Desalination 622 (2026) 119690

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Routes for reuse of aged pressure-driven membranes: Current status and future perspectives

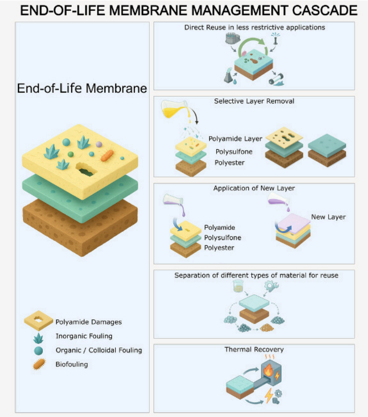
Fábio Ivan Seibel [a,*], Vandré Barbosa Brião [a], Samarah Graciola [a], Maxime Pontié [b], Ahmed Hannachi [c], Mehri Shabani [d], Eby Mohamedou Alyoun [e], M Hasan Shaheed [f]

[a] *Civil and Environmental Engineering Graduate Program, University of Passo Fundo (UPF), Passo Fundo, RS, Brazil*
[b] *Groupe of Analysis and Processes (GA&P), University of Angers, Angers, France*
[c] *University of Gabes, National Engineering School of Gabes, GPSI, Omar Ibnelkhattab St., 6029, Gabes, Tunisia*
[d] *UniLaSalle, Université d'Artois, ECLORE, ULR 7519, 35170, Bruz, France ESAIP La Salle Engineering School, Saint-Barthélemy-d'Anjou, France*
[e] *Université de Nouakchott, Faculté des Sciences et Techniques, Departement de Chimie, Nouakchott, Mauritania*
[f] *School of Engineering and Materials Science, Queen Mary University of London, London, United Kingdom*

HIGHLIGHTS

- Millions of RO membranes reach end-of-life annually, mostly landfilled.
- NaOCl oxidation converts EoL RO into NF/UF with viable costs (~US$ 8).
- Upcycling routes expand functionality but remain at lab scale.
- Updated hierarchy prioritizes direct reuse and staged RO → NF → UF.
- Framework links lab advances with circular water management.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
End-of-life membrane
Membrane recycling
Circular economy

ABSTRACT

The rapid expansion of reverse osmosis (RO) desalination generates millions of end-of-life (EoL) membrane elements each year, most of which are still landfilled. This review examines the technical and practical routes available to divert these polymers from disposal, while also refining the existing hierarchy of membrane reuse. The analysis encompasses temporary storage, rewetting, cleaning, direct reuse, recycling, and upcycling, providing a comprehensive framework that connects laboratory findings with practical implementation. Chlorine-based oxidation—especially NaClO—emerges as the most mature option, reliably converting EoL RO modules into ultrafiltration- or nanofiltration-like membranes with viable costs (~US$ 8 per element). Upcycling

---

* Corresponding author at: University of Passo Fundo (UPF), BR 285, São José, Passo Fundo, RS, 99052-900, Brazil.

E-mail addresses: fabioseibel@hotmail.com (F.I. Seibel), vandre@upf.br (V.B. Brião), 178902@upf.br (S. Graciola), maxime.pontie@univ-angers.fr (M. Pontié), ahmed.hannachi@enig.rnu.tn (A. Hannachi), mehri.shabani@unilasalle.fr (M. Shabani), ebymohamedou@univ-nkc.mr (E.M. Alyoun), m.h.shaheed@qmul.ac.uk (M.H. Shaheed).

https://doi.org/10.1016/j.desal.2025.119690
Received 24 July 2025; Received in revised form 24 November 2025; Accepted 26 November 2025

methods such as layer-by-layer coatings, interfacial polymerization, and ion-exchange grafting widen functionality but remain lab-scale, hindered by adhesion, fouling, and scale-up barriers. Standardized protocols, long-term field data, and supportive business models are now critical for industrial adoption and circular water management. This review also assessed the maturity of each technique, noting that most strategies are not yet ready for larger-scale deployment, and it introduces a quantitative bibliometric map of the field and proposes an expanded, processual hierarchy tailored to pressure-driven membranes. By coupling evidence-based literature analytics with an updated ordering of EoL options (prioritized direct reuse, staged RO → NF → UF conversion, advanced upcycling, and pre-disposal material recovery), the paper provides a novel, actionable framework for closing the loop in membrane technology.

1. Introduction

Membrane Separation Processes (MSPs) have become pivotal components in several industrial sectors due to their ability to selectively separate fluid components. MSPs find applications in water and wastewater treatment [1,2], food and beverage processing [3–6], pharmaceutical processes [7], gas separation [8], and others. In addition, the increasing global demand for water is projected to grow by 1 % each year, and membranes used for desalination have a highlighted position to supply this demand [9].

Advances in thin-film composite (TFC) membranes have allowed them to occupy an important role in water supply around the world. Modern TFC membranes are composed of a permeable support layer (providing mechanical strength) and a thin-film selective layer (typically made of polyamide), which is responsible for the separation process [7,10]. These membranes have higher permeability and selectivity than cellulose acetate membranes [11] and have driven a growth in membrane sales.

The growth of the reverse osmosis (RO) market over the past decades has been highlighted in several scientific studies. A comprehensive review by Ghaffour et al. [12] noted that desalination capacity has rapidly increased, driven by a combination of growing global water demand and significant cost reductions. These cost efficiencies were largely the result of major technological advances in the reverse osmosis process, solidifying the preference for membrane-based technologies over traditional thermal methods for desalination. However, other sources present more moderate and sustained estimates over longer time frames.

The European Commission's Blue Economy Observatory indicates that the global desalination capacity—predominantly based on reverse osmosis—has grown at an average rate of approximately 7 %/year since 2010. This trend has resulted in a substantial increase in installed capacity, from approximately 59 million m^3/day in 2010 to 95 million m^3/day in 2018 [13]. Similarly, a technical report by Santander X notes that between 2010 and 2020, the cumulative global desalination capacity increased by approximately 41 %, primarily driven by the commissioning of new reverse osmosis plants. Currently, reverse osmosis accounts for approximately 69 % to 73 % of the total global desalination capacity [14].

The widespread use of membranes for desalination has introduced a critical challenge: managing aged membranes or end-of-life (EoL) membranes. TFC membranes have a relatively short lifespan (2–5 years), primarily due to the decline in permeability and selectivity [15]. Failures arise from several factors, including biofouling [16], inorganic fouling [17], and organic fouling [18]. In addition, failures in pretreatment can lead to an inappropriate feedwater quality for membrane processes. Operation conditions can also damage membranes—such as water hammer or exceeding the recovery rate beyond salt saturation indexes. Additionally, chemical cleaning procedures can damage the membranes over time. While essential for removing fouling, studies show that repeated exposure to chemical agents, particularly oxidants like sodium hypochlorite, can alter the membrane's polymeric structure and morphology [19], which leads to losses in selectivity. Despite ongoing scientific and technical efforts to extend membrane lifespans, TFC membranes will inevitably fail, leading to the accumulation of large quantities of EoL membranes.

The disposal of EoL membranes has become an environmental concern [20,21], as the primary disposal method remains landfilling [22,23]. It is estimated that 14,000 tons of EoL membranes are discarded in landfills around the world each year [22,23]. This practice aligns with the linear economic model that assumes unlimited resources are available for continuous production. However, there is growing pressure for a transition toward a circular economy, where wastes are repurposed into resources for new products [23]. The European Union (EU) Waste Framework Directive outlines a hierarchy for waste management: (i) prevention, (ii) preparation for reuse, (iii) recycling, (iv) energy recovery, and (v) final disposal. Thus, the membrane trade market must move toward this new approach.

Researchers are exploring strategies to repurpose EoL membranes. Reuse and recycling are the preferred methods. Direct reuse [20,23,24] is the first option to repurposed EoL membranes as they can applied for less selective applications. Recycling RO membranes through oxidative processes can remove (partially or totally) the selective layer and the membrane can be applied as nanofiltration (NF) or ultrafiltration (UF) as in bioreactors [22], and electrodialysis [23]. Even with reprocessing costs, membrane reuse has been shown to be economically viable [25–29]. Thermal recovery is a third option, but side effects (i.e. generation of byproducts of thermal transformation) must be considered before this route is proposed [22].

Avlonitis et al. [30] addressed the issue of membrane recycling in 1992, prompting researchers to explore alternatives to landfill disposal for EoL membranes. Since then, several studies have been performed on the reuse, recycling, and upcycling of aged elements to extend their lifespan, but the information remains scattered. Some reviews on membrane recycling have been compiled to consolidate this scientific information. Tian et al. [31] investigated re-preparation technology for upcycling microfiltration (MF) and ultrafiltration (UF) membranes. Somrani et al. [32] addressed a mini overview to show the strategies and perspectives regarding membrane recycling, but they provided a general approach. Li et al. [29] reviewed the scenarios for recycling and upcycling membranes, highlighting the environmental and economic benefits of membrane recycling. Some studies have developed a Life Cycle Assessment (LCA) framework to evaluate the alternatives of reuse, recycling, upcycling, and thermal recovery [26–28,33]. These frameworks also demonstrate the environmental viability of these processes as an alternative to landfilling, and some businesses are emerging in membrane recycling, such as Memre (https://www.memre.de/) in Germany and Ecomemb (https://test.ecomemb.com/en/) in Spain. However, despite these efforts, the current literature on EoL membranes remains fragmented. It focuses primarily on specific aspects (e.g., recycling/upcycling chemistry or LCA studies) and neglects the complete, practical process for managing end-of-life elements. This gap motivated the present review.

In this review we propose a processual and practical management framework for EoL membranes. Unlike existing reviews, which describe available methodologies, our study addresses the practical execution and timing of reuse and recycling. It encompasses the entire technical and logistical sequence, from initial collection and temporary storage to the assessment of technological maturity for each processing route (including rewetting, cleaning, direct reuse, recycling, and upcycling). Furthermore, we introduce a quantitative bibliometric mapping of the field and propose an expanded, actionable management hierarchy for reverse osmosis RO membranes. Thus, we provide a structure that connects laboratory breakthroughs with practical field implementation.

Building on previous studies, this work aims to critically review the state of the art in scientific advances to propose a systematic hierarchy from a practical perspective, also considering temporary storage, rewetting, cleaning and the maturity of each technique to repurpose aged membranes.

2. Global scenario of end-of-life membranes

The desalination market constitutes a significant portion of the global membrane market. This correlation considers the vital role of water desalination in addressing the increasing global demand for freshwater. In 2012, the global volume of desalinated water reached approximately 500,000 $m^3 \cdot d^{-1}$. However, according to the International Desalination Association, in 2024, the daily capacity has exponentially grown to 109.2 million $m^3 \cdot d^{-1}$ [34]. The global scenario of membranes sales is show in Fig. 1.

The global water desalination market was valued at 13.12 billion USD in 2020, with a projected annual growth rate of 7.1 % (CAGR) from 2020 to 2028 [35]. The global membrane market, encompassing all types of membranes, is estimated to reach 19.44 billion USD by 2025, with a projected growth rate of 6.5 % by 2027 [36].

Membranes used for desalination in different sectors usually use pressure gradients as a driving force. This concept includes many types of membranes, such as MF, UF, NF, and RO. Other types of membranes use other driving forces, such as forward osmosis (FO), dialysis, electrodialysis (ED), pervaporation (PV), membrane distillation (MD), and pressure-retarded osmosis (PRO). This review focuses on the recycling of MF, UF, NF, and RO membranes because they comprise approximately 86 % of the membrane market (Fig. 1).

MF and UF are porous membranes, hydrophilic or hydrophobic, depending on the material. Both MF and UF membranes are typically made of polymeric materials, including polyethersulfone (PES), polyvinylidene fluoride (PVDF), polysulfone (PSf), regenerated cellulose, and others [37].

