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RECYCLING REVERSE OSMOSIS MEMBRANES: ADDRESSING THE CHALLENGES OF NON-BIODEGRADABILITY AND WASTE GENERATION

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Abstract- Non-biodegradable waste accumulation is a crucial environmental concern. One of the major drawbacks of modern desalination plants is the massive quantities of reverse osmosis (RO) membranes solid waste. This paper explores the problem of non-biodegradable membranes and the growing concern surrounding the massive accumulation of RO membrane waste. Furthermore, it investigates the feasibility and potential benefits of recycling and reusing RO membranes as a sustainable solution. Reverse osmosis membranes have a limited life span of between five to seven years. Tons of non-biodegradable RO membranes are disposed of annually in landfills which poses severe environmental concerns. Several challenges hinder the widespread adoption of recycling RO membranes, including the presence of irreversible fouling, the diverse composition of membranes, and the need for cost-effective and energy-efficient recycling methods. However, recent advances in pretreatment processes, antifouling membranes, anit-scalant solutions, and membrane characterization provide possibilities for overcoming these complications. By embracing recycling and reuse strategies for RO membranes, the water treatment industry can transition towards a more sustainable and environmentally responsible approach. Therefore, recycling RO membranes can offer large economic and environmental benefits.

Keywords- Membrane recycle; Desalination; Reverse osmosis; Sustainability.

1. INTRODUCTION

Reverse osmosis (RO) membrane recycling and reuse have gained widespread recognition in the scientific community [1-3]. Currently, reverse osmosis is the most applied technique for water desalination with a more than 70% share of the total desalination plants worldwide [4]. Reverse osmosis process has great potential in eliminating the dissolved contaminants in seawater, however, the membranes suffer from irreversible fouling over time and must be replaced frequently. Tons of end-of-life non-biodegradable membranes have been disposed into the ecosystem which poses serious environmental concerns [5]. A previous study estimated the mass destined for landfills due to the disposal of 9000 RO modules to be 121.5 tons/year [6]. Statistically, based on the linear economy approach embarrassed by industrial entities, more than 1.5 x 104 tons of RO modules are discarded annually [7]. The market for RO technology is forecasted to increase tremendously by 2030 (Figure 1) due to increased pollution and the lack of freshwater sources [8].

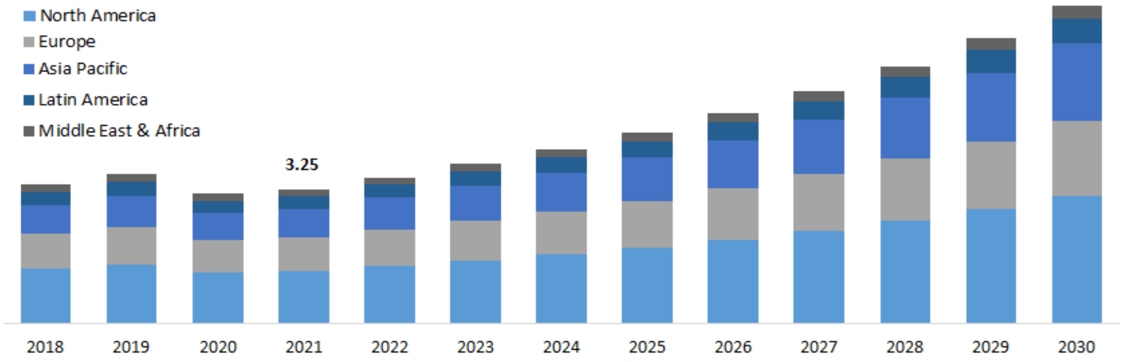

Figure 1 Forecast of the global membrane market size (USD Billion), region based.

