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Review

Sustainable membrane technology for water purification—Manufacturing, recycling and environmental impacts

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Abstract: Water pollution has become a serious threat to our ecosystem. Water contamination due to human, commercial, and industrial activities has negatively affected the whole world. Owing to the global demanding challenges of water pollution treatments and achieving sustainability, membrane technology has gained increasing research attention. Although numerous membrane materials have focused, the sustainable water purification membranes are most effective for environmental needs. In this regard sustainable, green, and recyclable polymeric and nanocomposite membranes have been developed. Materials fulfilling sustainable environmental demands usually include wide-ranging polyesters, polyamides, polysulfones, and recyclable/biodegradable petroleum polymers plus non-toxic solvents. Consequently, water purification membranes for nanofiltration, microfiltration, reverse osmosis, ultrafiltration, and related filtration processes have been designed. Sustainable polymer membranes for water purification have been manufactured using facile techniques. The resulting membranes have been tested for desalination, dye removal, ion separation, and antibacterial processes for wastewater. Environmental sustainability studies have also pointed towards desired life cycle assessment results for these water purification membranes. Recycling of water treatment membranes have been performed by three major processes mechanical recycling, chemical recycling, or thermal recycling. Moreover, use of sustainable membranes has caused positive environmental impacts for safe waste water treatment. Importantly, worth of sustainable water purification membranes has been analyzed for the environmentally friendly water purification applications. There is vast scope of developing and investigating water purification membranes using countless sustainable polymers, materials, and nanomaterials. Hence, value of sustainable membranes has been analyzed to meet the global demands and challenges to attain future clean water and ecosystem.

Keywords: sustainable; membrane technology; polymer; recycling; water purification

1. Introduction

For the purification of globally produced wastewater, membrane technology has been found most effective not only for treating the desired pollutants but also for large-scale processing [1]. However, previously synthesized and used water permeation membranes have low sustainability due to the non-green materials used. The entire life cycle assessment results also revealed the low sustainability of commercially used water-treating membranes [2]. The design of sustainable membranes obviously depends upon the use of green and recyclable raw materials like green polymers and biodegradable petroleum-derived polymers and non-hazardous solvents. Using sustainable materials based membranes can easily reduce the disposal burdens at the life cycle end as well as the expected environmental risks of non-degradable materials

[3]. Therefore, there is need of replacing the traditional commercial materials by using sustainable recyclable materials and green solvents for the membrane fabrication [4–6]. The recyclability studies of water purification polymeric membranes through mechanical, chemical, or thermal processes have pointed ways to future sustainable environmental materials [7].

Briefly, this review critically assesses recent developments towards the sustainability of membrane technology including nanofiltration, reverse osmosis, ultrafiltration, and other techniques. The use of degradable materials (polymers, solvents, chemicals) may lead to the transformations of the advanced membrane industry according to circular economy concept and safe ecosystem.

2. Sustainable water purification membranes

Membrane technology has played important part globally in efficient waste water management through superior separation efficiency consuming less energy [8–10]. This technology has further employed the microfiltration, nanofiltration, ultrafiltration, and reverse osmosis membrane processes for efficient water cleaning. Different membrane materials have been pragmatic so far to develop the water purification membranes [11–13]. **Table 1** exhibits examples of few membrane designs and specifications involved in the water treatment modules. Recent membrane technology has moved towards the green separation approaches due to the environment friendly and sustainability demands [14–16]. To enhance the membrane separation performances, modification routes have been preferred in this field [17,18]. At the end of membrane service, life cycle management techniques have been cast-off. In addition to the use of sustainable polymers, non-toxic solvents must be adopted for membrane processing [19–21].

Table 1. Design and specifications of few water purification membranes.

Polymeric material	Diameter/Size	Voltage requirement	Physical properties	Membrane flow rate	Reference
Polyethylene terephthalate with graphene nanoparticles	-	-	Percolation threshold 0.2 Scm^{-1}	Air gap ~3 cm; pressure 25 psi	[22]
Polyamide with graphene nanoparticles	76–338 nm	8–10 kV	113% increased Young's modulus and 250% rise in fracture toughness	0.05 mL h^{-1}	[23]
Aramid with carbon nanoparticles	~8 nm	-	Ultimate tensile stress increase by 700%	2–6 mL h^{-1}	[24]
Poly(ε-caprolactone) with graphene	100–130 nm	12 kV	304% increased tensile strength	1 mL h^{-1}	[25]
Poly(ε-caprolactone) with nanoparticles	121–154 nm	15–17 kV	Young's modulus 3771 MPa	0.8–1 mL h^{-1}	[26]