Commercial RO and NF membranes are multilayered membranes, usually made of TFC materials. While the TFC polyamide layer is the core of separation, RO units are complex, multicomponent structures composed of at least eight different materials. These include polyester (PET), acrylonitrile-butadiene-styrene (ABS), PSf, polyurethane (PU) glue, polyamide, polypropylene (PP), and glass fiber-reinforced thermoset epoxy. Therefore, the recycling of membranes involves a range of materials, making it more difficult to manage and process.

Recent developments in membrane technology have introduced novel materials to improve the selectivity, permeability, fouling resistance, and mechanical stability of all membrane types (MF, UF, NF, and RO). Graphene-family laminates and GO-based skins create tunable, laminar nanochannels with high water permeability and promising ion/salt selectivity, aided by interlayer spacing control and hydrophilic functional groups [38]. GO membranes allow for selective ion rejection and have shown strong potential in nanofiltration and desalination applications [39] for removing emerging contaminants [40,41], and metals such as Pb^{2+} and Ni^{2+} [42]. Carbon nanotubes (CNTs) have also been integrated into membrane matrices, offering high water flux due to their smooth, hydrophobic channels that facilitate fast molecular transport [43,44], large surface area, and ease of functionalization [44]. CNT additives introduce low-friction pathways that elevate flux; improved dispersion/orientation strategies help preserve selectivity by minimizing interfacial defects [45] and improve fouling mitigation [46]. CNT-based membranes find applications in water (seawater and brine desalination) and wastewater for oil–water separation, removal of heavy metals, and removal of organic pollutants [43].

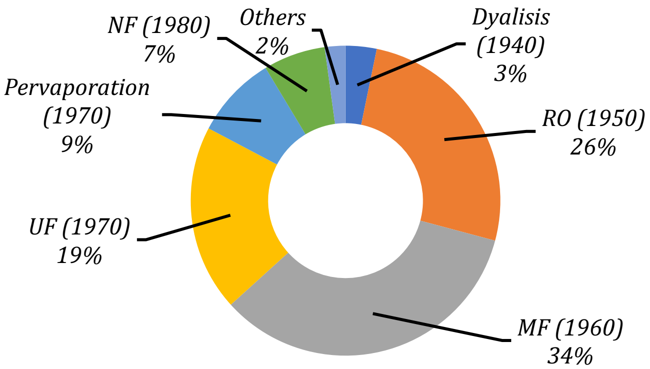


Fig. 1. Year of development and global market percentage of separation membranes (number in brackets represent the decade of development).

Ceramic membranes are usually made from oxide ceramics, such as alumina [47,48], zirconia, and silicon ceramics [49,50], are gaining attention for UF and MF, especially in high-temperature environments. Ceramic membranes offer chemical and thermal stability, making them ideal for industrial applications [51] and for treating aggressive effluents and industrial pretreatment [49,52]. Hybrid materials such as metal–organic frameworks (MOFs) and covalent organic frameworks (COFs) have introduced highly tunable pore structures and porous voids that provide secondary water channels [53] with enhanced separation selectivity while maintaining permeability. MOFs and COFs can be applied as selective layers or fillers in composite membranes, showing promise particularly in NF and RO systems for water [54] and environmental applications [55] including MOF composites on ceramic supports for water treatment [56]. Another important innovation is the use of biomimetic membranes that incorporate aquaporins, which are natural water-channel proteins, into synthetic membranes. These structures replicate biological filtration mechanisms, enabling high water permeability with excellent salt rejection, which is useful in desalination and potable water applications [57]. Biomimetics have emerged as an effective alternative for increasing productivity and reducing energy consumption [58]. Its design, incorporating aquaporins, replicates biological water channels by pairing exceptional permeability with strong salt rejection, progressing toward more stable and scalable formulations [59]. Thin-film nanocomposite (TFN) membranes are developed by embedding nanoparticles, such as TiO_2, SiO_2, or silver, into conventional polymer matrices. These additions enhance hydrophilicity and improve water flux, selectivity [60,61] and resistance to fouling, and in some cases, provide antimicrobial properties. However, their performance depends on controlling the loading and potential leaching of these nanoparticles [60,61]. When these advanced layers are built on recycled RO substrates (e.g., after PA removal or repair), they enable upcycling routes that rebuild selectivity and durability with modest environmental footprints, aligning material innovation with circular economy goals [24,62–65].

The current scenario suggests that the use of polymeric membranes for desalination will keep growing to meet the global demand for drinking water. By 2025, it is estimated that over 2,000,000 EoL reverse osmosis elements will be discarded annually worldwide, generating approximately 32,000 tons of waste. We designed two scenarios for membrane disposal up to 2030, focusing on replacement in desalination plants: the first is conservative and predicts an annual replacement rate of 5 %; the second predicts 35 %, reaching nearly 5 million discarded elements by 2030. Fig. 2 shows both scenarios, along with images of temporary EoL membrane storage collected by our team.

These projections are consistent with plant-scale observations, where end-of-life RO modules already emerge as a concentrated solid-waste stream in large desalination facilities, as documented by García-Pacheco et al. [66], reinforcing that the expansion shown in Fig. 2 will

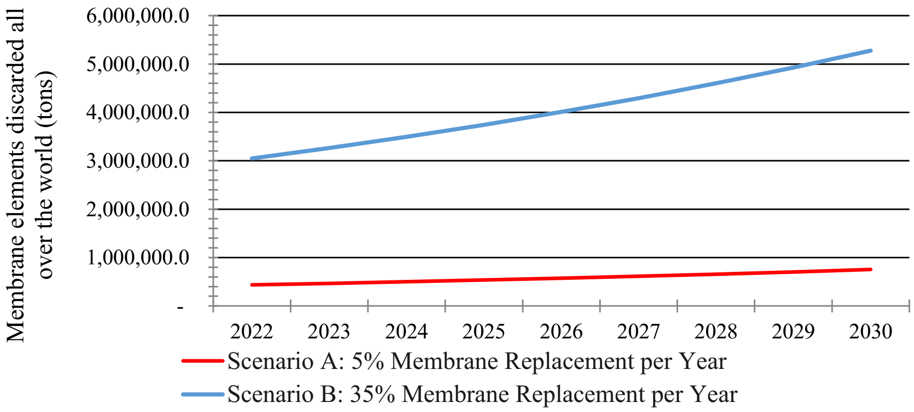


Fig. 2. Predicted scenarios of disposal of aged membrane elements throughout 2022–2030.

translate directly into increasing membrane residues that must be managed. Thus, the higher the number of desalination plants, the higher the increasing volume of inappropriately disposed membranes. Additionally, with the ongoing development of new types of membranes, similar challenges are expected to emerge.

3. Methodology

A quantitative analysis of scholarly publications addressing the reuse and recycling of pressure-driven membranes was conducted to establish the conceptual framework of the present study. A bibliometric search was performed in the Web of Science (WoS) Core Collection, encompassing peer-reviewed journal articles published between January 1, 2012, and June 1, 2024. The year 2012 was selected as the baseline because citation network analysis identified the seminal work of Lawler (2012) as the foundational publication initiating a cohesive research cluster on end-of-life (EoL) membrane management. Extending the temporal range to earlier years did not yield an integrated network or coherent citation cluster within the WoS database, thereby confirming 2012 as the onset of measurable research development in this domain.

Given that the reduction of membrane usage is often impractical in operational contexts, the analysis focused specifically on strategies of membrane reuse and recycling. The bibliometric query was formulated at the title level as follows: “separation membrane” AND (“membrane reuse” OR “membrane recycle” OR “end-of-life membrane”). The search results were restricted to the Membrane Science citation topic. Records falling outside the defined scope were excluded following title and abstract screening. The selection workflow is summarized in Fig. 3. The full bibliometric analysis is provided as supplemental material.

4. Optimizing end-of-life membranes: a processual hierarchy approach

Landaburu-Aguirre et al. [23] propose that membrane damage is inevitable despite efforts to improve lifespan. The author also emphasized the importance of incorporating worn membranes into the circular economy. Similarly, Lejarazu-Larrañaga et al. [24] argue that fouling and performance degradation are currently unavoidable drawbacks of membrane technology, and once performance declines, membranes must be replaced. Thus, waste generation is inevitable. Unfortunately, the most common fate of EoL RO membranes is landfill disposal, which results in greenhouse gas emissions, toxic leachates, unpleasant odors, and visual pollution. Reversing this scenario requires implementing a hierarchy of end-of-life (EoL) membrane management strategies. From bibliometric study (please see the supplemental material), we separated three domains of clusters:

(i) Direct reuse and secondary applications (e.g., reuse, UF/MF, pretreatment), describing the redeployment of intact modules for less-demanding duties;
(ii) Chemical transformation of RO/NF, notably the staged RO → NF → UF cascade via partial/controlled polyamide degradation, which aligns spent elements with lower-pressure specifications; and
(iii) Circular economy and sustainability, where terms such as circular economy, waste management, and LCA frame technical routes within system-level objectives [67–70].

Beyond the technical contributions already highlighted in this cluster, García-Pacheco et al. [71,72] outlined an integrated approach to managing and recycling EoL RO membranes, linking practical operation with regulatory and policy aspects. In parallel, García-Rubio and Guardiola [72] examined the Spanish desalination programme as an expanding pillar of national water supply, while Grossi et al. [73] compared different RO membrane waste-management options from both environmental and socioeconomic angles. Taken together, these studies show that EoL strategies for RO membranes cannot be designed in isolation, but need to be aligned with broader policy, economic, and sustainability goals.

“Reuse” was the most frequent keyword (Supplemental Material 1) and is used in two senses: regeneration (performance restoration) and repurposing (assignment to new services). In this review, reuse denotes restoring the performance of a used membrane (regeneration) or deploying it in a less demanding application without materially

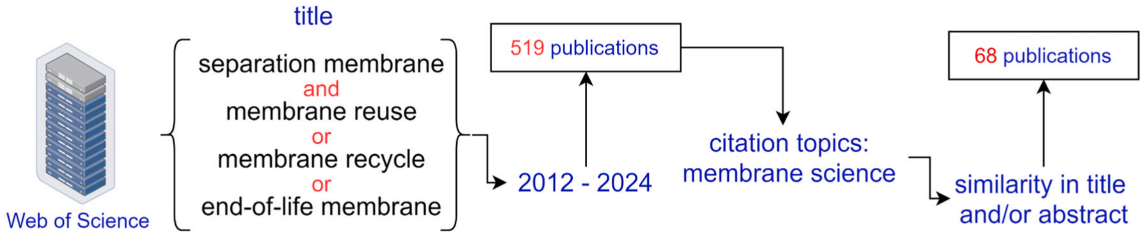


Fig. 3. Overview of the method for systematic review of recent papers in membrane reuse.

transforming its structure. In contrast, recycling involves material conversion, such as the partial or complete removal of the polyamide barrier to obtain NF-like or UF-like performance [20,23,24,32]. In practice, a module may first be reused until its performance declines and then recycled via controlled oxidation to extend its service life in a different separation regime [20,23,24,32]. Fig. 4 shows the proposal of Lejarazu-Larrañaga et al. [24] in a hierarchy approach to reuse the EoL membranes and our proposal for this hierarchy process of membrane recycling.

Senán-Salinas et al. [69] highlighted that the sequential degradation of polyamide can yield multiple products with distinct applications in a cascade approach. This model predicts the initial use of virgin RO modules, followed by conversion into recycled NF (r-NF), then into recycled UF (r-UF), and ultimately into recycled FO (r-FO) membranes.