There are many potential benefits of reusing and recycling RO membranes. For one thing, it can aid in reducing the cost of water treatment by extending the lifespan of the membranes and reducing the need to purchase new modules. It can reduce the environmental impact of the treatment process by reducing the amount of waste generated and conserving resources. Additionally, by reusing and recycling the materials used to create RO membranes, the amount of energy and resources required to manufacture new membranes in the future are reduced which reduces the carbon footprint of the desalination plants [8-10]. Despite the benefits of reusing and recycling RO membranes, several challenges should be tackled in order to commercialize the membrane recycling process. For instance, the lack of standardization in the industry and the technical challenges related to repairing and cleaning damaged or fouled membranes. In addition, the cost of reusing and recycling RO membranes may still be higher than the cost of simply purchasing new membranes. This can be due to the additional labor and equipment required for membrane conditioning and the fact that the average life span of a recycled membrane is 60% less than that of a new membrane. However, as technology continues to improve and the demand for more sustainable water treatment practices grows, it is likely that the cost of reusing and recycling RO membranes will decrease, making these practices more economically feasible. A recent study performed autopsy over RO membranes after approximately eight years of operation from a three-stage full-scale plant used to reclaim municipal wastewater to assess their end-of-life state and fouling behavior [11].

Silicon-related foulants dominated the third stage resulting in a rougher surface, the detection of siloxanes and other silicon species on end-of-life RO membranes suggest new research directions on fouling and its mitigation by improved chemical cleaning formulations. Another study investigated that fouled-membrane exposure to chlorine may prolong the membrane life span [12]. Fouling can be considered as a protective layer against chorine oxidation of the PA layer in RO membranes. Periodic chlorine exposure could be a valuable tool to extend the RO membrane lifespan in water reuse applications without losing the RO-type membrane selectivity. However, it is important to emphasize that striking the right balance between the dose and exposure length of chlorine oxidation exists for oxidation of solely membrane fouling. The aim of this work is to review the state-of-the-art RO membrane reuse and recycling, discuss the problems in current end-of-life RO membrane disposal, and states some of the proposed solutions to the current limitations in membrane recycling.

2. MEMBRANE DISPOSAL AND THE NON-BIODEGRADABILITY ISSUE

Non-biodegradable polymers are utilized extensively for RO membrane synthesis owing to their high thermal and chemical stability. The end-of-life RO membranes are commonly discarded into landfills. The accumulation of non-biodegradable RO membranes in the environment adversely affects wildlife and might affect human communities as well. The membranes tend to break down into their constituting monomers which are usually toxic [13]. Another pollution aspect is landfill leachate which is defined as the toxic liquid that forms due to the leaching of pollutants from a landfill by rainwater [14]. Landfill leachate is a growing environmental concern in low and middle income countries due to the adaptation of the lower-cost open dumps or non-engineered landfills [15]. The extraction of the degraded membrane pieces from either the water or land is expensive and tedious. Furthermore, the degraded pieces can be consumed by land and aquatic animals [16]. Figure 2 illustrates the possible harms caused by landfill leachate. The limited non-biodegradable polymers' recycling infrastructure and elevated mass of disposed materials may lead to the membranes ending up incinerated. End-of-life membrane incineration increases the carbon footprint of the process, contributes to global warming, and increases air pollution through the emission of toxic carbon, nitrogen, and sulfur oxides [17].

