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POSSIBILITIES OF RECYCLING END-OF-LIFE RO MEMBRANE MODULES AS A LOW-COST ALTERNATIVE TO WATER TREATMENT

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This study explores the possibilities of recycling end-of-life reverse osmosis membranes as a significant low-cost alternative to water treatment, addressing both waste reduction and affordable filtration solutions. Although reverse osmosis membranes play a vital role in water treatment, the limited lifespan of membrane modules presents environmental and economic challenges. Reverse osmosis membrane modules consist of multiple layers - including polymeric membranes, support materials and adhesives - often combined with fiberglass or metal housings, which makes the separation of individual materials and recovery difficult. Currently, most end-of-life membranes are disposed of in landfills or incinerated, resulting in ecological issues and the loss of valuable resources. Therefore, the drive to recycle and reuse end-of-life membranes over recent years stems from a desire to maximize resource efficiency and lower their environmental impact. The ability to reuse end-of-life reverse osmosis membranes as well as downcycle them into membranes with nanofiltration or ultrafiltration properties is the most effective and promising solution, providing such membranes with effective levels of water permeability and pollutant rejection comparable to commercial membranes.

Keywords: end-of-l ife reverse osmosis membrane, low-cost water treatment, recycling

1. Introduction

Despite its importance in sustaining life and for human usage, water is very susceptible to contamination [1]. One of the most significant challenges facing the world in the 21st century is the rising issue of water availability, both in terms of quantity and quality. This problem has worsened as a result of climate change, population growth and economic development, which have exacerbated the pollution of water resources [2]. In response to water-scarce conditions, seawater and brackish water desalination has emerged as a key solution to facilitate economic development, providing high-quality water for various uses, including irrigation, domestic supply and in industry. In line with this, in 2019, there were 21,123 desalination plants operating worldwide, producing approximately 126.57 million m^3 of freshwater per day [3]. Alongside a forecasted Compound Annual Growth Rate (CAGR) of approximately 10.3% between 2020 and 2025, reverse osmosis (RO) desalination is poised for continued expansion. The dominance of reverse osmosis in the desalination market is largely attributed to its status as the most energy-efficient industrial technology currently available, proven by the fact that RO systems constituted 84% of operational desalination plants in 2018 and produced 69% of the world's desalinated water that year [4]. Furthermore, according to market forecast data, the RO market worldwide was projected to be worth $11 billion by 2021, showing a 10.9% growth rate compared to in 2016 [5].

However, the use of RO technology raises certain environmental concerns. Once RO membranes used in seawater desalination reach their relatively short lifespan (5-10 years), they become end-of-life reverse osmosis (EoL RO) waste, which is ultimately disposed of through landfilling or incineration [6]. Disposing of spent RO membranes via incineration or landfill poses environmental challenges [7]. The volume of this waste is substantial, with more than 840,000 RO membrane modules being generated annually and forecasts predicting over 2 million discarded units by 2025 [8]. The limited options for the disposal of EoL RO membrane modules, such as incineration or landfill, have created an environmental issue that necessitates the development of alternative handling solutions.

Recently, recycling has become the most desirable solution for disposing of EoL RO membranes. This includes directly reusing or converting them into different types of membranes such as ultrafiltration (UF) and nanofiltration (NF) ones. Various recycling methods can be applied to EoL RO membranes, each producing membranes with distinct characteristics. This paper discusses down-cycling methods for converting EoL RO

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Table 1: Summary of studies on the recycling of EoL RO membranes