Our proposed hierarchical strategy for EoL membrane management is organized by ascending resource and effort requirements. We prioritize repurposing options that demand minimal intervention first, then progressively move to more resource-intensive recycling or upcycling methods only if simpler options are exhausted. This ensures that each membrane is given a new life with the least additional input necessary. Fig. 4b illustrates this stepwise hierarchy, and each stage is discussed in detail in the following sections. Before that, we summarized a list of recycling (or upcycling) technologies used in EoL membranes (Table 1). Overall, researchers have focused on recycling RO and UF EoL membranes used in desalination, wastewater treatment, and brackish water treatment. The most investigated technique has been the EoL membrane exposure to chemical solutions, including chlorine and sodium hypochlorite (NaClO). Furthermore, cutting-edge upcycling techniques such as interfacial polymerization, layer-by-layer polyelectrolyte deposition, and other processes have been studied. This wide range of papers highlights the important developments in membrane technology, which lead to more effective and environmentally friendly water treatment methods.

In addition, new methods are emerging, such as depolymerization of membrane materials, which aims to recover polymer monomers or even the polymer itself from fabricated membranes. This represents a recent frontier, as demonstrated by Li et al. [107]. They successfully depolymerized aged membranes to remove contaminants and subsequently refabricated them into new membranes through the dissociation and reformation of Diels–Alder adducts. Recent studies explore these aspects to incorporate green chemistry concepts in EoL membrane depolymerization [108]. However, because this review focuses on processes showing established pathways to practical application and technological maturity, we deliberately prioritized those methods (e.g., physical and oxidative recycling) that have gained traction in different application.

4.1. Reuse in less restrictive applications

Aged membranes are typically discarded due to two main factors: loss of rejection and changes in permeability. In general, various types of fouling contribute to the decline in permeability, while membrane cleaning processes may lead to a decrease in rejection performance. However, even when membranes reach the end of their operational lifespan, they can still be repurposed for applications where neither high rejection nor high permeability is strictly required.

Direct reuse of end-of-life membranes refers to transferring membranes no longer suitable for their original purpose to other facilities or processes where performance requirements are less stringent [92]. Examples of such secondary applications include pretreatment stages in RO desalination plants [109,110]. In experimental and pilot-scale applications, these reused membranes demonstrated similar performance to commercial ultrafiltration/nanofiltration membranes, improving feed water quality and extending the lifespan of the new membranes in the RO system [98]. These aged membranes have also been used for irrigation systems [78], industrial laundry wastewater treatment [109–111], and for filtration of water to make up a cooling tower [98].

The direct reuse of these membranes in less restrictive applications holds a significant position in the hierarchy of EoL membrane management. This approach not only aligns with environmental concerns but also represents the most sustainable option for managing membranes at the end of their lifecycle [20]. However, there are several challenges to bring this hypothesis to real business.

The first challenge is the logistical problems involved in transporting membranes from one site to another because costs will be involved in it [27,112]. Senán-Salinas et al. [27] and Senán-Salinas [112] performed a Life Cycle Assessment (LCA) to implement a full-scale direct recycling of RO membranes to evaluate the situation in Spain. They showed that logistic centers can be installed to reduce the effects of transport on the LCA. However, a business model to deal with it still doesn't exist, and maybe at this time the best solution is to reuse the EoL membranes in the same site they are used [112].

The second technical barrier is the temporary storage of EoL membranes. Many times they are still fouled and then removed from pressure vessels and stored dry with the fouled layer, but membranes must be wet to keep the permeability [78]. Thus, cleaning and rehydration are required prior to any reuse, but a regular protocol for cleaning and rehydration of EoL membranes does not exist. Still, due to the variety of fouling types—such as inorganic, organic, and biofouling—different protocols need to be tested to evaluate the effectiveness of fouling removal. From Fig. 5 we can see the EoL membranes are in a temporary dry storage. If a second life is proposed to these membranes, we will need to try to recover the permeate flux, test cleaning and rehydration protocols.

The recovery of permeate flux from EoL membranes is a primary task because sometimes the removal of hardened fouling can take time and cost, and maybe hinder the reuse of the membrane. The first step to recovery flux of EoL is the CIP (Cleaning in Place) cleaning. After the cleaning, the next step is try the rehydration.

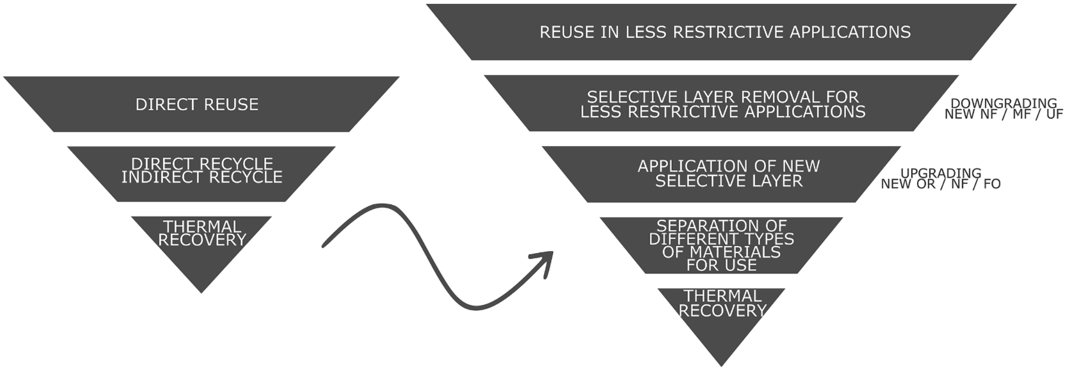


Fig. 4. Proposal of Lejarazu-Larrañaga et al. [24] on the left side (a) and we included more steps in our proposal on the right side (b).

Table 1
Recycling technologies used in EoL membranes for upcycling.

Reference	Membrane	Original application	Upcycling technology	New application
[74]	RO	Brackish water	NaClO exposure followed by filtration/adsorption of polystyrene sulfonic acid electrolyte solution	UF for application in a fungal microbial fuel cell
[24]	RO	Desalination	Exposure to NaClO	Anion exchange membrane (AEMs) for treatment of water
[75]	RO	Desalination	NaClO, NaOH, H_2O_2 and $KMnO_4$	Selective layer removal for less restrictive applications
[76]	RO	Desalination	NaClO exposure	UF
[66]	RO	Desalination	Chlorine exposure	Selective layer removal for less restrictive applications
[68]	RO	Brackish water	NaClO exposure followed by anion exchange resin surface attachment	Application of new selective layer
[77]	MF (PVDF)	Wastewater treatment plant	Cleaning–healing–interfacial polymerization (CH-IP)	MF–NF-like
[78]	RO	Brackish and seawater	NaClO exposure	Selective layer removal for less restrictive applications
[79]	RO	Brackish and seawater	Chlorine exposure	Selective layer removal for less restrictive applications
[80]	RO	–	NaClO exposure followed by polyelectrolyte multilayer coating	Application of new selective layer
[81]	RO (recycled as UF support)	Brackish water	NaClO exposure	Selective layer removal for less restrictive applications
[82]	RO	Brackish water	NaClO exposure	Selective layer removal for less restrictive applications
[83]	RO	Brackish water	Ultrasonic bath and $KMnO_4$-exposure	Selective layer removal for less restrictive applications
[84]	RO	–	Exposure to NaClO and chlorine	Application of new selective layer
[62]	UF	PAH solution	Layer-by-layer deposition of anionic and cationic polyelectrolytes	NF for brackish water treatment
[85]	UF	Desalination	Layer-by-layer deposition of anionic and cationic polyelectrolytes	NF for salt removal
[86]	RO	Brackish water	NaClO exposure, acetone solution *N*-methyl-2-pyrrolidone	Selective layer removal for less restrictive applications
[63]	UF	Desalination	Layer-by-layer deposition of anionic and cationic polyelectrolytes	Application of new selective layer
[87]	UF	Wastewater	Exposure to PEI and gallic acid	Application of new selective layer
[27]	RO	Brackish and Seawater	Exposure to NaClO	Selective layer removal for less restrictive applications
[33]	NF	Biological wastewater treatment for reuse	NaClO exposure	Selective layer removal for less restrictive applications
[60]	RO	Desalination	NaClO exposure followed by electrospinning technique	Application of new selective layer
[88]	RO	Brackish water	Exposure to NaClO followed by interfacial polymerization	FO
[89]	RO	–	DIP-coating using catechol (CA) and polyethyleimine (PEI)	Selective layer removal for less restrictive applications
[90]	RO	–	NaClO exposure	Selective layer removal for less restrictive applications
[91]	PSf membrane (support layer)	Desalination	Non-solvent phase inversion	Application of new selective layer
[92]	RO	Desalination	Phosphoric acid clarification	Selective layer removal for less restrictive applications
[93]	MF	Wastewater	Addition of sodium dodecylbenzene sulfonate (SDBS)	Application of new selective layer
[94]	MF	Municipal wastewater treatment	NaClO exposure, polydopamine self-polymerization, interfacial polymerization	Application of new selective layer
[31]	RO	–	Separation of layers using dimethyl formamide (DMF)	Separation of different types of materials for use
[95]	RO	Wastewater	–	Application of new selective layer
[96]	MF PVDF	Bioreactor	Exposure to methyl-5-(dimethylamino)-2-methyl-5-oxopentanoate (MDMO)	Reuse in less restrictive applications
[97]	PVDF hollow fiber	MBR municipal wastewater treatment plant	Chemical cleaning-solvent treatment-hydrophilic modification	Application of new selective layer
[98]	MF	–	Cleaning-tannic acid-iron (TA-Fe) healing-interfacial polymerization	Application of new selective layer
[99]	RO	Wastewater	UV radiation	Application of new selective layer
[100]	RO	Oil refinery wastewater treatment	Exposure to NaClO	Selective layer removal for less restrictive applications
[101]	RO	Brackish water	Exposure to NaClO	Selective layer removal for less restrictive applications
[102]	RO	Steel industrial plant wastewater treatment	Exposure to NaClO	Selective layer removal for less restrictive applications
[103]	RO	Coal mine water treatment	Cross-linking rejuvenation with polyacrylic acid	Application of new selective layer
[104]	RO	–	Exposure to NaClO with $MgCl_2$ or $CaCl_2$	Selective layer removal for less restrictive applications
[105]	RO	Brackish water desalination plant	NaClO exposure followed by co-deposition of polydopamine and polyethylene glycol	Application of new selective layer
[106]	RO	Municipal wastewater treatment plant	Oxidative-cleaning-healing-interfacial polymerization	Application of new selective layer

RO: reverse osmosis, NF: nanofiltration, UF: ultrafiltration, MF: microfiltration, FO: forward osmosis.

Fig. 5. End-of-life (EoL) reverse osmosis membranes stored in dry conditions after use in a desalination system to feed water for a boiler.

4.1.1. *Cleaning*

Chemical cleaning is an essential step for reuse, recycle, or upcycle of membranes. Clean-in-place (CIP) involves using specific chemical products to dissolve or dislodge organic and inorganic fouling substances [28,94]. The choice of cleaning agents depends on the nature of the fouling and the membrane material. Chemical products used for CIP include acids, alkalis, oxidizing agents, and chelating agents. Acidic solutions like citric acid or hydrochloric acid are effective in removing mineral scale and metal oxides (inorganic fouling). Alkaline solutions such as sodium hydroxide or sodium carbonate can dissolve organic matter and saponify fatty deposits. Oxidizing agents like hydrogen peroxide or chlorine-based compounds are used to sanitize and remove biofilm and organic deposits. In fact, sodium hypochlorite (NaClO) is a common cleaning agent used in membrane technologies to restore membrane performance [106].

De Paula, Gomes, and Amaral [75] performed tests for chemical cleaning before membrane oxidation, aiming at membrane recycling. The membranes used in the study were EoL RO membranes, specifically the FilmTec BW30 model, previously employed in industrial wastewater treatment and boiler feedwater systems. Prior to oxidation, the membranes were exposed to simulated organic fouling agents. They tested chemical agents such as alkaline (NaOH), acid (HCl), and chelating agents (citric and oxalic acid). Reversible fouling, caused by deposition or gel formation, was removed by physical washing, while irreversible fouling, due to adsorption or pore blockage, required chemical cleaning. Alkaline cleaning with NaOH was effective, with significant fouling removal observed in the first few minutes. After 30 h of fouling followed by 2 h of alkaline cleaning with 0.1 % NaOH at 25 °C, the membranes recovered 81.6 % of the initial water permeability on average across 0.5–2.0 bar. [75].