Polyesters have been identified as sustainable green materials for membranes [27–29]. Polyethylene membranes especially recycled membranes from petroleum products have advantages of antifouling, chemical. and chlorine resistance. These membranes have high separation ability towards water pollutants, organic wastes, salts, etc. Ma et al. [30] performed life cycle assessment of polyesters. These polymeric membranes had facile processing and sustainability opportunities. Park et al. [31] developed nanofiltration polyester membranes for desalination and dye removal. The polyester membrane design and salt or dye removal towards water purification is given in **Figure 1**. The physicochemical features of polyester membranes and salt or dye rejection efficiencies for polluted water have been assessed.

Figure 1. Polyester membrane for water purification by desalination and dye removal [31]. Reproduced with permission from Elsevier.

Donnakatte Neelalochana et al. [32] produced sustainable polyethylene terephthalate based anion exchange membranes. These water purification membranes have alkaline stability and ionic conductivity of about 432 h (1 M KOH) and 5.3×10^{-2} S·cm^{-1}, respectively. The membrane degradation pathways and mechanisms have been investigated in the alkaline conditions. Fan et al. [33] designed the polyester membrane with superior physicochemical properties for drinking water purification. High-performance membranes have fine chlorine resistance and antifouling performance.

Polypropylene based sustainable water purification membranes [34–36]. Particularly such membranes have been industrialised for oil-water separations. However, these membranes have high prices, low efficiency, and limited environmental pollutant removal for industrial oil-water separations [37–39]. Yuan et al. [40] fabricated the membranes based on polypropylene wood pulp fiber composite nonwoven fabric for kerosine-water separations. **Figure 2** shows gravity-driven oil-water separation system, oil-water separation device, and gravity-driven oil-water separation vs. time. Kerosine oil was stained with oil red. Oil-water mixture was gradually poured in the designed separation device. Upon passing through polypropylene membrane, oil-water separation may efficiently occur which can be visualized in photographs. Scanning electron microscopy images of polypropylene-wood pulp fiber composite nonwoven membrane are given in **Figure 3**. The micrographs of the wood pulp fiber side and polypropylene fibres side of the polypropylene wood pulp fiber composite nonwoven fabric samples were scanned. The diameter of polypropylene fibres was observed at 10 μm, which was much lesser than that of the wood pulp fiber (35 μm). In these composites, oil-water separation was observed in the range of 50%–75%. **Figure 4** depicts a simple design used for polypropylene membranes for oil-water separation.

The oil-water contact interface was found to be affected by the polypropylene-wood pulp fiber nonwoven membrane was found depending upon the nature and diameter of fibers used in the composites. The membranes revealed high efficiency towards oily wastewater purification.

Polysulfone-based sustainable membranes have been found effective for waste water treatment [41–43]. Huang et al. [44] designed the thin film nanocomposite membrane using polysulfone with cellulose nanocrystals and piperazine through interfacial polymerization technique (**Figure 5**). These membranes have sufficient hydrophilic surfaces with optimum water permeation flux pf about 10 $L \cdot m7^{-2} \cdot h^{-1}$. High salt rejection was observed in the range of 96%–99% for $MgSO_4$, Na_2SO_4, and related salts. Thus, the nanocomposite membranes have been active water desalination and refinement effects.

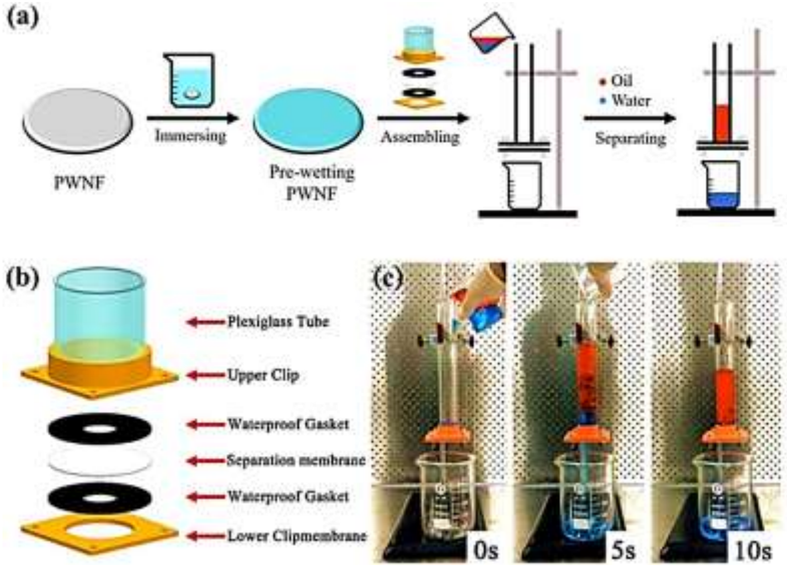


Figure 2. (a) schematic of the gravity-driven oil-water separation; **(b)** lab made oil-water separation device; **(c)** gravity-driven oil-water separation experiments as a function of time. In the experiment, kerosene was stained with Oil Red O, whereas water was stained blue with industrial water-based pigment [40]. Reproduced with permission from ACS.

