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Hybrid membrane process for water treatment: a short review

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ABSTRACT

Water shortage is one of the most difficult issues confronting people all over the world. Rapid urbanization and water scarcity necessitate immediate action to improve sustainable water management without jeopardizing global socioeconomic growth. Thus, conventional water treatments are implemented for the purpose of eradicating various pollutants in wastewater. Traditional water treatment methods, whether in water treatment facilities or reverse osmosis (RO) plants, have run across a number of roadblocks that have significantly hampered their performance and efficiency. Integrating the membrane process with other remediation technologies in a hybrid process is a novel technique to improve contaminant extraction efficiency for our target streams. This process is termed the hybrid membrane process (HMP). On this aspect, this paper would highlight the benefits of using the HMP compared to conventional methodologies and their applications conducted in various sectors around the world. Some case studies are also reviewed illustrating its cost analysis in comparison to conventional methodologies accentuating the merits of using HMPs.

Key words: conventional water treatment plants, fouling, hybrid membrane process, nanofiltration, reverse osmosis, ultrafiltration

HIGHLIGHTS

- This paper highlights the benefits of using the HMP compared to conventional methodologies and their applications conducted in various sectors around the world.
- We were able to identify significant benefits of the HMP over traditional water treatment methods, such as cost-effectiveness and reduced energy usage than traditional processes.
- As per our survey, the HMP has been shown to be superior to conventional processes.

INTRODUCTION

Water is among the most indispensable resources that succor and feed human existence on this planet, and it is abundant in our immediate environment. Fresh water is used for a variety of applications daily. The global demand for freshwater has risen dramatically in recent decades due to population growth, urbanization, development of agricultural areas, and climate change (Alardhi *et al.* 2020). Agriculture (70%), industry (19%), and home usage (11%) are the three primary water consumption industries worldwide (Aquastat 2013). The water scarcity crisis has emerged from several factors including water pollution, inappropriate water control, climate change, and population increase. Due to this, freshwater shortage has become a serious issue in recent years and it has a considerable impact on human activity and economic development. According to the United Nations (Nanda 2018), 1.2 billion people reside in locations where actual water shortage exists, and approximately, 1.6 billion people around the globe (almost a quarter of the worldwide people) suffer financial water shortage. Over 3.4 million deaths occur worldwide every year as a consequence of water-related illnesses, according to the World Health Organization (WHO) (Pruss-Ustun & Organization 2008). Aside from that, water scarcity poses a serious threat to agriculture, resulting in a reduction in food supply and, in some cases, starvation (WATER 2007). The situation is exacerbated by the fact that the world's population is growing at an annual rate of 80 million inhabitants, meaning that clean water demand will only steadily rise in the coming years (Service 2006). Due to rapid industrialization, the reclaimed effluent should be viewed as an alternate source of water for irrigated agriculture in order to attain water

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efficiency (Rizzo *et al.* 2020), as well as ground or surface water discharge (Pecson *et al.* 2018). The removal of contaminants from wastewater is done in conventional wastewater treatment plants (WWTPs); however, they are not very effective at successfully removing the contaminants due to a variety of reasons. In order to tackle these problems, hybrid membrane processes (HMPs) are considered. Hybrid membrane methods have shown considerable promise in terms of increasing the quality of water and separating efficiency, as well as cheap capital and operational costs, low energy usage, temperature-controlled operations with really no phase shift, and system stability. Thus, the focus of this paper is to highlight the significance of the HMP, its application in various sectors, economic viability, and advantages over conventional water treatment strategies.

CONVENTIONAL WATER TREATMENT

A common approach of wastewater treatment that can lessen the undesirable qualities of water-carried trash and make it less harmful and repellent to humans is referred to as conventional wastewater treatment. Coagulation–flocculation, sedimentation, sand filtering, disinfection, and ozonation are all used in most contemporary drinking water treatment plants to produce fresh potable water. However, conventional treatment facilities, on the other hand, are having trouble providing potable water owing to human activities such as the disposal of industrial wastes and the pollution of water resources. This is mostly due to a considerable reduction in the quality of feed water. This is especially true in poor and underdeveloped nations, where there are insufficient protocols in place to protect water quality and legal limits in place to prohibit industrial waste from being discharged into rivers. The Water Act makes it illegal to dump pollutants into water bodies over a certain level, and it also imposes fines for non-compliance. As a result, typical treatment systems would only be able to eliminate a fraction of the increasing industrial toxins in water, if they can even remove them at all.