The cleaning of EoL membranes with persistent scaling must be carefully evaluated. Seibel et al. [21] cleaned coupons of 200 cm^2 from an EoL RO membrane used for the treatment of brackish water. They showed by Scanning Electron Microscopy (SEM) that even after a standard CIP protocol (acid followed by alkaline cleaning), the membrane surface still presented scaling by calcite. Wang et al. [99] studied EoL RO membranes fouled with hard Si—Al combinations and applied a strategy in which the membrane was submerged in NaOH 0.1 M for 24 h and subsequently exposed to NaClO oxidation. The membrane soaked in NaOH showed better removal of Si—Al complexes and better oxidation of the polyamide layer, transforming the RO membrane into an NF-like membrane. Thus, EoL membranes with inorganic scaling should be carefully evaluated for direct recycling. Moreover, barriers arise in chemical cleaning as the polymeric materials of the membranes have restrictions regarding extreme pH and oxidant agents. It is crucial to identify the foulant agents in order to choose the best strategy for flux recovery.

New cleaning agents are still under development. Tian et al. [31] used methyl-5-(dimethylamino)-2-methyl-5-oxopentanoate (MDMO), developed based on Hansen solubility principles. This solvent was applied to remove irreversible fouling from polyvinylidene fluoride ultrafiltration membranes. After treatment, the water permeance of the EoL membrane increased from 47.6 ± 4.7 to 390.9 ± 8.2 $L{\cdot}m^{-2}{\cdot}h^{-1}{\cdot}bar^{-1}$. The authors also confirmed that the solvent could be reused without detrimental effects on the membrane matrix. While such chemicals remain at the lab scale, classic cleaning methods are still the main strategies for removing membrane fouling.

4.1.2. *Rehydration*

The rehydration of EoL membranes is a critical step for their reuse, recycling, or upcycling. When polymeric membranes dry, a significant decrease in water permeability is observed due to structural and physicochemical changes [78,99]. The main mechanisms behind the flux reduction include pore collapse due to capillary forces [99], polymer matrix compaction caused by the loss of water as a plasticizer [35], and the disappearance of the hydration layer associated with hydrophilic functional groups on the membrane surface [77]. García-Pacheco et al. observed that an EoL RO membrane stored dry for two months recovered only 27 % of its original permeability (from 1.92 to 2.44 $L{\cdot}m^{-2}{\cdot}h^{-1}{\cdot}bar^{-1}$) after 92 h of exposure to Milli-Q water, underscoring the persistent impacts of drying on membrane structure [78].

García-Pacheco et al. demonstrated the effectiveness of ethanol rehydration on dried RO membranes previously subjected to sodium hypochlorite degradation. Membranes soaked in a 50 % (w/w) ethanol solution for 15 min exhibited a flux recovery from 51 to 98 $L{\cdot}m^{-2}{\cdot}h^{-1}$, representing a 92 % increase in permeability. Their methodology involved oxidative damage of the polyamide selective layer, followed by rehydration and performance testing, revealing that ethanol treatment significantly improves flux recovery when compared to water-only rehydration [78].

Future research in membrane recycling should prioritize flux recovery, particularly considering that harsh chemical agents such as hypochlorite can damage the polyamide layer more severely than other polymers like polyvinylidene fluoride (PVDF), due to the former's higher chemical susceptibility [32]. However, we must test the conditions of rehydration on a full scale before choosing a rehydration step as a standard procedure for flux recovery.

4.2. Selective layer removal for less restrictive applications

EoL RO membranes can be repurposed for less restrictive applications by removing or degrading the selective polyamide layer. The most studied method for this transformation is oxidation with chlorine-based agents, particularly sodium hypochlorite (NaClO). Table 1 of this review shows that chlorine oxidation is the dominant strategy across the literature, featured in over 25 referenced studies, either as a standalone treatment or combined with physical or chemical enhancements.

This widespread use is attributed to NaClO's high reactivity with polyamide, availability, and compatibility with both bench- and full-scale operations. Polyamide membranes possess drawbacks concerning their interaction with chlorine. When polyamide membranes come into contact with chlorine, it can result in the degradation and harm of the membrane material [21,32]. The presence of chlorine can initiate an attack on the amide bonds found within the polyamide structure, causing the bonds to break and diminishing the overall performance of the membrane. Prolonged exposure of polyamide to chlorine leads to the deterioration of the active layer, and in certain instances, it can entirely remove the polyamide, revealing the support layer of the membrane [21,82,113]. This recycling procedure aims to convert the membranes into a less restrictive barrier, enabling their use in applications with lower requirements. As a result, the membranes acquire properties such as NF, UF, or MF, including rejection capacity and hydraulic permeability, while still retaining their spiral wound configuration [67]. The removal of the selective layer from these membranes can take place in two ways: they can be processed within their original module; alternatively, the modules are opened, and disassembled, and the flat sheets are managed individually.

Chlorine oxidization has been evaluated at the lab scale using membrane coupons to show the proof of concept of the technique. NaClO exposure at basic pH can significantly increase permeability while reducing salt rejection, indicating partial to complete removal of the selective layer [86]. In some cases, oxidized membranes reached UF performance after 122 to 242 h of exposure. Exposure of 240,500 ppm·h resulted in complete removal of polyamide, and permeability reaching 51 $L{\cdot}m^{-2}{\cdot}h^{-1}{\cdot}bar^{-1}$ with no measurable salt rejection [80]. FTIR analysis confirmed the disappearance of amide bands typical of intact polyamide layers. These findings were reinforced by additional studies, showing that NaClO could raise permeability up to 117 and even 313 $L{\cdot}m^{-2}{\cdot}h^{-1}{\cdot}bar^{-1}$ in EoL RO brackish water membranes [32,82]. Alternative oxidants such as $KMnO_4$, H_2O_2, and $NaHSO_3$, or combined treatments such as sonication plus NaClO [83], were also tested but showed lower stability over time or higher operational cost. Overall, chlorine oxidation remained the most effective and scalable strategy. Note that all these papers used membrane coupons to demonstrate scientific feasibility. A remaining challenge is replicating lab-scale results in full-scale systems, as bench conditions are not always scalable; therefore, oxidation must also be evaluated in full-scale membranes [38].

On the other hand, Table 1 also includes examples of chlorine-based oxidation applied to full modules. Intact EoL RO spiral-wound modules treated using passive NaClO immersion achieved permeability values up to 45 $L{\cdot}m^{-2}{\cdot}h^{-1}{\cdot}bar^{-1}$ [78]. Senán-Salinas et al. [27] reported that a passive (non-recirculating) NaClO immersion process for recycling RO membranes can reduce overall environmental impacts by roughly 66–70 % compared to an active recirculation process. Results also showed that transforming RO membranes into NF or UF in a staged approach (RO → NF → UF) is more efficient than attempting a direct conversion to UF. Evidence indicates that a staged conversion—first obtaining NF-like performance by partial polyamide removal and only then proceeding to UF—yields higher overall flux/selectivity than a one-step RO → UF approach. Controlled oxidation to an intermediate NF state preserves functionality and enables a second down-rating step with improved outcomes in practice [86,99,114].

Practical applications of these oxidized modules in real wastewater scenarios have been demonstrated [82,98], highlighting the effectiveness of recycled membranes to remove turbidity, COD, and microbial indicators, and their transition to UF-like behavior. Long-term field operation of chlorine-treated household RO modules in remote areas also maintained stable performance for six months, producing potable water [76].

The breadth of applications for chlorine-oxidized membranes is significant, spanning across sectors and treatment targets:

a) Water and wastewater treatment: Recycled membranes have been used for treating brackish water [21], surface water [45], laundry wastewater [107–109], and greywater [82]. In these cases, NF- or UF-like properties were sufficient to meet water reuse or discharge standards.
b) Membrane bioreactors and biofilm reactors: RO membranes have been repurposed into gas-permeable structures for membrane biofilm reactors (MBfRs), expanding their utility beyond conventional filtration [79].
c) Decentralized and emergency water supply: Recycled membranes applied in gravity-driven membrane (GDM) systems have shown that UF-like and NF-like recycled membranes were capable of delivering safe drinking water over short periods in rural and disaster-affected areas [76,89]. However, permeability was relatively low (2.8 $L{\cdot}m^{-2}{\cdot}h^{-1}$), and the system experienced strong fouling. Permeate flux declined without cleaning over 30 days, highlighting a trade-off between robustness and simplicity.
d) Industrial effluents and specialized applications: Oxidized RO membranes have been used for the clarification of wet-process phosphoric acid, achieving 70 % suspended solids removal [91]. These chemical recovery processes can extend to non-conventional streams in the fertilizer and chemical industries.
e) Electrodialysis and ion exchange membranes: Advanced chemical modifications after chlorine oxidation (e.g., polyelectrolyte coating or resin grafting) enabled the transformation of RO substrates into anion exchange membranes, as reported by multiple authors [68,78].

These applications have shown the versatility of chlorine-oxidized membranes, particularly those achieving NF or UF characteristics. Although full-module oxidation presents operational challenges, such as slower reaction rates and the need for cleaning prior to oxidation, the benefits of maintaining module integrity and avoiding disassembly are substantial. Chlorine oxidation stands as a cornerstone method to give a second life for EoL membranes by combining chemical simplicity with broad applicability across environmental and industrial contexts. However, the presence of fouling, particularly inorganic scaling (Si—Al complexes or calcite), can interfere with the oxidation process. An alkaline pre-treatment followed by NaClO exposure has been shown to deconstruct complex Si-based scaling and remove the PA layer [99]. Similarly, CIP cleaning followed by oxidation is effective in removing heavily fouled RO membranes with calcite [21].

The reduction of NaClO demand during the chemical attack was studied using catalytic enhancement with divalent salts such as $CaCl_2$ and $MgCl_2$ [66]. These salts catalyzed the degradation of the polyamide layer during oxidation and promoted the formation of reactive chlorine species. At the same time, the use of NaClO to recycle membranes generates wastewater containing this oxidative compound, and Soto-Salcido et al. [101] specifically investigated strategies to mitigate this issue. In their study, they added divalent salts such as $CaCl_2$ and $MgCl_2$ to catalyze the degradation of the polyamide layer during NaClO oxidation and to promote the formation of reactive chlorine species. This catalytic approach accelerated the transformation of EoL RO membranes into UF-like membranes while reducing the required oxidant dose: with Ca^{2+}, complete degradation of the polyamide layer was achieved at 12,700 ppm·h, compared to 300,000 ppm·h without a catalyst. The process allowed control over membrane selectivity, increasing MWCO up to 27,100 $g \cdot mol^{-1}$, and preserved the integrity of the support layer for potential upcycling. Moreover, the catalytic action of Ca^{2+} and Mg^{2+} contributes to reducing oxidative waste and operational costs associated with NaClO use [101].

These findings highlight that chlorine-based oxidation—particularly with sodium hypochlorite—is the most investigated and widely applied route for repurposing end-of-life (EoL) membranes. Its ability to selectively degrade the polyamide layer, applicability from lab coupons to full spiral-wound elements, and the resulting UF- or NF-like properties explain its broad adoption across the literature. The variety of reported applications—including water and wastewater treatment, industrial effluents, membrane bioreactors, and decentralized supply—underscores its practical relevance. Despite operational limitations such as fouling sensitivity and the environmental burden of residual chlorine, recent studies incorporating pre-treatment strategies and Ca^{2+}-catalyzed oxidation have reduced oxidant demand and improved process control. From an economic standpoint, an LCA-based estimate indicates an operational cost of ≈ US$ 8.5 per recycled spiral-wound element [33]. Practical pilots further show the passive route to be more cost-effective—€ 25–42 per module, roughly half the active recirculation route (€ 55–74 per module) [27]. On a harmonized basis—functional unit one 8040 element (~40 m^2) and euro amounts converted to 2024 USD at 1 € = US$ 1.08—passive recycling totals US$ 27.06–45.47 per module (≈ US$ 0.68–1.14 m^{-2}) and active recycling US$ 59.54–80.11 per module (≈ US$ 1.49–2.00 m^{-2}), while the LCA-based figure corresponds to ≈ US$ 0.21 m^{-2} [27,33]. For comparison, public distributor prices for new 8″ brackish-water Toray modules are US$ 637.50–705.00 per element (≈ US$ 15.94–17.63 m^{-2}) (Supplementary Material S2). As such, chlorine oxidation remains a key pathway for extending membrane service life within circular water-treatment strategies [21,27,66].

