

ENVIRONMENTAL PROBLEMS CAUSED BY THE USE OF REVERSE OSMOSIS MEMBRANE ELEMENTS, AND WAYS TO SOLVE THEM

A. V. Tyvonenko¹, T. Ye. Mitchenko¹, S. L. Vasilyuk¹

¹ National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute» 37, Prospect Peremohy, Kyiv, Ukraine, email: temarr98@gmail.com

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More than 70 percent of our planet is covered with water. And yet water is a scarce resource, and it is our future. According to the World Wildlife Fund, 1.1 billion people do not have access to it, and 2.7 billion experience a shortage of drinking water at least once a year. By 2025, two-thirds of the world's population may face water shortages.

The shortage of drinking water and the search for renewable resources are of the most important problems in the modern world, the solution of which is directed to considerable intellectual and financial resources. Reverse osmosis is one of the most common technologies for obtaining high-quality drinking water. Technological solutions constantly improve the process of reverse osmosis and reverse osmosis spiral wound membrane elements used, science and business go hand in hand. But the price of this progress is the annual generation of a large amount of waste generated from used reverse osmosis roll membrane elements, which are usually sent to the landfill, while there are no technological solutions for their disposal.

This work provides information on the available amount of such waste in the world and the dynamics of its growth in order to assess the scale of environmental damage that occurs as a result. The work collected information about the market of reverse osmosis spiral wound membrane elements in the world, and directions of their use. The structure, composition of components and technical characteristics of reverse osmosis spiral wound membrane elements are considered in detail, which makes it possible to evaluate the ways and possibilities of their utilization. The problems of surface contamination due to various types of fouling are considered. The main attention in the work is given to the reasons that cause the formation of waste. Based on the collected data, the scale of annual waste generation, which is formed due to spent reverse osmosis roll membrane elements, was analyzed. The possibility of reusing reverse osmosis spiral wound membrane elements and the main methods of their safe disposal are also considered. Summarizing the work carried out, recommendations were made on ways to solve the problem.

Keywords: *reverse osmosis spiral membrane elements; desalination; fouling; reuse; utilization*

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Introduction

Lack of qualitative drinking water is today perhaps the most important problem in the world, to solve which membrane reverse osmosis technology is used more and more

often (Aliyu, et al., 2018; García-Pacheco et al., 2015; Hailemariam et al., 2020; Verbeke et al., 2020; Contreras-Martínez et al., 2021).

Analysis of current trends shows (figure 1) that over the past decade there has been a steady significant growth of the global market

for membrane desalination and water purification systems (Gonzalez-Gil et al., 2021).

Reverse osmosis (RO) membrane elements are accounted for approximately 10% of the cost of systems. Today, the total market share of RO membrane elements for various purposes is about 2 billion USD. According to marketers, further rates of use of this technology will grow by 5% per year, and at the same time the market of RO membrane

elements designed for seawater desalination, sewage treatment, and for the treatment of tap water will grow proportionally. And this, in turn, means that there will be a proportional increase in the number of spent RO membrane elements, which becomes a significant environmental problem (García-Pacheco et al., 2015; Contreras-Martínez et al., 2021; Lawler et al., 2012; Asadollahi et al., 2017).