Protocol	Membrane obtained	Permeability ($L.m^{-2}.h^{-1}.bar^{-1}$)	Salt rejection (%)	Ref.
Exposure to NaOCl, sonication for 30 mins	MF membrane	377.2	0.71 NaCl	[16]
Exposure to 300,000 ppm.h of NaOCl	UF membrane	59	< 1 NaCl	[17]
Exposure to 13,000-240,500 ppm.h of NaOCl	NF membrane	18	92 NaCl, 98 $MgSO_4$	[18]
Exposure to 50 ml of 0.5% NaOCl for 4h	NF membrane	27	62 Na_2SO_4	[19]
Exposure to 300,000 ppm.h of $KMnO_4$	UF membrane	68.1	11.1 NaCl	[20]
Exposure to 300,000 ppm.h of NaOCl	UF membrane	17.2	< 5 NaCl	[21]
Exposure to 150,000 ppm.h of NaOCl	UF membrane	18	< 5 NaCl	[22]

membranes into reconditioned membranes and presents their performance test results.

2. EoL RO membrane recycling methods

Thin-layer composite RO membranes - frequently employed in saltwater desalination, brackish water treatment as well as water recycling for residential and commercial uses - primarily utilize aromatic polyamides (PAs) due to their outstanding ability to separate substances. A layer of non-woven polyester, a microporous polysulfone (PSF) support and a dense PA layer are the typical components of these RO membranes [9]. Constant fouling by suspended particles, dissolved organic matter and solids as well as bacteria might cause the performance of RO modules to irreparably decline, moreover, ultimately lead to the end of their usable life. Recently, EoL RO membranes have been reused by cleaning the fouling and removing the PA layer, thereby reducing the filtration power of the membrane. Among different methods, downcycling is a common technique employed to treat EoL RO membranes and is discussed in the following subsection.

EoL membranes are chemically treated using downcycling methods to create recycled membranes directly with reduced separation accuracy. Specifically, the main method involves partly or completely removing the selective layer of RO membranes by often utilizing chemicals such as $KMnO_4$ [10], NaOCl [11] and H_2O_2 [12] to eliminate the polyamide coating from the fouled membrane. The most widely utilized chemical agent for downcycling EoL RO membranes is NaOCl, since polyamide material is susceptible to it [13].

Downcycling is achieved through careful regulation of the NaOCl concentration and duration of exposure or by specifying the desired NaOCl treatment strength, which is quantified in ppm.h [14]. The final properties of the membrane are a direct consequence of the concentration of and duration of exposure to free chlorine in the solution. The degradation of the PA layer caused by hypochlorite solutions leads to increased membrane permeability (L) and a reduction in the salt rejection coefficient (SR).

Despite these challenges, EoL RO membranes can be modified into NF-like membranes by carefully degrading their PA coating [15]. This involves an initial treatment with NaOCl solution to create UF membranes, followed by a layer-by-layer (LbL) polyelectrolyte deposition technique to achieve NF properties. Studies in which EoL RO membranes were transformed into microfiltration (MF), UF and NF ones are summarized in *Table 1*.

3. Application of recycled EoL RO membranes

Recently, several studies have been conducted to convert EoL RO membranes and use them for different purposes. In a 2024 study, Moreira et al. investigated the potential of recycled membranes for treating uranium-contaminated groundwater in order to produce safe drinking water [23]. Two EoL RO membranes denoted as NF-1 and NF-2 were subjected to various oxidative treatments with 440,000 and 220,000 ppm.h of NaOCl, respectively. The NF-1 membrane exhibited a permeate flux of 21.4 ± 0.3 $L.m^{-2}.h$ at 0.5 bar and achieved approximately a water recovery of 90%. However, after a recovery of 40%, the uranium concentration in the permeate was 0.03 mg/L. In contrast, the NF-2 membrane effectively removed uranium down to concentrations compliant with drinking water standards, as illustrated in *Figure 1c*. This module performed excellently since its contaminant levels remained below the maximum threshold, even at higher percentages of recovery. With a rejection rate of 71.6%, it closely met the expectations for nanofiltration membranes.