4.3. Upcycling the EoL membranes — application of a new selective layer

Upcycling EoL membranes represents an advanced recycling strategy aimed not only at extending the membrane lifespan but also at redefining its functionality. Unlike direct reuse or selective layer removal for low-demand applications, upcycling involves removing the original selective polyamide layer and depositing a new functional layer, thereby generating a membrane with properties tailored to new separation needs. This process aligns strongly with circular economy principles, as it recovers and enhances material value. However, technical limitations, operational costs, and long-term performance uncertainties still pose significant challenges.

The first step – controlled degradation of the polyamide layer – is most commonly achieved through exposure to sodium hypochlorite (NaClO). Table 1 shows that NaClO was the most used technique and it has proven effective in oxidizing the polyamide layer, leaving the underlying polysulfone support intact [27,66,74].

Once the selective layer is removed, new functional layers can be added using several techniques:

(a) Layer-by-layer (LbL) deposition: LbL assembly of polyelectrolytes is a straightforward, low-energy technique that has been widely employed to re-establish a selective barrier on oxidized membrane supports. Using this method, recycled UF membranes have been converted into NF-like membranes with appreciable rejection of multivalent ions [24,38,62,63]. However, LbL coatings are typically very thin and prone to degradation under shear stress or aggressive cleaning conditions, raising concerns about the long-term durability of such modifications in real operating environments [62].

(b) Interfacial polymerization: Interfacial polymerization (IP), the conventional method used to form thin-film composite polyamide layers, has also been applied in upcycling to generate a new selective skin on oxidized membrane substrates. This approach can effectively reconstruct an NF-like membrane with enhanced salt rejection performance [92]. However, IP requires careful control of monomer concentrations, solvents, and reaction times to produce a defect-free polyamide layer. Moreover, scaling up this process to full-size spiral-wound modules remains unexplored, and ensuring strong adhesion between the newly formed polyamide film and the aged support has proven challenging.

(c) Electrospinning: Electrospinning has been explored as an upcycling technique by depositing a nanofibrous polymer layer onto the membrane surface. Such electrospun coatings can substantially increase water permeability and improve fouling resistance due to their high porosity and tailored surface properties. Recycled membranes modified via electrospinning have shown promise in treating saline wastewaters. However, the inherent fragility of the nanofiber layer and the difficulty of achieving a uniform, adherent coverage on full-size spiral-wound modules remain major barriers to industrial-scale adoption [45].

(d) Chemical functionalization with charged compounds, for example by layer-by-layer polyelectrolyte deposition to introduce permanent surface charge [63], or by grafting anion-exchange functional groups onto recycled RO supports to produce anion-exchange membranes (AEMs) [24,68], has enabled the conversion of aged RO elements into AEMs suitable for electrodialysis and other ion-separation applications [23,68]. Despite promising lab-scale results, these upcycled versions must contend with the fundamental permeability–selectivity tradeoff inherent to ion-exchange membranes. Efforts to enhance selectivity by modifying the membrane's chemical and structural properties almost invariably lead to a decrease in permeability, representing a critical performance barrier that still requires significant innovation to overcome [115].

(e) Hybrid approaches, involving nanoparticles or surface grafting, are emerging but remain mostly at the proof-of-concept stage. The use of reactive compounds, such as polyacrylic acid or tannic-acid-based complexes [98,100], has been shown to improve membrane hydrophilicity and, in some cases, enhance selective rejection.

Regarding applications, upcycled membranes have been tested across diverse scenarios:

a. In water and wastewater treatment: NF membranes generated by polyelectrolyte coating or interfacial polymerization showed good performance for brackish water treatment, surface water polishing, and greywater reuse [82,89]. Nonetheless, fouling control is a limitation, especially due to the increased roughness and porosity of oxidized supports [22], which are harder to clean compared to commercial NF membranes.

b. In membrane biofilm reactors (MBfRs) and aerobic membrane bioreactors (aMBRs): Upcycled membranes have been used as structural support with modified permeability. These membranes could facilitate gas transfer and remove organic matter [79,92], but their mechanical rigidity and lack of antifouling coatings could compromise long-term biofilm management.

c. Grafted AEMs produced from recycled RO supports have been successfully evaluated in lab-scale electrodialysis systems, showing promising ion-exchange performance [23,24,68]. The costs for upcycling membranes are now well known. For example, Wang et al. [95] revitalized EoL PVDF MF membranes used in large-scale membrane bioreactors for wastewater treatment. The process combines a short NaClO and oxalic acid cleaning step with sequential surface treatment using ferric chloride and tannic acid, followed by interfacial polymerization with piperazine and trimesoyl chloride to form a new polyamide layer. The transformation is completed in under 20 min and achieved at an estimated cost of US$ 4.9/m^2—substantially lower than the US$ 10–30/m^2 typical of new membranes. However, the procedure did not address the steps related to module disassembly or reassembly.

Thus, upcycling offers a technically feasible route for repurposing EoL RO membranes into membranes with tailored functionality. It leverages chemical and physical surface engineering to deliver new selective performance. However, the main barriers to its broad implementation include:

(i) variability in aged membrane condition;
(ii) reproducibility and adhesion of new layers;
(iii) mechanical and chemical stability under real conditions;
(iv) lack of standardized protocols for full-module treatment.

Then, future research should focus on scaling up promising lab-scale methods to explore long-term stability and cleaning protocols, and developing modular systems that can accommodate the inherent variability of recycled materials.

4.4. *Separation of different types of material for use*

End-of-life membranes can also be disassembled to recover individual components for recycling. However, this approach requires more effort than direct reuse or active layer oxidation, as it relies on manual operations due to the lack of dedicated equipment.

Pontié et al. [22] proposed separating the RO spacers from end-of-life membranes to produce flat-sheet membranes for membrane distillation (MD). They blended 60 % polypropylene (PP) recovered from RO spacers with 40 % low-density polyethylene (LDPE) to fabricate the MD membrane. The recycled membrane exhibited properties similar to those of a virgin MD membrane. Although the procedure involves separating different materials, the final outcome represents an upcycling of the EoL membrane.

EoL TFC membranes are composite materials composed of different polymer layers tightly bonded together. Mechanical methods are unable to separate the distinct polymers due to the complexity of the composite structure. In solvent-based recycling, a specific solvent dissolves one polymer while leaving the others intact, enabling the selective separation of these components. This method allows the recovery of valuable materials such as polyamide and polysulfone. Therefore, the solvent-based approach represents a more effective and feasible strategy for recycling EoL membranes. Guclu et al. [93] employed a solvent-based technique to recover value-added polymers from end-of-life (EoL) reverse osmosis (RO) membranes. They submerged the membranes in the organic solvent dimethylformamide (DMF), and separated the polyamide selective layer, the polysulfone support layer, and the nonwoven polyethylene terephthalate (PET) backing. After separation, both PET and polysulfone underwent purification. The recovered polysulfone replaced virgin material in the production of new membranes and in applications in the medical and electronics sectors, following circular economy principles. The PET layer was also recovered for use in textiles, packaging films, bottles, and other products. The tests were performed at a laboratory scale, and further studies are needed to evaluate the process at a larger scale and determine how much material can be recovered by polymer type in larger operations.

4.5. *Thermal recovery*

Thermal recovery has a potential pathway for the valorisation of EoL RO membranes, particularly in situations where reuse or chemical recycling is infeasible, such as in cases of severe fouling or physical degradation. This approach relies primarily on pyrolysis, a thermochemical process that converts polymeric components into fuel gases, oils, and solid residues under an oxygen-free atmosphere. Pontié et al. [22] performed one of the first studies evaluating the pyrolytic potential of RO membranes. They found that membrane sheets and polypropylene (PP) spacers accounted for 43 % and 18 % of module mass, respectively. Thermogravimetric analysis (TGA) showed that PP spacers decompose between 370 °C and 470 °C, and produced up to 85.7 % liquid hydrocarbons with a heating value of 46.4 MJ/kg and 11 % gases with an even higher value of 67 MJ/kg. In contrast, membrane sheets, which contain oxygen and sulfur, presented more complex degradation up to 650 °C, producing lower-quality fuels. Overall, the process led to 48.5 % mass reduction and energy recovery of 8.13 GJ/ton of RO modules, equivalent to 2210 kWh.

Liang et al. [65] applied a two-stage process using pyrolysis followed by hydrothermal treatment with H_2O_2. They converted membrane waste into char, oil, gas, and wax, and further transformed the char into nitrogen- and sulfur-doped carbon dots—nanomaterials with high water dispersibility and selective Fe^{3+} detection properties. This route for membrane recycling has dual valorization: energy recovery and chemical product generation. The method was limited to small-scale laboratory setups, and the operational complexity raises concerns about scalability and economic feasibility.

Yousef et al. [116] evaluated pyrolysis of end-of-life polysulfone UF membranes, showing volatile organics with high fractions of phenol and benzoic acid, both with industrial value; they also reported gaseous emissions (NO_x and SO_x) and VOCs, indicating the need for emission-control systems during scale-up [114].

Despite its potential, thermal recovery presents some limitations:

a) High energy input is required to reach pyrolysis temperatures (typically 500 °C–600 °C).
b) The process does not preserve the membrane's structural integrity, limiting its role to material destruction and energy extraction, which ranks lower in the waste management hierarchy.
c) Emission control systems are essential to avoid air pollution from volatile degradation products.

Thermal recovery is not the preferred route in a circular economy framework due to its destructive nature and operational costs. However, it can be an important complementary solution for membranes that cannot be reused, recycled, or upcycled—transforming them into energy or chemical feedstocks rather than waste. Nonetheless, the integration of pyrolysis within waste-to-energy frameworks in desalination plants or waste management units could offer co-benefits—reducing landfill volume while offsetting fossil fuel use. Further studies are required to optimize process parameters, assess environmental impacts, and evaluate economic viability at scale.

5. Conclusion

This review advances the field beyond recent syntheses by integrating a quantitative bibliometric map with an expanded, membrane-specific EoL hierarchy. Positioned along the literature's progression—Lawler (2015) → Landaburu-Aguirre (2016) → Lejarazu-Larrañaga (2022) → this proposal—our framework prioritizes direct reuse, clarifies the boundaries between reuse and recycling, formalizes staged RO → NF → UF conversion, and elevates advanced upcycling and material recovery before energy recovery and disposal. The result is a coherent, implementable and updated ordering of options that aligns technical feasibility with circular economy outcomes.

Membrane recycling and upcycling technologies have progressed significantly, with chlorine-based oxidation emerging as the most mature and scalable method for repurposing end-of-life RO membranes.

Applications in water reuse, wastewater treatment, and decentralized systems already demonstrate technical and economic viability in some cases.

Despite these advances, most upcycling strategies—such as layer-by-layer deposition and interfacial polymerization—remain confined to the lab scale, limited by challenges in adhesion, durability, and full-module implementation. Fouling, lack of standardization, and logistical barriers also constrain broader adoption.

Future progress depends on scaling up proven methods, validating long-term performance under real conditions, and integrating recycling practices into industrial and regulatory frameworks. With targeted research and collaboration, membrane recycling can evolve from experimental practice into a reliable component of circular water management.