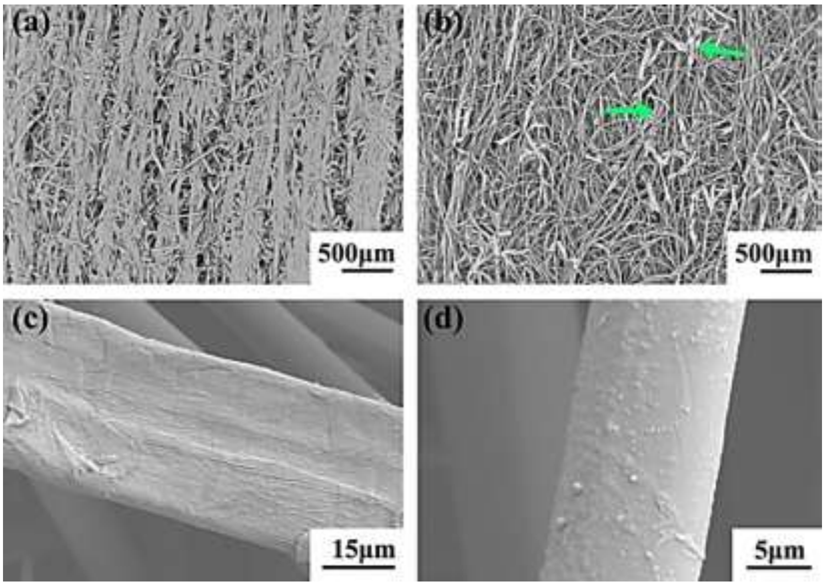


Figure 3. (a) scanning electron microscopy (SEM) image of the wood pulp fibres side of polypropylene-wood pulp fiber composite nonwoven fabric (PWNF); **(b)** SEM image of the polypropylene fibres side of PWNF. The green arrow indicates the intertwined structure; **(c)** SEM image of a single ribbon of a wood pulp fibre; **(d)** SEM image of a single cylindrical polypropylene fibre [40]. Reproduced with permission from ACS.

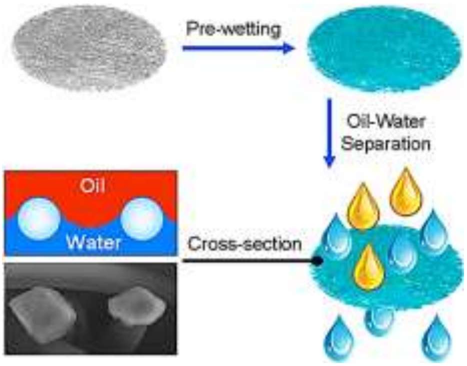


Figure 4. Polypropylene membrane for oil water separation [40]. Reproduced with permission from ACS.

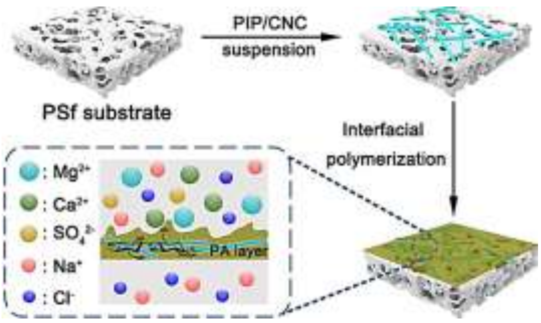


Figure 5. Sustainable thin film polysulfone (PSf) nanocomposite membranes with cellulose nanocrystals (CNC) and piperazine (PIP) [44]. Reproduced with permission from ACS.