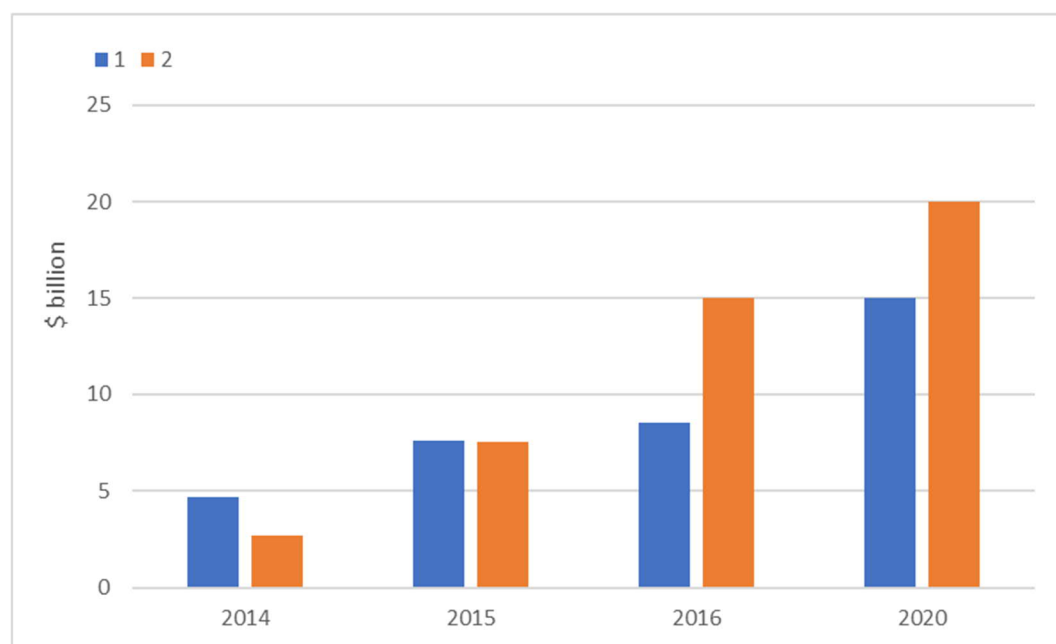


Fig. 1. Dynamics of growth of the markets of membrane systems of seawater desalination (1) and local systems of fresh water purification (2)

Characteristics of RO membrane elements

The most common elements used in reverse osmosis technology include thin-film composite polyamide membranes arranged in spiral rolls. Such elements are the most practical: they are easy to use, transport and store. The structure of the spiral RO element is shown in figure 2 (Gonzalez-Gil et al., 2021).

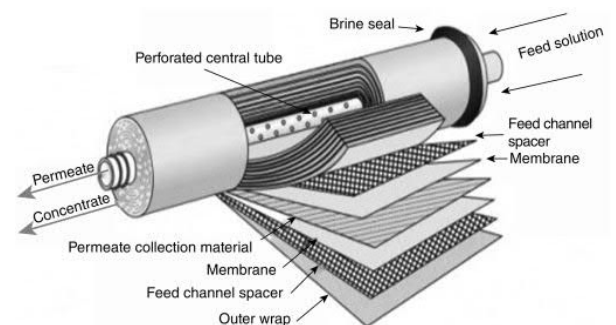


Fig. 2. The structure of the spiral RO membrane element

The membranes themselves consist of an active layer of polyamide with thickness of 0.2 μm , supported on a polysulfone substrate

with thickness of 40 μm , and a polyester nonwoven material with thickness of 120 μm (figure 3). The selective layer of the membrane is the polyamide layer. The polysulfone layer serves as a support, due to which the membrane can withstand high pressures without rupture. The polyester material provides the strength of the membrane film as a whole in the technological processing and assembling of elements (Hailemariam et al., 2020; Verbeke et al., 2020; Contreras-Martínez et al., 2021; Lawler et al., 2012; Adel et al., 2022; Qasim et al., 2019). Thin-film composite polyamide membranes are most often made by interfacial polymerization between m-phenylenediamine or piperazine and trimesoyl chloride (Hailemariam et al., 2020; Verbeke et al., 2020; Lawler et al., 2012; Landaburu-Aguirre et al. 2016). Membranes made by this method provide a high flow of permeate, are characterized by mechanical stability, and can operate at temperatures up to 45 $^{\circ}\text{C}$ and at significant pH differences (1-11).

In addition to the membrane, the elements contain other components made of different types of plastic:

Perforated tube - acrylonitrile-butadiene styrene;

Power spacer - polypropylene;

Permeate spacer - polyethylene tetraphthalate;

Outer wrapper - fiberglass (for industrial membranes);

Sealants - rubber.

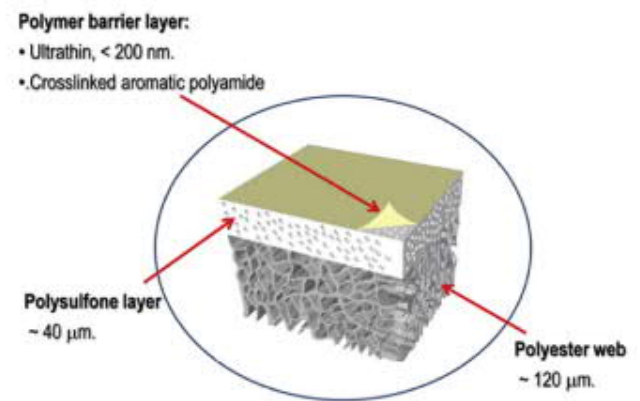


Fig. 3. Structure of polyamide thin-layer composite membrane (Qasim et al., 2019)

Different manufacturers produce RO membrane elements of the same size and classify their products by length and diameter and, accordingly, by performance and purpose (table 1) (Gonzalez-Gil et al., 2021).