CRediT authorship contribution statement

Fábio Ivan Seibel: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Conceptualization. **Vandré Barbosa Brião:** Writing – review & editing, Supervision. **Samarah Graciola:** Writing – original draft. **Maxime Pontié:** Formal analysis. **Ahmed Hannachi:** Supervision. **Mehri Shabani:** Writing – review & editing. **Eby Mohamedou Alyoun:** Conceptualization. **M Hasan Shaheed:** Writing – review & editing, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no competing interests.

Acknowledgments

The author Fábio Ivan Seibel gratefully acknowledges the financial support from the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brazil (CAPES, financial code 001), and also thanks Alessandra Kuhn for her valuable support and assistance during the preparation of this manuscript.

The authors thank the iMERMAID (www.imermaid.eu) research program in the EU (Innovative Solutions for Mediterranean Ecosystem Remediation via Monitoring and Decontamination from Chemical Pollutants, GA number 1011121824), in which Maxime Pontié and Ahmed Hannachi are partners, and which is associated with the work of Vandré Barbosa Brião.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.desal.2025.119690.

Data availability

The data related to the bibliometry has been shared within the supplemental material.

References

[1] H.F. Giraldo Mejía, J. Toledo-Alarcón, B. Rodriguez, J. Rivas Cifuentes, F. Ovalle Porré, M.P. Loebel Haeger, N. Vicencio Ovalle, C. Lacoma Astudillo, A. García, Direct recycling of discarded reverse osmosis membranes for domestic wastewater treatment with a focus on water reuse, Chem. Eng. Res. Des. 184 (2022) 473–487, https://doi.org/10.1016/j.cherd.2022.06.031.

[2] M.J. McKie, S.A. Andrews, R.C. Andrews, Conventional drinking water treatment and direct biofiltration for the removal of pharmaceuticals and artificial sweeteners: a pilot-scale approach, Sci. Total Environ. 544 (2016) 10–17, https://doi.org/10.1016/j.scitotenv.2015.11.145.

[3] C. Garnier, W. Guiga, M.L. Lameloise, C. Fargues, Water reuse in the food processing industries: a review on pressure-driven membrane processes as reconditioning treatments, J. Food Eng. 344 (2023) 111397, https://doi.org/10.1016/j.jfoodeng.2022.111397.

[4] D. Yadav, S. Karki, P.G. Ingole, Nanofiltration (NF) membrane processing in the food industry, Food Eng. Rev. 14 (2022) 579–595, https://doi.org/10.1007/s12393-022-09320-4.

[5] K. Yamjala, M.S. Nainar, N.R. Ramisetti, Methods for the analysis of azo dyes employed in food industry — a review, Food Chem. 192 (2016) 813–824, https://doi.org/10.1016/j.foodchem.2015.07.085.

[6] L. Consoli, M.D. Hubinger, M.M. Dragosavac, Encapsulation of resveratrol via spray-drying of oil-in-water emulsions produced by ultrasound or membrane emulsification, J. Food Eng. 350 (2023) 111488, https://doi.org/10.1016/j.jfoodeng.2023.111488.

[7] R.W. Baker, Membrane Technology and Applications, 3rd ed., John Wiley & Sons, 2012.

[8] R. Xu, B. Wang, Y. Cai, Author correction: preparation and structures of PEBA gas separation membrane modified by fumed silica for oil vapor separation, Sci. Rep. 12 (2022) 1, https://doi.org/10.1038/s41598-022-05064-7.

[9] N. Hilal, C. Wright, Exploring the current state of play for cost-effective water treatment by membranes, NPJ Clean Water 1 (2018) 1–4, https://doi.org/10.1038/s41545-018-0008-8.

[10] T. Melin, R. Rautenbach, Membranverfahren: Grundlagen der Modul- und Anlagenauslegung, Springer-Verlag, 2007.

[11] A.M. Hanra, V. Ramachandhran, RO performance analysis of cellulose acetate and TFC polyamide membrane systems for separation of trace contaminants, Desalination 104 (1996) 175–183, https://doi.org/10.1016/0011-9164(96)00040-9.

[12] N. Ghaffour, T.M. Missimer, G.L. Amy, Technical review and evaluation of the economics of water desalination: current and future challenges for better water supply sustainability, Desalination 309 (2013) 197–207, https://doi.org/10.1016/j.desal.2012.10.015.

[13] European Commission, Directorate-General for Maritime Affairs and Fisheries, A. M. Addamo, A. Calvo Santos, J. Guillén, et al., The EU Blue Economy Report 2022, Publications Office of the European Union, 2022, https://doi.org/10.2771/793264.

[14] X. Santander, Global Water Desalination Market 2023 — Industry Trends and Forecasts, 2023.

[15] C.A. Scholes, Durability of membrane (lifetime of membrane), in: Encyclopedia of Membranes, 2015, pp. 1–2, https://doi.org/10.1007/978-3-642-40872-4_820-4.

[16] S. Nejati, S.A. Mirbagheri, D.M. Warsinger, M. Fazeli, Biofouling in seawater reverse osmosis (SWRO): impact of module geometry and mitigation with ultrafiltration, J. Water Process Eng. 29 (2019) 100782, https://doi.org/10.1016/j.jwpe.2019.100782.

[17] S. Gutiérrez Ruiz, J.A. López-Ramírez, M. Hassani Zerrouk, A. Egea-Corbacho Lopera, J.M. Quiroga Alonso, Study of reverse osmosis membranes fouling by inorganic salts and colloidal particles during seawater desalination, Chin. J. Chem. Eng. 28 (2020) 733–742, https://doi.org/10.1016/j.cjche.2019.10.004.

[18] L.N. Sim, T.H. Chong, A.H. Taheri, S.T.V. Sim, L. Lai, W.B. Krantz, A.G. Fane, A review of fouling indices and monitoring techniques for reverse osmosis, Desalination 434 (2018) 169–188, https://doi.org/10.1016/j.desal.2017.12.009.

[19] Y. Lebron, V. Moreira, P. Da Costa, A. Alkmin, L. De França Neta, A. Cerqueira, M. Amaral, Chemical cleaning procedures on permeability recovery and lifespan of MBR membranes treating petroleum refinery wastewater: from bench- to pilot-scale applications, J. Water Process Eng. (2021) 102411, https://doi.org/10.1016/j.jwpe.2021.102411.

[20] W. Lawler, J. Alvarez-Gaitan, G. Leslie, P. Le-Clech, Comparative life cycle assessment of end-of-life options for reverse osmosis membranes, Desalination 357 (2015) 45–54, https://doi.org/10.1016/j.desal.2014.10.013.

[21] F.I. Seibel, G.O.M. Giubel, V.B. Brião, M. Shabani, M. Pontié, End-of-life reverse osmosis membranes: recycle procedure and its applications for the treatment of brackish and surface water, J. Appl. Res. Water Wastewater 8 (2021) 77–87.

[22] M. Pontié, S. Awad, M. Tazerout, O. Chaouachi, B. Chaouachi, Recycling and energy recovery solutions of end-of-life reverse osmosis (RO) membrane materials: a sustainable approach, Desalination 423 (2017) 30–40, https://doi.org/10.1016/j.desal.2017.09.012.

[23] J. Landaburu-Aguirre, R. García-Pacheco, S. Molina, L. Rodríguez-Sáez, J. Rabadán, E. García-Calvo, Fouling prevention, preparing for re-use and membrane recycling: towards circular economy in RO desalination, Desalination 393 (2016) 16–30, https://doi.org/10.1016/j.desal.2016.04.002.

[24] A. Lejarazu-Larrañaga, J. Landaburu-Aguirre, J. Senán-Salinas, J.M. Ortiz, S. Molina, Thin film composite polyamide reverse osmosis membrane technology towards a circular economy, Membranes 12 (2022) 864, https://doi.org/10.3390/membranes12090864.

[25] J.A. Sanmartino, M. Khayet, M.C. García-Payo, Reuse of discarded membrane distillation membranes in microfiltration technology, J. Membr. Sci. 539 (2017) 273–283, https://doi.org/10.1016/j.memsci.2017.06.003.

[26] J. Senán-Salinas, A. Blanco, R. García-Pacheco, J. Landaburu-Aguirre, E. García-Calvo, Prospective life cycle assessment and economic analysis of direct recycling of end-of-life reverse osmosis membranes based on geographic information systems, J. Clean. Prod. 282 (2021) 124400, https://doi.org/10.1016/j.jclepro.2020.124400.

[27] J. Senán-Salinas, R. García-Pacheco, J. Landaburu-Aguirre, E. García-Calvo, Recycling of end-of-life reverse osmosis membranes: comparative LCA and cost-effectiveness analysis at pilot scale, Resour. Conserv. Recycl. 150 (2019) 104423, https://doi.org/10.1016/j.resconrec.2019.104423.

[28] S. Huang, C. Liu, H. Wu, Life cycle sustainability assessment of end-of-life reverse osmosis membranes management options, Desalination 613 (2025) 119050, https://doi.org/10.1016/j.desal.2025.119050.

[29] J. Li, C. Lu, J. Sun, H. Peng, Q. Li, S.S. Hosseini, Y. Zhu, M. Sun, B. Ma, Membrane recycling and resource utilization: latest progress and prospects, J. Environ. Sci. 156 (2025) 346–359, https://doi.org/10.1016/j.jes.2024.07.004.

[30] S. Avlonitis, W.T. Hanbury, T. Hodgkiess, Chlorine degradation of aromatic polyamides, Desalination 85 (1992) 321–334, https://doi.org/10.1016/0011-9164(92)80014-Z.

[31] C. Tian, T. Wang, H. Han, R. Dai, Z. Wang, Green solvent cleaning removes irrecoverable foulants from end-of-life membranes in membrane bioreactors: efficacy and mechanisms, Environ. Sci. Technol. 56 (2022) 12563–12572, https://doi.org/10.1021/acs.est.2c02321.

[32] A. Somrani, K. Abohelal, M. Pontié, A mini review of reused end-of-life reverse osmosis (EoL RO) membranes, Membranes 15 (2025) 217, https://doi.org/10.3390/membranes15070217.

[33] E. Coutinho de Paula, M.C. Santos Amaral, Environmental and economic evaluation of end-of-life reverse osmosis membranes recycling by means of chemical conversion, J. Clean. Prod. 194 (2018) 85–93, https://doi.org/10.1016/j.jclepro.2018.05.099.

[34] IDRA, Desalination and Reuse Handbook — International Desalination Association. https://idadesal.org/e-library/idra-water-security-handbook/, 2024 accessed July 23.

[35] Grand View Research, Water Desalination Equipment Market Size, Share & Trends Analysis Report, 2023.

[36] Markets and Markets, Membrane Filtration Market — Industry Analysis, Types, Advantages, and Forecast. https://www.marketsandmarkets.com/Market-Reports/membrane-filtration-market-68840418.html, 2024 accessed July 23.

[37] D.M. Warsinger, S. Chakraborty, E.W. Tow, M.H. Plumlee, C. Bellona, S. Loutatidou, L. Karimi, A.M. Mikelonis, A. Achilli, A. Ghassemi, L.P. Padhye, S. A. Snyder, S. Curcio, C.D. Vecitis, H.A. Arafat, J.H. Lienhard, A review of polymeric membranes and processes for potable water reuse, Prog. Polym. Sci. 81 (2018) 209–237, https://doi.org/10.1016/j.progpolymsci.2018.01.004.

[38] Z. Wang, C. Ma, C. Xu, S.A. Sinquefield, M.L. Shofner, S. Nair, Graphene oxide nanofiltration membranes for desalination under realistic conditions, Nat. Sustainability 4 (2021) 402–408, https://doi.org/10.1038/s41893-020-00674-3.

[39] S.K. Tiwary, M. Singh, S.V. Chavan, A. Karim, Graphene oxide-based membranes for water desalination and purification, NPJ 2D Mater. Appl. 8 (2024) 27, https://doi.org/10.1038/s41699-024-00462-z.