DRAWBACKS OF CONVENTIONAL WATER TREATMENT

Some of the drawbacks of typical water treatment plants in conjecture with pretreatment processes are highlighted as follows:

- Defilement of water resources

Enhanced treatment facilities are necessary for typical water systems to create fresh drinking water from heavily polluted water supplies (Xia *et al.* 2004). Pharmacologically active substances (e.g., antibiotics) and their intermediates, for example, are difficult to eliminate with conventional WWTPs (Kraemer *et al.* 2019). Such compounds have always been susceptible to harm the environment and public health, particularly, if discharges from WWTPs are reused for culture (Helmecke *et al.* 2020; Pedrero *et al.* 2020). Heavy metals, which pose a significant health risk, are key water pollutants that have to be addressed (Molinari *et al.* 2008; Anito *et al.* 2020; Peng *et al.* 2020). Cu_2 ions, for instance, are essential micronutrients, but prolonged exposure damages the liver and kidneys and induces DNA mutations (Yin *et al.* 2020). Copper toxicity is further related to brain illnesses such as Wilson's disease and Alzheimer's disease. Toxins, pesticides, pharmaceutical residues, arsenic, and herbicides have all been found in contaminated water supplies, and traditional treatment has been proven to be ineffective (Xia *et al.* 2004; Gibs *et al.* 2007; Sarkar *et al.* 2007; Harisha *et al.* 2010; Saitúa *et al.* 2012). Ozonation and granular activated carbon (GAC) filtering are two highly advanced pesticide treatment technologies that were shown to be efficient in removing pesticides, although issues with the process continue to arise. Some of these issues arise as a result of active carbon overloading as well as the generation of harsh toxins in GAC filters (Jiang & Adams 2006; Ormad *et al.* 2008; Plakas & Karabelas 2012). Due to these faults, membrane technology has been developed, which can compete cheaply with complex treatment approaches while also providing multifaceted characteristics. Membrane technology, when seen in this light, can open up new possibilities for process design, rationalization, and optimization.

- Susceptibility toward microbial attack

Due to the sheer amount of organic substances in the Oise River, bioremediation utilized there at the Mery-sur-Oise water treatment facility in France refused to eliminate all organic substances, enabling bacteria to grow inside the supply system (Cyna *et al.* 2002). A similar event was discovered at the conventional water treatment plant at Cheng Ching Lake Water Works, where the system did not completely remove algae and other bacteria (Yeh *et al.* 2000). Customers expressed their dissatisfaction with the treated water's unpleasant taste and odor. This is another flaw in traditional therapeutic approaches.

- Hardness of water

Furthermore, water from typical treatment facilities may be excessively hard and require further softening (Schaep *et al.* 1998). Cold and hot lime softening, as well as pellet softening, require a lot of lime and humic acids; resulting in a lot of sludge (Sombekke *et al.* 1997).

- By-product contamination

Chlorination has been used as a disinfection technique to eliminate viruses and germs. However, this will lead to another issue: the development of carcinogenic disinfection byproducts that are difficult to eliminate (Van der Bruggen & Vandecasteele 2003).

- Performance fluctuations using conventional pretreatment

SDI-level fluctuations, extensive re-washing, high reagent utilization events (compounding and pH adjustment), and compact media filters were all hallmarks of standard processing (Ebrahim *et al.* 2001). The filtering system had to be partially or completely closed whenever seasonal fluctuations increased as a result of atmospheric smoke and air conditioning, and it was determined that you would not be able to convert this large gross seawater SDI into tolerable SDI water. This situation was also observed at the Adur SWRO desalination plant (Al-Sheikh 1997). The SDI of seawater varies from season to season. The dual media filter was unable to produce pure water with an SDI of less than 2.7 when pushed to the limit. As a result of this incident, the RO membrane is severely damaged. Efforts are being made to rectify this part of the standard pretreatment to predict seasonal variability in saltwater quality, particularly, in the area of coagulant volume, pH adjustment, and to improve the performance of the back bath (Hussain & Ahmed 1998). Such tweaks can improve the system slightly but are challenging to maintain, mainly whenever the volume depends on the water input position. This condition of the feed solution, which includes pH, temperature, environmental pollutants, and turbulence, determines the appropriate coagulant capacity. The correct dose is difficult to calculate as it is affected by various conditions, significantly when raw water quality fluctuates. As a result, a decrease or override is possible. Regular (pot tests) and automatic processes will not be able to provide a quick weather forecast whenever the green water level changes. Other significant pretreatment errors include the removal of a low percentage of particles smaller than 10–15 m and efficiently removing particles larger than 10–15 m. Even during the proper operation of filters, there is an opportunity for the particles to enter. Large amounts of suspended particles fall immediately after washing behind the filter, as well as how compounds such as coagulants and antiscalants affect RO networks (Wolf *et al.* 2005).