Disposal of spent RO membrane elements

The analysis of the information shows that at present the treatment of spent membrane elements worldwide contradicts the principles of the European Directive (Directive 2008/98/EC, 2008) on pyramidal waste management. According to this directive, the preferred options are:

- waste prevention,
- reuse,
- recycling,
- utilization

in the appropriate priority order (Directive 2008/98/EC, 2008).

Table 1. Classification of membrane elements by nominal size

Purpose	Length, inches (mm)	Diameter, inches (mm)	Productivity, GPD (m ³ /day)
Industrial water treatment	40 (1016)	8.0 (201)	6000 – 14700 (22.68 – 55.57)
Household and commercial water treatment	40 (1016)	4.0 (99)	2000 – 3000 (7.56 – 11.34)
	21 (533)	4.0 (99)	800 – 1200 (3.02 – 4.54)
	14 (356)	4.0 (99)	350 – 800 (1.32 – 3.02)
Household water purification systems	12 (305)	3.0 (76)	200 – 600 (0.76 – 2.27)
	12 (305)	2.0 (50)	50 – 250 (0.19 – 0.95)
	12 (305)	1.8 (45)	24 – 150 (0.09 – 0.57)

Waste prevention

During the operation of RO membrane elements over time there is a decrease in permeate flow and increase in transmembrane pressure, as well as reduced selectivity due to the formation of fouling - a layer of contaminants that blocks membrane pores (Adel et al., 2022; Qasim et al., 2019). Thus, contamination of membrane elements is one of the main reasons for the need to replace them (Goh et al., 2018), thus, leads to waste generation. Other causes are chemical damage of the membrane web, most often due to oxidation, and physical damage of the web or element.

Contamination of the membrane element is a complex phenomenon, as its formation is influenced by many factors such as: water composition, methods of its purification preceding reverse osmosis, operating parameters of the membrane process and more.

Membrane contamination can be divided into several types: organic, inorganic, colloidal, and biological. Figure 4 shows the scanning electron microscope images of different types of contaminants of the RO membrane (Jiang et al., 2017).

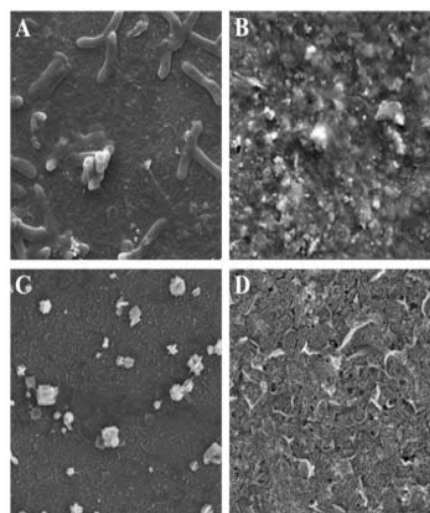


Fig. 4. Images of contaminants on RO membranes obtained using a scanning electron microscope:

A - biofouling, B - organic fouling, C - scaling, D - colloidal fouling

There are two fundamentally different approaches to prevent the contamination of RO membrane elements. The first approach is to remove all impurities that can form deposits on the membrane from the water before reverse osmosis - for example, by sorption methods of water softening, removal of iron and manganese, etc. It is obvious that such water treatment is an effective, but extremely costly solution to the problem of contamination of RO membrane elements and significantly reduces both economic and environmental benefits of reverse osmosis demineralization. As a result, in order to ensure the smooth and efficient operation of membrane installations - especially reverse osmosis systems - another method of preventing contamination is increasing in popularity - dosing reagents that inhibit the formation of deposits, namely antiscalants, into purified water (Mitchenko et al., 2019).

These methods can significantly extend the life of reverse osmosis elements, but it is impossible to completely avoid the formation of fouling on the surface of the membranes, which does not allow to make the process completely zero-waste.

Reuse

According to Directive 2008/98/EC, the reuse of waste means the cleaning, repair or recovery of materials in such a way that they can be reused (Directive 2008/98/EC, 2008).

There are two main methods of cleaning of membrane elements - physical and chemical. Physical cleaning is applied mainly after a short period of membrane operation and removes mostly loose layer of colloidal contamination - it is rapid backwashing of the membrane element with water (Othman et al., 2021).