[40] J.S. Cadore, L.F. Fabro, G.O.M. Giubel, L.F.S. Costa, M.J.R. Pires, V.B. Brião, Synthesis of composite membranes modified with graphene oxide and polyethylene glycol for the removal of emerging contaminants from water, Colloids Surf. A Physicochem. Eng. Asp. 696 (2024) 134348–134362, https://doi.org/10.1016/j.colsurfa.2024.134348.

[41] U. Kamran, K.Y. Rhee, S.Y. Lee, S.J. Park, Innovative progress in graphene derivative-based composite hybrid membranes for contaminant removal: a review, Chemosphere 306 (2022) 135590, https://doi.org/10.1016/j.chemosphere.2022.135590.

[42] A. Ali, F. Rehman, M.A. Khan, F.H. Memon, F. Soomro, M. Iqbal, J. Yang, K. H. Thebo, Functionalized graphene-oxide lamellar membranes with tunable nanochannels for ionic and molecular separation, ACS Omega 7 (2022) 32410–32417, https://doi.org/10.1021/acsomega.2c03907.

[43] M. Barrejón, M. Prato, Carbon nanotube membranes in water treatment applications, Adv. Mater. Interfaces 9 (2022) 2100126.

[44] I. Ihsanullah, Carbon nanotube membranes for water purification: developments, challenges, and prospects, Sep. Purif. Technol. 209 (2019) 307–337, https://doi.org/10.1016/j.seppur.2018.07.043.

[45] K. Wang, D. Chen, Q. Wang, Y. Ying, W. Gao, L. Xie, Recent advances in applications of carbon nanotubes for desalination: a review, Nanomaterials 10 (2020) 1203, https://doi.org/10.3390/nano10061203.

[46] C. Li, J. Yang, L. Zhang, S. Li, Y. Yuan, X. Xiao, X. Fan, C. Song, Carbon-based membrane materials and applications in water and wastewater treatment: a review, Environ. Chem. Lett. 19 (2021) 1457–1475, https://doi.org/10.1007/s10311-020-01112-8.

[47] J. Ma, J. He, Y. Niu, C. Cheng, One-step fabrication of asymmetric alumina ceramic membranes with tunable pore parameters for oil–water separation, J. Water Process Eng. 58 (2024) 104739.

[48] W. Shi, C. Yang, M. Qiu, X. Chen, Y. Fan, A new method for preparing α-alumina UF membrane at low sintering temperature, J. Membr. Sci. 642 (2022) 119992.

[49] J. Wang, X. Wang, Q. Fu, J. Fu, F. Zhai, S. Li, Silicon carbide ceramic membrane support sintered at 800 °C with low-temperature sintering aid, Ceram. Int. 49 (2023) 25612–25619.

[50] Y. Wang, Y. Liu, Z. Chen, Y. Liu, J. Guo, W. Zhang, P. Rao, G. Li, Recent progress in pore-size control of silicon-carbide ceramic membranes, Ceram. Int. 48 (2022) 8960–8971.

[51] S.L.S. Rani, R.V. Kumar, Insights on applications of low-cost ceramic membranes in wastewater treatment: a mini-review, Case Stud. Chem. Environ. Eng. 4 (2021) 100149, https://doi.org/10.1016/j.cscee.2021.100149.

[52] M.B. Asif, Z. Zhang, Ceramic membrane technology for water and wastewater treatment: a critical review of performance, full-scale applications, membrane fouling and prospects, Chem. Eng. J. 418 (2021) 129481, https://doi.org/10.1016/j.cej.2021.129481.

[53] S. Dutta, R. Fernández de Luis, J. Goscianska, A. Demessence, R. Ettlinger, S. Wuttke, Metal–organic frameworks for water desalination, Adv. Funct. Mater. 34 (2024) 2304790, https://doi.org/10.1002/adfm.202304790.

[54] Y. Wen, R. Dai, X. Li, X. Zhang, X. Cao, Z. Wu, S. Lin, C.Y. Tang, Z. Wang, Metal–organic framework nanoflakes enable ultraselective polyamide RO membranes, Sci. Adv. 8 (2022) eabm4149, https://doi.org/10.1126/sciadv.abm4149.

[55] Q. Zhang, H. Yang, T. Zhou, X. Chen, W. Li, H. Pang, Metal–organic frameworks and their composites for environmental applications, Adv. Sci. 9 (2022) 2204141, https://doi.org/10.1002/advs.202204141.

[56] X. Wang, M. Wang, M. Chen, Y. Zhang, A mini review of ceramic-based MOF membranes for water treatment, Membranes 13 (2023) 751, https://doi.org/10.3390/membranes13090751.

[57] A. Fuwad, H. Ryu, E.D. Han, J.H. Lee, N. Malmstadt, Y.R. Kim, Y.H. Seo, S. M. Kim, T.J. Jeon, Highly permeable and shelf-stable aquaporin biomimetic membrane based on an anodic aluminum oxide substrate, NPJ Clean Water 7 (2024) 11, https://doi.org/10.1038/s41545-024-00301-0.

[58] A. Beratto-Ramos, J. Dagnino-Leone, J. Martínez-Oyanedel, M. Aranda, R. Bórquez, Fabrication and filtration performance of aquaporin biomimetic membranes for water treatment, Sep. Purif. Rev. 51 (2021) 340–357, https://doi.org/10.1080/15422119.2021.1948865.

[59] A. Azarafza, M.A. Islam, Y. Golpazirsorkheh, I. Efteghar, M. Sadrzadeh, M. Kamkar, A.F. Shojaei, M. Younas, T.M. Aminabhavi, M. Rezakazemi, Aquaporin-based biomimetic membranes for low-energy water desalination and separation applications, Adv. Funct. Mater. 33 (2023) 2213326, https://doi.org/10.1002/adfm.202213326.

[60] S. Wu, L.E. Peng, Z. Yang, P. Sarkar, M. Barboiu, C.Y. Tang, A.G. Fane, Next-generation desalination membranes empowered by novel materials: where are we now? Nano Micro Lett. 17 (2025) 91, https://doi.org/10.1007/s40820-024-01606-y.

[61] Z. Yang, P.-F. Sun, X. Li, B. Gan, L. Wang, X. Song, H.-D. Park, C.Y. Tang, A critical review on thin-film nanocomposite membranes with interlayered structure, Environ. Sci. Technol. 54 (2020) 15563–15583, https://doi.org/10.1021/acs.est.0c05377.

[62] R. Malaisamy, M.L. Bruening, High-flux nanofiltration membranes prepared by adsorption of multilayer polyelectrolyte membranes on polymeric supports, Langmuir 21 (2005) 10587–10592, https://doi.org/10.1021/la051669s.

[63] J. de Grooth, R. Oborný, J. Potreck, K. Nijmeijer, W.M. de Vos, The role of ionic strength and odd–even effects on the properties of polyelectrolyte multilayer nanofiltration membranes, J. Membr. Sci. 475 (2015) 311–319, https://doi.org/10.1016/j.memsci.2014.10.044.

[64] J. Contreras-Martínez, C. García-Payo, M. Khayet, Electrospun nanostructured membrane engineering using reverse osmosis recycled modules: membrane distillation application, Nanomaterials 11 (2021) 1601, https://doi.org/10.3390/nano11061601.

[65] Y. Liang, K.M. Knauer, Trends and future outlooks in circularity of desalination membrane materials, Front. Membr. Sci. Technol. 2 (2023) 1169158, https://doi.org/10.3389/frmst.2023.1169158.

[66] R. García-Pacheco, J. Landaburu-Aguirre, A. Lejarazu-Larrañaga, L. Rodríguez-Sáez, S. Molina, T. Ransome, E. García-Calvo, Free chlorine exposure dose (ppm·h) and its impact on RO membranes ageing and recycling potential, Desalination 457 (2019) 133–143, https://doi.org/10.1016/j.desal.2019.01.030.

[67] T. Tavares, J. Tavares, F.A. León-Zerpa, B. Peñate-Suárez, A. Ramos-Martín, Assessment of processes to increase the lifetime and potential reuse and recycling of reverse osmosis membranes towards a circular economy: case study of Cape Verde and Macaronesia area, Desalin. Water Treat. 263 (2022) 189–199, https://doi.org/10.5004/dwt.2022.28577.

[68] A. Lejarazu-Larrañaga, J.M. Ortiz, S. Molina, S. Pawlowski, C.F. Galinha, V. Otero, E. García-Calvo, S. Velizarov, J.G. Crespo, Nitrate removal by Donnan dialysis and anion-exchange membrane bioreactor using upcycled end-of-life reverse osmosis membranes, Membranes 12 (2022) 101, https://doi.org/10.3390/membranes12020101.

[69] J. Senán-Salinas, J. Landaburu-Aguirre, R. García-Pacheco, E. García-Calvo, Recyclability definition of recycled nanofiltration membranes through a life-cycle perspective and carbon footprint indicator, Membranes 12 (2022) 854, https://doi.org/10.3390/membranes12090854.

[70] T. Navarro, Water reuse and desalination in Spain — challenges and opportunities, J. Water Reuse Desalin. 8 (2018) 153–168, https://doi.org/10.2166/wrd.2018.043.

[71] W. Lawler, Z. Bradford-Hartke, M.J. Cran, M. Duke, G. Leslie, B.P. Ladewig, P. Le-Clech, Towards new opportunities for reuse, recycling and disposal of used reverse osmosis membranes, Desalination 299 (2012) 103–112, https://doi.org/10.1016/j.desal.2012.05.030.

[72] M. García-Rubio, J. Guardiola, Desalination in Spain: a growing alternative for water supply, Int. J. Water Resour. Dev. 28 (2012) 171–186, https://doi.org/10.1080/07900627.2012.642245.

[73] L. Grossi, E. Neves, L. Lange, M. Amaral, Sustainability in reverse osmosis membranes waste management: environmental and socioeconomic assessment, Desalination (2024) 117338, https://doi.org/10.1016/j.desal.2024.117338.

[74] A. Somrani, M. Shabani, Z. Mohamed, N. Ghaffour, F. Seibel, V.B. Brião, M. Pontié, Transforming an end-of-life reverse osmosis membrane in a cationic exchange membrane and its application in a fungal microbial fuel cell, Ionics 27 (2021) 3169–3184, https://doi.org/10.1007/s11581-021-04070-5.

[75] E.C. De Paula, J.C.L. Gomes, M.C.S. Amaral, Recycling of end-of-life reverse osmosis membranes by oxidative treatment: a technical evaluation, Water Sci. Technol. 76 (2017) 605–622, https://doi.org/10.2166/wst.2017.238.

[76] V.R. Moreira, Y.A.R. Lebron, L.V.S. Santos, M.C.S. Amaral, Low-cost recycled end-of-life reverse osmosis membranes for water treatment at the point-of-use, J. Clean. Prod. 362 (2022) 132495, https://doi.org/10.1016/j.jclepro.2022.132495.

[77] R. Dai, H. Han, T. Wang, J. Li, Z. Wu, C.-Y. Tang, Z. Wang, Cleaning–healing–interfacial polymerization strategy for upcycling real end-of-

life polyvinylidene fluoride microfiltration membranes, ACS Sustain. Chem. Eng. 9 (2021) 10352–10360, https://doi.org/10.1021/acssuschemeng.1c03481.

[78] R. García-Pacheco, J. Landaburu-Aguirre, P. Terrero-Rodríguez, E. Campos, F. Molina-Serrano, J. Rabadán, D. Zarzo, E. García-Calvo, Validation of recycled membranes for treating brackish water at pilot scale, Desalination 433 (2018) 199–208, https://doi.org/10.1016/j.desal.2017.12.034.