Polyamide matrices have been employed for sustainable water purification membranes [45–47]. Polyamide membranes have been explored for durability, facile processing, superior water flux, and salt rejection as well as pollutant removal characteristics. Zhao et al. [48] fabricated the polyamide-derived water purification membranes using tannic acid functional carbon nanotube and silver nanoparticles. The interfacial polymerization method was used for the fabrication of reverse osmosis membranes (**Figure 6**). In these membranes, hydrogen binding and π-π stacking interactions were perceived between the matrix nanofiller. The polyamide nanocomposite membranes have high water permeability of about 5 L m^{-2} h^{-1} bar^{-1} and NaCl salt rejection of 50%–99%. These membranes have fine antibacterial effects due to silver nanoparticles and also the bio-fouling effects.

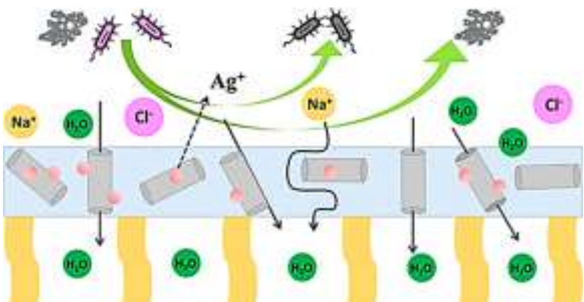


Figure 6. Schematic of tannic acid functionalized carbon nanotubes embedded with silver nanoparticle membranes for water purification [48]. Reproduced with permission from ACS.

3. Environmental impact assessment of sustainable water purification membranes

After membrane filtration processes for waste water, environmental impact assessments need to be analysed at the end-of-life management [49–51]. Here, environmental and sustainability demands need the treatment of large amounts of wastes from water pollution. **Figure 7** shows waste management opportunities in a hierarchal order. Specifically, the parameters regarding reverse osmosis membranes have been focused.

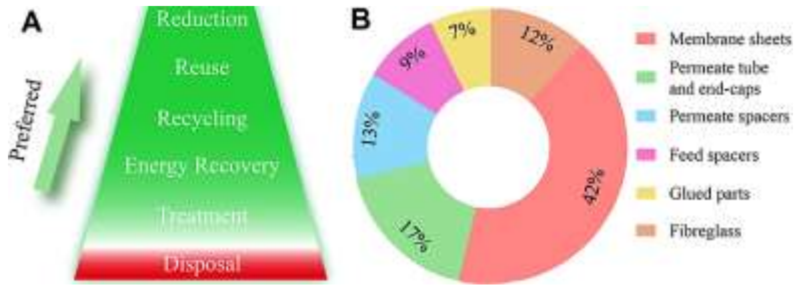
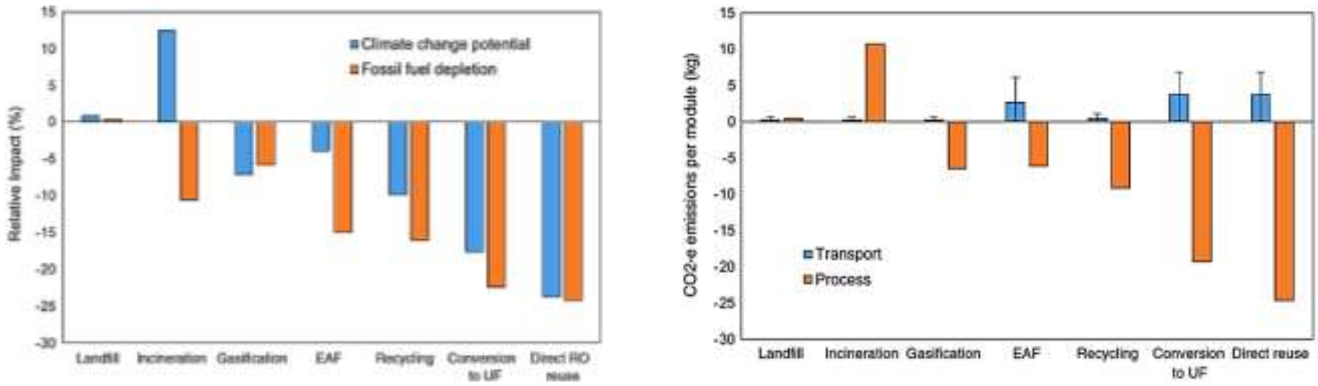


Figure 7. (A) waste management hierarchy from most to least preferred options; **(B)** composition of a typical reverse osmosis (RO) membrane element [52]. Reproduced with permission from Elsevier.

Figure 8. Membrane life cycle [53]. Reproduced with permission from Elsevier.