For chemical cleaning, it is important to choose the composition of the reagent according to the type of contamination. In addition to the ability to effectively remove fouling, a prerequisite for chemical reagents is that they must not damage the selective membrane layer. As the action of chemical reagents on contamination, chemical reactions occur that are aimed at reducing the strength of cohesion between contaminants and the adhesion of the latter to the membrane surface. These processes facilitate the removal of contaminants (Varin et al., 2013).

Bases, acids, chelating agents, and surfactants are commonly used as chemical reagents. Alkaline solutions, such as sodium hydroxide, are used to remove biological fouling and organic contaminants. Such acids as hydrochloric, orthophosphoric, sulfuric, and citric are used to remove inorganic contaminants (scaling) (Agnihotri et al., 2020). Sodium hypochlorite, ozone or hydrogen peroxide may be effective in removing biofouling (Ling et al., 2017; Ouali et al., 2021). Ethylenediaminetetraacetic acid solution is often used as a chelating agent (Jiang et al. 2017). Surfactants used for cleaning typically contain both hydrophobic and hydrophilic groups (Jiang et al. 2017). The efficiency of chemical cleaning is influenced by the duration of cleaning, pH of the system, temperature and flow rate of the circulating reagent. In general, the correct use of cleaning technologies can extend the service life of reverse osmosis elements for industrial and commercial purposes up to 5-8 years, which contributes to a significant reduction in waste generation.

However, attempts to clean household membranes in a similar way cause a significant deterioration of their initial characteristics, so this process is ineffective

and is not used today. One of the reasons for this is that the regeneration of elements in industry occurs when the efficiency of the element is reduced by 20-30%, which means that contaminants can be relatively easily removed. At the same time, household elements work to almost 100%, when the contamination already forms a strong layer on the surface of the membrane and other components of the element, which prevents further leakage of water. Removal of contaminants in this case is a much more difficult task, which requires other methods.

Recycling

According to the EU Directive, "recycling" is the process by which waste is processed into products and materials for original or other purposes (Directive 2008/98/EC, 2008). The recycling of membrane elements can be divided into 2 types, namely direct processing while preserving the structure of the element, and indirect.

Direct recycling

The process of direct recycling of spent RO membrane elements means the process of obtaining filter elements with new properties as a result of partial or complete degradation of the active layer of polyamide under the action of various chemicals. This process was studied in detail during the study of aging of reverse osmosis membranes (Donose et al., 2013) or the impact on the web of various oxidants, namely chlorine compounds (hypochlorite, chlorine dioxide, chloramines, etc.), hydrogen peroxide, ozone, potassium permanganate (Khaless et al., 2021; Kang et al., 2007; Moradia et al., 2019; Donose et al., 2013; Cran et al., 2011; Ling et al., 2019; Yu

et al., 2019). As shown by several authors, in the latter case the polyamide layer changes its morphology, resulting in changes in its selectivity (Lawler et al., 2012; Goh et al., 2018; Paula et al., 2018; Pontie et al., 2017). Due to this effect, it is possible, following certain technological guidelines, to obtain nano- or ultrafiltration membranes from spent reverse osmosis ones, the efficiency of which can no longer be restored by the methods described above.

However, direct recycling or reuse of the membrane element is not always possible due to high contamination or physical or chemical damage. Therefore, the next step in the waste management hierarchy is an indirect recycling strategy, which involves the deconstruction of the membrane element [40]. This strategy involves the conversion of all or part of the element into industrial products for other purposes.

Indirect recycling

As noted earlier, membrane elements consist of various polymeric materials. In addition to the membrane itself, it contains food and permeate spacers, which are made of polypropylene and polyethylene tetraphthalate. Permeate tubes are made of acrylonitrile-butadiene styrene (Dai et al., 2021). Each of these elements can be separated and recycled using mechanical or chemical methods.

Indirect recycling of membrane modules includes various methods, from the most practical, such as the manufacture of fillers for composite concrete or frame building materials, including sandwich panels, to exotic methods, such as decoration for clothing (Al-Salem et al., 2009).

The simplest materials for recycling are permeate tubes and permeate spacer, as these

materials come into contact mainly with clean water and do not need to be pre-cleaned. For example, polyethylene terephthalate is widely processed in beverage containers. The main problem for the processing of polypropylene is its contamination, which must first be removed. But these are simple and well-known technologies for recycling plastics.

There are also known methods of using parts of membrane elements in agriculture. For example, membrane sheets were recycled into geotextiles that were used under a layer of gravel to reduce weed growth and preserve the position of decorative stones (Ould et al., 2010). Spacers have been used as lawn protection nets (Dai et al., 2021).