[79] J. Morón-López, L. Nieto-Reyes, S. Aguado, R. El-Shehawy, S. Molina, Recycling of end-of-life reverse osmosis membranes for membrane biofilm reactors (MBfRs): effect of chlorination on the membrane surface and gas permeability, Chemosphere 231 (2019) 103–112, https://doi.org/10.1016/j.chemosphere.2019.05.108.

[80] M.R. Moradi, A. Pihlajamäki, M. Hesampour, J. Ahlgren, M. Mänttäri, End-of-life RO membranes recycling: reuse as NF membranes by polyelectrolyte layer-by-layer deposition, J. Membr. Sci. 584 (2019) 300–308, https://doi.org/10.1016/j.memsci.2019.04.060.

[81] S. Molina, J. Landaburu-Aguirre, L. Rodríguez-Sáez, R. García-Pacheco, J.G. de la Campa, E. García-Calvo, Effect of sodium hypochlorite exposure on polysulfone recycled UF membranes and their surface characterization, Polym. Degrad. Stab. 150 (2018) 46–56, https://doi.org/10.1016/j.polymdegradstab.2018.02.012.

[82] J. Ahmed, Y. Jamal, A pilot application of recycled discarded RO membranes for low-strength greywater reclamation, Environ. Sci. Pollut. Res. 28 (2021) 34042–34050, https://doi.org/10.1007/s11356-020-11117-z.

[83] Y.S. Khoo, W.J. Lau, S.W. Hasan, W.N.W. Salleh, A.F. Ismail, New approach of recycling end-of-life reverse osmosis membranes via sonication for microfiltration process, J. Environ. Chem. Eng. 9 (2021) 106731, https://doi.org/10.1016/j.jece.2021.106731.

[84] A. Pompa-Pernía, S. Molina, A. Lejarazu-Larrañaga, J. Landaburu-Aguirre, E. García-Calvo, Validation of recycled nanofiltration and anion-exchange membranes for the treatment of urban wastewater for crop irrigation, Membranes 12 (2022) 746, https://doi.org/10.3390/membranes12080746.

[85] L.Y. Ng, A.W. Mohammad, C.Y. Ng, C.P. Leo, R. Rohani, Development of nanofiltration membrane with high salt selectivity and performance stability using polyelectrolyte multilayers, Desalination 351 (2014) 19–26, https://doi.org/10.1016/j.desal.2014.07.020.

[86] R. García-Pacheco, J. Landaburu-Aguirre, S. Molina, L. Rodríguez-Sáez, S.B. Teli, E. García-Calvo, Transformation of end-of-life RO membranes into NF and UF membranes: evaluation of membrane performance, J. Membr. Sci. 495 (2015) 305–315, https://doi.org/10.1016/j.memsci.2015.08.025.

[87] S. Zhao, Z. Wang, A loose nanofiltration membrane prepared by coating HPAN UF membrane with modified PEI for dye reuse and desalination, J. Membr. Sci. 524 (2017) 214–224, https://doi.org/10.1016/j.memsci.2016.11.035.

[88] L. Rodríguez-Sáez, J. Landaburu-Aguirre, S. Molina, M.C. García-Payo, E. García-Calvo, Study of surface modification of recycled ultrafiltration membranes using statistical design of experiments, Surf. Interfaces 23 (2021) 100978, https://doi.org/10.1016/j.surfin.2021.100978.

[89] R. García-Pacheco, Q. Li, J. Comas, R.A. Taylor, P. Le-Clech, Novel housing designs for nanofiltration and ultrafiltration gravity-driven recycled membrane-based systems, Sci. Total Environ. 767 (2021) 144181, https://doi.org/10.1016/j.scitotenv.2020.144181.

[90] M. Saxena, S. Sharma, A. Bhattacharya, Impacts of recycled polysulfone on the salt separation performance of thin film poly(piperazine-amide) membranes, J. Environ. Chem. Eng. 9 (2021) 105869, https://doi.org/10.1016/j.jece.2021.105869.

[91] K. Khaless, B. Achiou, R. Boulif, R. Benhida, Recycling of spent reverse osmosis membranes for second use in the clarification of wet-process phosphoric acid, Minerals 11 (2021) 637, https://doi.org/10.3390/min11060637.

[92] R. Dai, J. Chen, H. Han, H. Zhou, Z. Wang, Interfacial wettability regulation enables one-step upcycling of the end-of-life polymeric microfiltration membrane, ACS EST Eng. 3 (2023) 479–486, https://doi.org/10.1021/acsestengg.2c00329.

[93] S. Guclu, N. Kizildag, B. Dizman, S. Unal, Solvent-based recovery of high-purity polysulfone and polyester from end-of-life reverse osmosis membranes, Sustain. Mater. Technol. 31 (2022) e00358, https://doi.org/10.1016/j.susmat.2021.e00358.

[94] L. Rodríguez-Sáez, S.I. Patsios, J. Senán-Salinas, J. Landaburu-Aguirre, S. Molina, E. García-Calvo, A novel application of recycled ultrafiltration membranes in an aerobic membrane bioreactor (aMBR): a proof-of-concept study, Membranes 12 (2022) 218, https://doi.org/10.3390/membranes12020218.

[95] X. Wang, H. Han, H. Zhou, T. Wang, R. Dai, Z. Wang, Rapid upcycling of end-of-life microfiltration membrane mediated by the healing of metal–organic complex, ACS Sustain. Chem. Eng. 10 (2022) 9841–9849, https://doi.org/10.1021/acssuschemeng.2c01697.

[96] X. Zheng, Y. Chen, L. Zheng, R. Cheng, H. Hua, Recycling of aged RO membranes as NF/UF membranes: biosafety evaluation and aging process, Desalination 538 (2022) 115845, https://doi.org/10.1016/j.desal.2022.115845.

[97] C.P.M. de Oliveira, M.M. Viana, G.R. Silva, L.S. Frade Lima, E. Coutinho de Paula, M.C.S. Amaral, Potential use of green TiO_2 and recycled membrane in a photocatalytic membrane reactor for oil refinery wastewater polishing, J. Clean. Prod. 257 (2020) 120526, https://doi.org/10.1016/j.jclepro.2020.120526.

[98] Z.U. Rehman, H. Amjad, S.J. Khan, M. Yasmeen, A.A. Khan, N.K. Khanzada, Performance evaluation of UF membranes derived from recycled RO membrane: a step towards circular economy in desalination, Membranes 13 (2023) 628, https://doi.org/10.3390/membranes13070628.

[99] H. Wang, Y. Xu, B. Ma, W. Zou, J. Zeng, R. Dai, Z. Wang, Alkaline pre-treatment enables controllable downcycling of Si–Al fouled end-of-life RO membrane to NF and UF membranes, J. Membr. Sci. 690 (2024) 122209, https://doi.org/10.1016/j.memsci.2023.122209.

[100] Y. Hai, X. Wen, R. Ma, C. He, X. Yang, R. Xiong, J. Chen, Q. Sun, pH-responsive polyacrylic acid chemical cross-linking for end-of-life reverse osmosis membrane rejuvenation, Desalination 566 (2023) 116932, https://doi.org/10.1016/j.desal.2023.116932.

[101] L.A. Soto-Salcido, A. Pihlajamäki, M. Mänttäri, Reuse of end-of-life membranes through accelerated polyamide degradation, Waste Manag. 171 (2023) 124–133, https://doi.org/10.1016/j.wasman.2023.08.025.

[102] A. Alkhouzaam, M. Khraisheh, Towards sustainable management of end-of-life membranes: novel transformation of end-of-life reverse osmosis membranes for efficient dye/salt separation, Desalination 571 (2024) 117104, https://doi.org/10.1016/j.desal.2023.117104.

[103] J. Cui, Y. Chen, P. Guo, W. Su, L. Xu, Y. Zhang, Recycling end-of-life RO membranes for NF membranes via layer-by-layer assembly and interfacial polymerization, Ind. Eng. Chem. Res. 62 (2023) 9837–9848, https://doi.org/10.1021/acs.iecr.3c01042.

[104] J.M. Frick, L.A. Féris, I.C. Tessaro, Evaluation of pretreatments for a blowdown stream to feed a filtration system with discarded reverse osmosis membranes, Desalination 341 (2014) 126–134, https://doi.org/10.1016/j.desal.2014.02.033.

[105] B. Peñate, L. García-Rodríguez, Current trends and future prospects in the design of seawater reverse osmosis desalination technology, Desalination 284 (2012) 1–8, https://doi.org/10.1016/j.desal.2011.09.010.

[106] T. Yu, L. Meng, Q.B. Zhao, Y. Shi, H.Y. Hu, Y. Lu, Effects of chemical cleaning on RO membrane inorganic, organic and microbial foulant removal in a full-scale plant for municipal wastewater reclamation, Water Res. 113 (2017) 1–10, https://doi.org/10.1016/j.watres.2017.01.068.

[107] B. Li, S. Wang, X.J. Loh, Z. Li, T.-S. Chung, Closed-loop recyclable membranes enabled by covalent adaptable networks for water purification, Proc. Natl. Acad. Sci. USA 120 (2023) e2301009120, https://doi.org/10.1073/pnas.2301009120.

[108] C.Y. Loh, A.D. Burrows, M. Xie, Sustainable polymeric membranes: green chemistry and circular economy approaches, ACS ES&T Eng. 5 (2025) 1882–1906, https://doi.org/10.1021/acsestengg.5c00282.

[109] A. Beratto-Ramos, K. Jaramillo, P. Zapata, J. Romero, J. Martínez, M. Meléndrez, F. Saravia, H. Horn, R. Borquez, L. Pino-Soto, Characterization and evaluation of the recovery process of saturated reverse osmosis membranes by chemical oxidation, Desalination 594 (2024) 118273, https://doi.org/10.1016/j.desal.2024.118273.

[110] A. Alauifi, G. Devi, Design of wastewater treatment unit using end-of-life (EoL) reverse osmosis membrane, IOP Conf. Ser. Earth Environ. Sci. 1401 (2024) 012012, https://doi.org/10.1088/1755-1315/1401/1/012012.

[111] A. Somrani, Z. Mohamed, K. Abohelal, S. Larhrib, N. Ghaffour, M. Pontié, Transforming end-of-life SWRO desalination membranes into nanofiltration membranes for the treatment of brackish water and wastewater, Sci. Rep. 15 (2025) 88818, https://doi.org/10.1038/s41598-025-88818-3.

[112] J. Senán-Salinas, Strategies for Evaluating Recyclability of End-of-life Nanofiltration Membranes Through Life Cycle Assessment and Carbon Footprint Indicators, Ph.D. Dissertation, Universidad Autónoma de Madrid, 2020.

[113] J. Wang, J. Xing, G. Li, Z. Yao, Z. Ni, J. Wang, S. Liang, Z. Zhou, L. Zhang, How to extend the lifetime of RO membrane? From the perspective of the end-of-life RO membrane autopsy, Desalination 561 (2023) 116702, https://doi.org/10.1016/j.desal.2023.116702.

[114] B. Zappulla Sabio, R. García Pacheco, P.V. Pàrraga, I.A. Bernades, H. Monclús Sales, G. Blandin, Gravity-driven ultrafiltration and nanofiltration recycled membranes for tertiary treatment of urban wastewater, J. Water Process Eng. 53 (2024) 103745, https://doi.org/10.1016/j.jwpe.2024.105545.

[115] H. Fan, Y. Huang, N. Yip, Advancing ion-exchange membranes to ion-selective membranes: principles, status, and opportunities, Front. Environ. Sci. Eng. 17 (2022), https://doi.org/10.1007/s11783-023-1625-0.

[116] S. Yousef, J. Eimontas, N. Striūgas, A. Mohamed, M. Praspaliauskas, M. A. Abdelnaby, Phenol and benzoic acid recovery from end-of-life polysulfone ultrafiltration membranes and its thermochemical kinetic behaviour, Energy Sources Pt A 45 (2023) 6043–6061, https://doi.org/10.1080/15567036.2023.2213669.