In majority of practices, solid wastes are used to be disposed in landfills. Sustainable strategies need to be applied to dispose the water wastes. Safe management approaches must be adopted on priorities to meet the sustainable environmental needs [52]. The components of reverse osmosis membranes after recycling have been extracted and recycled through chemical or mechanical recycling processes. Lawler et al. [53] studied a normal membrane lifecycle leading from raw material extraction to end-of-life possibilities (**Figure 8**). Furthermore, greenhouse gas emissions resulting from disposal reverse osmosis membranes have been portrayed (**Figure 9**). Membrane processes as well as transportation contribute towards the gaseous and disposes emissions to environment. The entire membrane model can be seen as raw material extraction, synthesis or engineering, packaging, and delivery or transport processes. Major impacts of membrane disposition and recycling have been assessed on climate changes and fossil fuel deletions. All the recycling emissions have affected the environmental sustainability scenarios.



(A) **(B)**

Figure 9. (A) greenhouse gas emissions and resource depletion for the disposal of one reverse osmosis (RO) membrane element. Results are displayed in terms of relative offset of membrane production; **(B)** contribution of transportation and process to the climate change emissions of the different scenarios [52]. Reproduced with permission from Elsevier.

4. Sustainable membrane recycling

Polymers especially the petroleum derived polymers have been recycled using efficient techniques such as mechanical recycling, chemical recycling, and thermal recycling [54–56]. Soundness of membrane recyclability processes depends upon the membrane material used for water purification [57–59]. Most widely used process is mechanical recycling including physical grounding of plastics or membranes and contaminant separation based on particle sizes [60–62]. The mechanically recycled material can be used for producing new desired products [63]. The economic viability of the mechanical recycling process has been found important to consider in addition to environmental safety [64,65]. Polymers like polypropylene, polyamide, and polysulfone are chemically resistant and may need toxic solvents for degradation, therefore mechanical recycling is preferred for these membranes [66–68]. Similarly, polyester can be better recycled using the mechanical processes [69]. The recycled membrane materials have been studied for maintained physical properties to be further employed for technical uses [70].

Second important recycling method used is chemical recycling of the membrane materials [71–73]. This technique involves the degradation or depolymerisation of membranes into valuable raw materials for petrochemical uses. The plastic material is usually degraded to small molecules or chains which can be easily recycled or used. Polyesters based membranes have been degraded easily through the chemical route via polycondensation reaction [74]. However, using chemical recycling on the contaminated materials may result into the production of ecologically hazardous products [75]. Consequently, materials need to be pre-treated before the chemical recycling.

Another important recycling process used is thermal recycling of the membrane materials [76]. Thermal recycling may involve the pyrolysis in the absence of oxygen and through gasification processes [77]. This method has been found safe depending upon the nature of material recycled. Here, gasification typically includes the simple waste residue treatments with less toxic emissions. Mixed plastic wastes based on recyclable green polymers can be easily processed using thermal method. Hence, different water purification polymeric membranes can be easily recycled to attain sustainable processing [78–80].

5. Future and conclusions

Design and essential properties of water permeation membranes have been scrutinized in this article. After developing the sustainable water purification membranes, permeability, desalination, salt removal, dye elimination, toxic ion removal, and antibacterial effects have been studied. The microstructure, water flux, and flow rate of the membranes have been considered important for pollutant removal. Moreover, major functional demands of water purification membranes include durability and strength while filtration. According to the modern global sustainability and environmental demands of waste water treatment, recyclable and degradable membrane materials have been focused. Various sustainable membrane designs with polymers based on polyesters, polyamides, and other green polymers and efficient techniques (micro-, nano-, ultra-, reverse osmosis, etc.) have been considered. Appropriate membrane fabrication process may lead to well defined membrane structure and optimum membrane properties. Subsequently, smooth molecular transportation, superior flux, and barrier features were observed for membranes. After designing and successful use, recycling of polymeric membranes through appropriate processes has been found desirable. Here, according to the material type, heat, mechanical, or chemical routes have been applied for degrading the membrane material. The choice of membrane material as well as recycling process have been found challenging. The detailed overall life cycle assessments of the membranes must be carried out to resolve the sustainability and environmental challenges in this field.

Hence, current and future research on water purification membranes must focus on various parameters like the (i) development of efficient ecofriendly ultrafiltration, reverse osmosis, nanofiltration, and microfiltration processes; (ii) sustainable membrane manufacturing; (iii) choice of sustainable polymers like polyesters, polyamide, polysulfone, and others; (iv) choice of non-toxic solvent; (v) impact of membrane processes on the desalination or other filtration processes; (vi) recycling through mechanical, chemical, or thermal processes; (vii) use of life cycle assessment tool; and (viii) environmental impact of using sustainable water purification membranes.

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