- Biofouling: The Achilles heel of membrane processes is biofouling. The accumulation of organic foulants and bacteria in the membrane area reduces penetration and membrane health, and increases energy usage. It is caused by bacteria in water and dissolved organisms/particles trapped on the membrane or inside. Biofouling reduces the flow of membranes and affects the quality of permeate while using more energy and shortening the life of the membrane (Wu *et al.* 2020). Particulate fouling, organic fouling, inorganic fouling, and biofouling are the four forms of membrane fouling (Lim & Bai 2003).
  i. Particulate fouling: Whenever a colloidal material attaches to the membranes, there is a problem. As the particles accumulate in the membrane, they form a 'cake' layer that prevents water from flowing through the holes, indicating symptoms such as increased pressure reading and energy consumption (Guo *et al.* 2012). Particle/colloid contamination is caused by the presence of organic and inorganic particles (e.g., mud or clay) in the food solution, especially whenever the stream is produced on the surface and in groundwater. The silt density index (SDI) of the feed stream is often used by water treatment specialists to estimate the associated risk of particle/colloidal contamination. The SDI standards are very important when building RO systems as RO systems have smaller holes than any membrane filtering system, and thus, are at greater risk of particle contamination (Stergios & Anastasios 2003).
  ii. Organic fouling: Organic fouling is the buildup of carbon-based materials on a membrane filter. As a consequence of the degradation of animals and plants, natural organic matter is composed of carbon-based compounds found in soil, groundwater, and surface water (Amy 2008). Organic matter is, typically, extremely volatile and its foulant potential is influenced by a number of factors, including its propensity for membrane material. Facilities can lessen organic fouling problems by using some type of raw water treatment and/or selecting a membrane material that resists organic material adherence to the membrane (Mi & Elimelech 2010).

- Scaling

Also termed as inorganic fouling. This is indicated by the presence of crystallized salts, hydroxides, etc. inside the effluent water (Gloede & Melin 2008). Ionic components come out of the solution, and polish or bind to the surface of the membrane whenever the solution grows too focused on the membrane feed, and eventually, exceeds the limit of the solution. In RO/NF systems, with high conversion rates, measurement is a problem, especially when input distribution has a high concentration of calcium or magnesium (Karabelas *et al.* 2020). In industries, various scale remedial actions have indeed been utilized, and they are classified into three categories: modifying process water qualities, introducing an antiscalant, and adjusting characteristics of operation and conceptual design. Acidification is by far the most often used technique for adjusting the characteristics of feed solution by adjusting the pH, and as a result, scaling dissolution in the liquid. On the other hand, acids like sulfuric acid have the ability to promote the formation of sulfate scaling (Antony *et al.* 2011). Ion exchange softening, on the other hand, might be a valuable approach to control scale development (Zeiher *et al.* 2003). Due to the considerable initial and running costs associated with this technology, other solutions appear to be more tempting and acceptable. By lowering product recuperation in order to enhance control conditions, the risk of scaling is reduced. A decline in productivity, however, would have an economic clout on the plant's operating efficiency. Because of these problems, antiscalants are now widely used as a scale prevention strategy. Phosphates, polyphosphates, and organophosphates are the three types of antiscalants (Vrouwenvelder *et al.* 2000). Despite the fact that antiscalants may successfully prevent the development of the scale, there have been some reservations regarding their use in RO desalination plants. Antiscalants have been discovered to render biofouling more effectively, as RO structures can be fouled 10 times more with the fundamental biological proliferation. (Semiat *et al.* 2003). Due to the shortcomings of traditional pretreatment technology, several studies are available on alternate pretreatment techniques, specifically, the potential of using transmembrane and inclusion of complex structures as a preparation. In the subsequent sections, we will go through it in further depth.