However, these solutions are relevant for industrial and commercial membrane elements, and unfortunately not for household, the size of the components of which are too small for most of the above ways of indirect recycling. Today, the way of utilization seems more promising for them.

Utilization

As an alternative to indirect processing methods, which allows to process any membrane elements, there are energy methods, the most effective of which is pyrolysis. This method is based on obtaining synthesis gas with a high energy content due to the process of gasification of plastics. Compared to traditional combustion, pyrolysis has a few advantages, including lower emissions and a high-energy fuel product.

Conclusions

The analysis of information showed that the world annually produces and uses in the process of demineralization and water purification of about 1.5 billion reverse osmosis membrane elements, which then go to landfills in the form of plastic waste weighing about 20 million tons per year with annual growth of at least 5%. Today it has grown into a serious environmental problem, which can be solved in different ways. The most promising of them (according to the European Directive 2008/98/EU on pyramidal waste management) are the following:

- wider use of existing and development of new technologies for adjusting the composition of feed water to provide operating conditions that help extend the service life of RO membrane elements;

- the use of technologies for the restoration of functions and reuse of spent RO membrane elements for their intended purpose;

- development and use of technologies for direct recycling of spent RO membrane elements into filter elements of other types to extend the service life;

- search for ways of indirect recycling of spent RO membrane elements into raw materials or intermediate products for other purposes.

Particular attention should be paid to finding ways to extend the service life and reuse of household RO membrane elements, the situation with which today is most acute.

All these solutions are aimed at extending the life of RO elements and, thus, reducing waste. Today, the use of the pyrolysis process is considered to be the most rational for the final solution of the issue of plastic waste disposal.

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ЕКОЛОГІЧНІ ПРОБЛЕМИ, ВИКЛИКАНІ ВИКОРИСТАННЯМ ЗВОРотноОСМОТИЧНИХ МЕМБРАННИХ ЕЛЕМЕНТІВ, ТА ШЛЯХИ ЇХ ВИРІШЕННЯ

А. В. Тивоненко¹, Т. Є. Мітченко¹, С. Л. Василюк¹

¹ Національний технічний університет України «Київський політехнічний інститут імені Ігоря Сікорського», Київ, Україна; email: temarr98@gmail.com

Понад 70 відсотків нашої планети вкрито водою. І все ж вода є дефіцитним ресурсом, і це наше майбутнє. За даними Всесвітнього фонду дикої природи 1,1 мільярда людей не мають доступу до неї, а 2,7 мільярда відчують нестачу питної води принаймні раз на рік. До 2025 року дві третини населення світу можуть зіткнутися з нестачею води.

Дефіцит питної води і пошук відновлювальних ресурсів є однією з найважливіших проблем у сучасному світі, на вирішення яких направлені чималі інтелектуальні та фінансові ресурси. Зворотний осмос є однією з найрозповсюдженіших технологій отримання питної води високої якості. Технологічні рішення постійно удосконалюють процес зворотного осмосу і зворотньоосмотичні рулонні мембранні елементи, що використовуються, наук і бізнес йдуть поруч. Але ціною цього прогресу є щорічне утворення великої кількості відходів, що утворюються з використаних зворотньоосмотичних рулонних мембранних елементів, котрі зазвичай направляються на сміттєзвалище, при цьому відсутні технологічні рішення щодо їх утилізації.

В даній роботі наведено інформацію що до наявної кількості таких відходів в світі та динаміки її зростання для оцінки масштабів екологічної шкоди, яка внаслідок цього виникає.

В роботі проведено збір інформації про ринок зворотньоосмотичних рулонних мембранних елементів в світі, та напрямків їх використання. Детально розглянута будова, склад компонентів і технічні характеристики зворотньоосмотичних рулонних мембранних елементів, що дає змогу оцінити шляхи і можливості їх утилізації. Розглянуті питання забруднення поверхні за рахунок різних типів фоулінгу. Основну увагу в роботі приділено причинам, що викликають утворенню відходів. На основі зібраних даних проаналізовано масштаби утворення щорічних відходів, що формуються за рахунок відпрацьованих зворотньоосмотичних рулонних мембранних елементів. Також розглянута можливість повторного використання зворотньоосмотичних рулонних мембранних елементів і основні методи їх безпечної утилізації. Підсумовуючи проведену роботу сформувані рекомендації щодо шляхів вирішення проблеми.

Ключові слова: зворотньоосмотичні рулонні мембранні елементи; знесолення; фоулінг; повторне використання; утилізація