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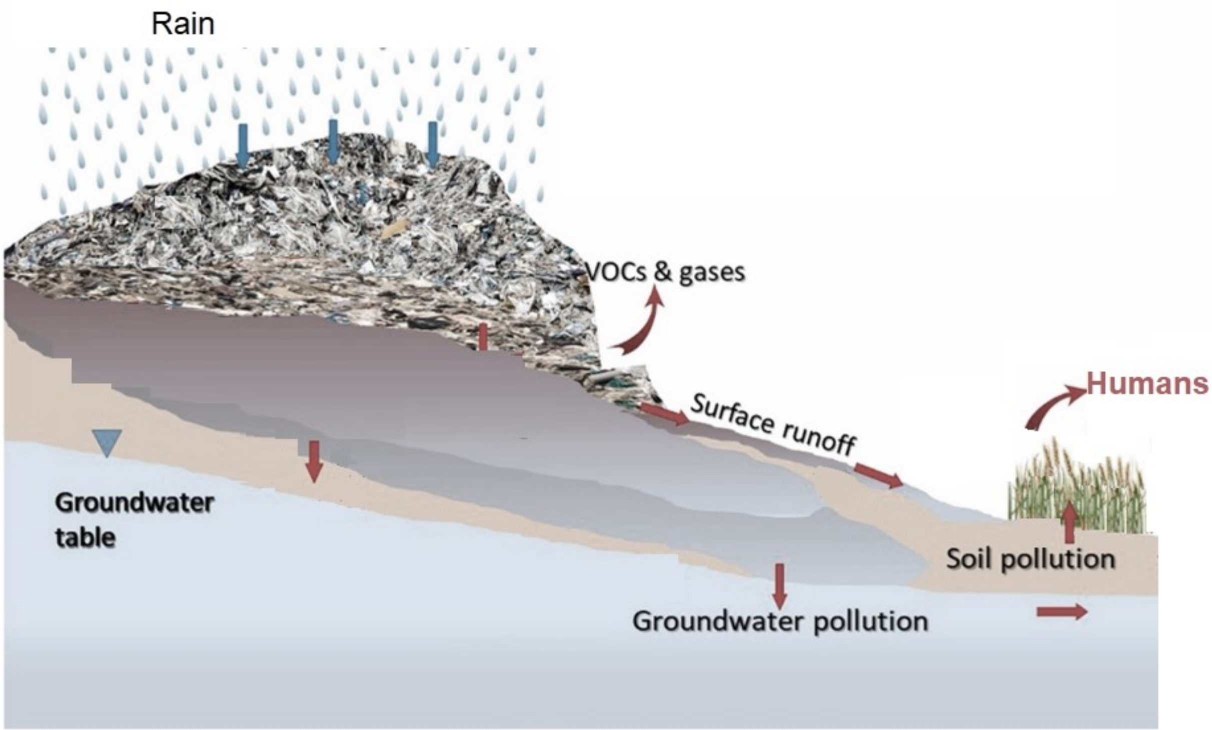

Figure 2 Possible pollutants that leach out to the environment from landfills and the possible pathways.

3. CURRENT MEMBRANE REUSE OPTIONS

The waste management hierarchy for RO membranes (Figure 3) prioritizes the possible pathways for reducing environmental pollution from discarded RO membranes. Minimizing the generation of new RO modules is the best option in terms of waste management. Disposal and incineration are the least desired options with efficient energy recovery being a preferable choice than disposal. Direct membrane reuse is recommended over recycling.

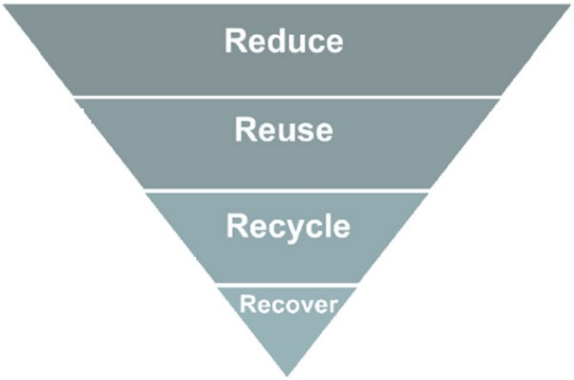

Figure 3 End-of-life reverse osmosis membrane management hierarchy.

I. *Direct Reuse*

The research on this approach is very limited in the literature. Two recent publications were reviewed to assess the current state of direct membrane reuse. Pacheco, R. et.al reused discarded 8’’ RO membranes from a seawater desalination plant for the treatment of landfill leachate [18]. The authors did not specify the first lifespan of the membrane, however, they stated that the average span considered is within 1 to 3 years. Membrane regeneration to eliminate fouling comprised the use of a chemical wash solution with controlled concentration, pH, and contact time. The membranes with no physical damage could be applied for large-scale treatment while the membranes with external physical damage were used for laboratory tests. Six out of 12 studied membranes could be successfully used for the landfill leachate treatment system. The treatment plant consisted of 12 RO modules in a series double-flow configuration. The plant was operated for 27 months with a combination of the reused membranes and new membranes. The system performance was compared to the system using completely new RO membranes. The treatment results are given in Figure 4. It can be seen that the proper direct reuse of end-of-life RO membranes with new RO membranes could be economically feasible. The transmembrane pressure (TMP) was lower when 50% of the membranes were reused membranes. This is due to the fact that pores expansion occurred during the initial operation period of the membrane and by the chemical cleaning. Remarkably, The treatment efficiency did not vary considerably and remained within the acceptable ranges for water discharge.

