EDCs by RO membranes under various operating conditions. The availability of these predictive tools, together with the experimental findings, can be used to confirm the rejection of EDCs with different characteristics. Artificial intelligence has become an increasingly important tool in scientific research, especially for data analyses, computer modeling, and machine learning [67]. In the context of EDC removal, artificial intelligence can help with the monitoring and control of the treatment process, thereby improving treatment consistency and reducing operating costs. In addition, artificial intelligence is helpful to identify and quantify EDCs that are present in a specific area, allowing for targeted treatment strategies.

Another challenge related to the application of RO as an EDC treatment technology is the negative effects posed by RO concentrate. Reverse osmosis concentrate is a highly concentrated solution of dissolved salts and other contaminants that are rejected by the RO membrane during the purification process. The issue with RO concentrates that contains rejected EDCs is that they contains a concentrated level of EDC compounds, which can have adverse environmental impacts if not handled properly. These EDC compounds can be reintroduced into water bodies if the concentrate is discharged directly into rivers, lakes, or oceans. RO concentrate can be treated using evaporation and crystallization techniques to separate the water from the salts and other solid substances, which is often an effective way to reduce the volume of waste stream and produce a solid waste that can be handled easily. However, this process can be energy-intensive. It is therefore recommended to explore sustainable methods for the complete removal of EDCs from RO concentrate. A sustainable option for treating RO concentrate is biological treatment, which involves the use of microorganisms to decompose EDC compounds in the waste stream. For instance, a bioremediation approach based on white rot fungus Trametes versicolor has been reported to be able to break down specific types of EDCs present in RO concentrate [68]. Biological processes are effective in removing a wide range of contaminants, but more innovations are required to shorten the treatment time.

Despite efforts to reduce the environmental load of EDCs, additional treatment processes have been associated with an increased cost of wastewater treatment. The operation of RO requires relatively high operating and maintenance costs compared to conventionally used physical processes. The cost of RO systems for EDC treatment is influenced by various factors, including the capacity of the system, the quality of the feedwater, and the level of the pretreatment required. Cost analyses of both-lab scale and pilot-scale research are essential to provide practical information about the economic feasibility of the proposed membrane-based EDC removal technology. These analyses can help to determine the total costs of operation, which include equipment, energy, maintenance, and membrane replacement. It is therefore recommended that cost analysis be conducted in consideration of the total life cycle cost, which includes the materials used for RO membrane fabrication and membrane testing. The cost of energy used during RO operation should also be estimated based on the energy consumption of the entire RO system. Additionally, the cost of managing the concentrate generated by the RO system and the treatment of EDC compounds in the waste stream can also be significant; therefore, careful planning is required to minimize the cost while ensuring compliance with environmental regulations. Overall, proper optimization of the membrane system design and operation conditions such as using a high-recovery membrane and optimizing the pretreatment process can help to reduce the cost of operation.

6. Conclusions

Despite the associated challenges and limitations, RO is still regarded as a useful technology for EDC removal. Studies conducted to date have revealed that membrane design and operating condition optimization are the two major directions that can heighten the performance of RO for EDC removal. On the other hand, the cost of membranes remains a major challenge, particularly for RO. Therefore, there is also a need for further research to reduce membrane costs while optimizing the performance of membrane technology to make such technology more accessible and affordable for widespread use in EDC treatment. With the current knowledge in advancing RO processes to address the current bottlenecks, it is expected that RO will continue to serve as an attractive candidate to treat EDC-containing wastewater at the commercial scale.

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Abbreviations

AgNPs	Silver nanoparticles
BPA	Bisphenol A
EDC	Endocrine-disrupting chemical
GO	Graphene oxide
MF	Microfiltration
NF	Nanofiltration
RO	Reverse osmosis
TFC	Thin-film composite
TFN	Thin-film nanocomposite
TNT	Titania nanotube
UF	Ultrafiltration

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