In another work, Wang et al. converted Si-Al fouled RO membranes into NF and UF-like ones using NaOCl treatment methods [19]. The results, depicted in *Figure 1a*, demonstrated that the water permeance of downcycled membranes considerably increased and the rate of Na_2SO_4 rejection gradually declined over extended periods of exposure. Furthermore, as depicted in *Figure 1b*, a 24-hour alkaline wash and subsequent NaOCl treatment yielded a loose, NF-like membrane with a water permeability of 27 $L.m^{-2}.h^{-1}.bar^{-1}$ and 62% Na_2SO_4 rejection. The recycled membrane, exhibiting ultrafiltration-like properties, also demonstrated a significantly higher degree of water permeability, ranging from approximately 60 to 90 $L.m^{-2}.h^{-1}.bar^{-1}$, but its rejection of Na_2SO_4 was less than 5%.

In an independent study, Moreira et al. examined recycled household EoL-RO systems as point-of-use ones for groundwater treatment [24]. The researchers successfully repurposed the EoL RO membranes by treating them with 440,000 ppm.h of NaOCl and confirmed their long-term viability by operating them for an extended period of time. Their findings indicated a significant increase in water permeability from 4.5 to 50.4 $L.m^{-2}.h^{-1}.bar^{-1}$ coupled with a substantial decrease in salt rejection from 99.4 to 11.6%, suggesting the effective transformation of the RO membrane into an UF membrane. Furthermore, the modified membrane demonstrated an efficient level of water treatment and minimal fouling over a prolonged period of use at its point of use. Monitoring data revealed a consistent permeate flux of 21.2 ± 0.46 $L.m^{-2}.h$ and a filtration resistance of 6.37 ± 0.16 * 10^{14} m^{-1}, resulting in a total permeate production of 3,000 L, comparable to commercially available filtration systems.

A recent study by Nieminen et al. examined the process of repurposing EoL desalination membranes for nanofiltration applications [25]. The new membrane demonstrated a pure water permeability of 17 $L.m^{-2}.h^{-1}.bar^{-1}$. Additionally, it achieved a retention rate of 88% for $MgSO_4$ and 8% for NaCl with a molecular weight cut-off of 320 Da. Remarkably, the membrane achieved over a 95% reduction in the phosphorus concentration while also removing over 80% of various pharmaceutical micropollutants.

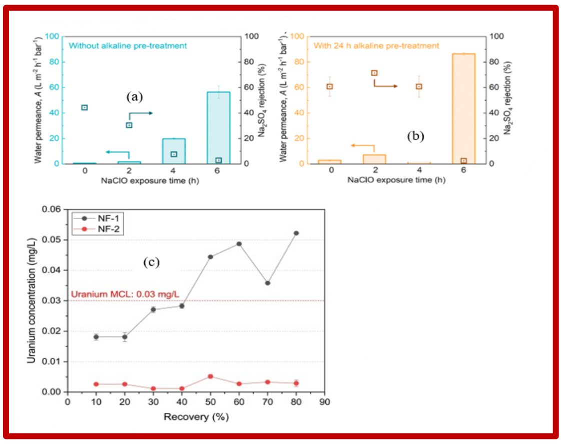

Figure 1: Performance of downcycled EoL RO membranes (a) without alkaline pre-treatment, (b) with alkaline pre-treatment for 24 h while exposed to different NaOCl concentrations [19], and (c) with uranium concentrations in NF-1 and NF-2 permeating at varying rates of permeate recovery [23]

4. Conclusions

Different management strategies are necessary, considering the significant environmental concern that end-of-life reverse osmosis membranes pose. The present study surveyed several methods for reusing these membranes such as repurposing them for different applications, employing less severe treatments and thoroughly cleaning them with chemicals to facilitate their rejuvenation. Studies have demonstrated that recycled RO membranes can achieve a comparable level of performance to commercial membranes in different application areas, which makes them an affordable option for water desalination and wastewater treatment. It is anticipated that extending the lifespan of EoL RO membranes as well as recycling and reusing them will ultimately lower the social and environmental costs associated with their use, promoting a greater degree of sustainability.

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