Another study utilized discarded RO membranes to treat water from a wastewater treatment plant collected after the secondary clarifier step (TDS ~ 1100 ppm, pH ~ 8.05, Total Kjeldahl nitrogen = 33.1 mg/L). The discarded RO membranes were collected from the primary and secondary treatment desalination units and are coded M1 and M2, respectively. Both membranes were initially compared with standard RO membranes against saline water (TDS ~ 33,000 ppm) to assess their performance. The M1 membrane achieved a high rejection of salt (97%) compared to 50% rejection from the M2 membrane. The M1 membrane flux was 34% lower than the standard membrane and that of the M2 membrane was 14% lower than the standard. This is an important result that the feed characteristics to a reverse osmosis membrane during its first lifespan are determinantal to its fate. However, when the membranes were tested for the treatment of secondary wastewater, both membranes achieved high treatment efficiency. The flux was in the range of 56 – 59 L/m2.h and the salt rejection was always higher than 96% at a TMP of 40 bar. Therefore, the membrane state was not a limiting factor in treating mild feeds.

Direct reuse of RO membranes without any additional processing is apparently the most environmentally viable solution. However, a proper assessment of the current state and performance is a must and an efficient chemical cleaning can be essential. A crucial step in membrane reuse is the validation of the old membranes as permeability, rejection, and integrity must be evaluated before involving the membrane back in the process. To do this, a detailed performance report of the membranes after their planned operation time should be acquired from specialized laboratories [19].

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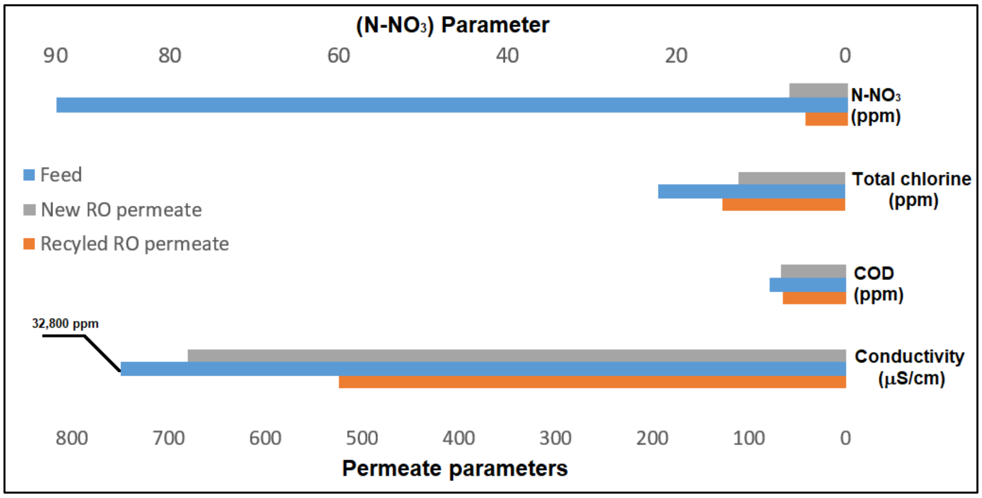

Figure 4 Comparison of the permeate quality from the treatment of landfill leachate.

II. *Polyamide Layer Degradation*

Most RO membranes utilized currently in industrial applications are thin-film composites consisting of a thin polyamide top layer followed by a porous polysulfone layer, and a polyester support. Therefore, degradation of the polyamide layer can increase the porosity of the RO membrane and achieve water permeabilities within the range of nanofiltration or ultrafiltration [20]. The dense polyamide top layer is prone to degradation by common oxidation agents; Previous studies used different oxidants including sodium hypochlorite, sodium dodecyl sulfate, hydrogen peroxide, potassium permanganate, and acetone [21-25]. The polyamide layer oxidation can be carried out by contacting the membrane in either immersion or active recirculation modes. Active circulation was found to be more effective than passive immersion due to enhanced kinetics and mass transfer [26]. A previous study investigated the effect of contact time of various chemicals on the degradation of the polyamide layer [22]. N-methyl-2-pyrrolidone (NMP), acetone and 10% sodium hypochlorite were the tested chemicals. Acetone and NMP did not show pronounced improve in the membrane permeability; the permeability only improved by 10% and 36%, respectively after 92h of immersion. Dilute sodium hypochlorite was found to be the most efficient in the degradation of the polyamide layer; the permeability was improved by 10 folds after 92h of immersion. The contact time in passive immersion mode had a great influence on the final product permeability and salt rejection. The membrane performance was tested as a function of exposure time to sodium hypochlorite against synthetic brackish water feed (2000 ppm NaCl, 2000 ppm $MgSO_4$, and 250 ppm dextrose). Results showed that the membrane conversion reaction started after 10 hours of modification. Up to 86 hours of degradation the membrane behavior resembled that of a nanofiltration membrane. After 86 hours of degradation, the behavior starts to shift to that of an ultrafiltration membrane. This is obvious from the water permeability and the deterioration in the rejection of the ions. After the first 10 hours, the rejection of the monovalent ions deteriorated rapidly which is an indication of a nanofiltration membrane behavior. After 86 hours, the water permeability increased significantly and the salt rejection started to drop considerably which is an indication of an ultrafiltration membrane.

Larrañaga, A. et.al utilized polysulfone in the preparation of an anion exchange membrane. The polyamide layer was completely eliminated by circulating a 14 wt.% sodium hypochlorite solution [27]. The anion exchange membrane was prepared by casting and phase inversion. The anion exchange resin was mixed with a casting solution containing polyvinyl chloride and the whole solution was cast onto the converted end-of-life RO membrane. The recycled membrane achieved a treatment efficiency that is 87% similar to a standard anion exchange membrane.

4. CURRENT LIMITATIONS IN RO MEMBRANE RECYCLING

Recycling of RO membranes is indeed promising in both environmental and economic aspects. However, certain limitations hinder the widespread use of the technology. A main limitation is the use of a proper cleaning solution for a specific membrane condition. If the washing solution is too alkaline, too acidic, or applied for longer periods than required, the membrane will be damaged. Moreover, the current cleaning technologies require a large residence time which in turn increases the capital cost of a large-scale process. In addition, RO membrane cleaning can be ineffective at removing certain contaminants (e.g. bacterial biofilms). Cracking and physical damage to the membrane are other limitations to the process. improper handling during membrane installation can lead to membrane damage and minor cracks development. Moreover, applying overpressure above recommended limits can cause the membrane to crack [28]. In order to overcome these limitations, the membrane must be operated properly during its initial lifespan. The implementation of effective pretreatment processes such as dissolved air floatation, ozonation, adsorption, etc. Moreover, improving the research on antifouling membranes and proper anit-scalant solutions minimizes the requirement for periodic cleaning of the membrane consequently reducing the extent of membrane damage [29].

5. CONCLUSION

Membrane recycling and reuse offer numerous advantages. The current methods adapted for end-of-life membrane management such as landfills or incineration are a great waste and adversely affect the environment. The latest trends include using the end-of-life membrane as it is and chemical conditioning for a different application. Reusing the membrane is economically attractive but, the membrane condition strongly affects its applicability. Recycling on the other hand is less affected by the condition of the membrane but requires proper chemical modification. In light of the previous findings, to achieve the circular economy in RO membrane applications, proper handling of the RO membrane in its initial lifespan is mandatory. The operators must ensure regular maintenance, balanced process-chemicals dosing, and the effectiveness of the pretreatment system. A well-established pre-treatment system not only prolongs the lifetime of the RO membrane but also sustains the membrane condition for effective recycling. There is a big improvement in the membrane antifouling properties to avoid the early membrane aging. In this way, research efforts on improving the membrane process efficiency and avoiding membranes to become waste have been mainly focused on developing efficient pretreatment and cleaning processes as well as preparing novel antifouling membranes. In addition, it shows that hybrid systems are the cutting edge technologies applied for this purpose.

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