HYBRID MEMBRANE PROCESS

If the combination of different separation methods results in a finer approach than two techniques employed individually, a hybrid or integrated process is known as a '$1 + 1 > 2$' process (Alardhi *et al.* 2020). Membrane integration methodology was introduced in the mid-1980s (Avramescu *et al.* 2008). HMPs are those in which one or even more membrane processes are combined with other unit processes such as coagulation, adsorption, and ion exchange (Fane 1996). To complete a given task, all of these procedures are merged into a single system. The amalgamation of treatment approaches used in hybrid membrane technology gives a chance to go beyond the boundaries of traditional procedures (Garg & Joshi 2014). The fundamental goal of this integrated/hybrid membrane system is to outperform any of the individual components. Other processes in the integrated system can compensate for flaws in particular operations. Membrane fouling has long been recognized as the primary impediment to membrane functioning. For example, the fouling problem could be significantly reduced by combining a coagulation process with a membrane unit in the treatment of groundwater resources (Wu *et al.* 2020). HMPs are important 'green' technologies that increase the capabilities of both traditional treatment techniques and membrane processes (molecular separation), resulting in synergy for both technologies and reducing environmental and economic consequences (Dhangar & Kumar 2020; Phoon *et al.* 2020). The membrane allows for continuous operation in systems where the pollutant is removed, and high-quality filtered water is produced at the same time. Other possible benefits of HMPs include increased energy efficiency, modularity, and ease of scaling up (Molinari *et al.* 2017). From Zouboulis *et al.* (2014), we can convey that using a hybrid membrane system such as ozonation-ceramic MF for the treatment of surface water effluent, indicate that hybrid systems were 22% more efficient compared to conventional methodologies. Other papers such as Venzke *et al.* (2018) showcase similar results where hybrid systems such as RO-electrodialysis reversal gives a removal efficiency of 87.3%. Thus, enunciating more on the abovementioned point, various literature studies are provided validating the statement of hybrid methodologies being beneficial compared to conventional methodologies. Thus, we would now be discussing its various applications in water treatment processes and how it is beneficial compared to conventional treatments which are listed in Table 1.

Table 1 | Applications of the HMP

Sr. No.	Hybrid membranes	Effluent	Operating conditions	Result and observations	References
1	Ozonation with microfiltration	Surface water	Feed gas at 0.2 bar, permeate flow rate 7.2 l/h, H_2O_2 added to the experimental unit at various concentrations, ozone/hydrogen peroxide ratios of 0.2, 0.1, and 0.05 (mili mole O_3/mili mole H_2O_2).	22% more efficient compared to conventional treatment process at 0.2 l/min rate of flow of ozone–oxygen gas combination.	Zouboulis *et al.* (2014)
2	Coagulation with nanofiltration/reverse osmosis	Brackish water	Initial concentration of humic acid is 20 ppm, cross-flow velocity is 42 cm/s, 27 °C temp., 10 bar pressure	Antiscalant at low doses (2 and 5 ppm) improves membrane flux and salt aversion.	Ang *et al.* (2016)
3	Reverse osmosis with electric dialysis reversal	Petrochemical wastewater	Pressure 8 bar, reject flow rate 300 l/h	Removal efficiency is 87.3%, rejection decreases from 51 to 12.7%	Venzke *et al.* (2018)
4	Coagulation with inorganic ceramic membrane	River water	Initial permeate flux 750 l/h·m^2, COD concentration is <2 mg/l	The hybrid method was able to remove COD more effectively than either coagulation or membrane filtration alone, with removal percentages ranging from 34 to 54%.	Li *et al.* (2011)
5	Membrane bio reactor with nanofiltration	Textile wastewater	Operating pressure 6–8.5 bar, feed and permeate flow rate 2,402.1 ± 23.7 l/h to 2,304.8 ± 26.6 l/h	The efficiency of hybrid system came out to be 90% removal of COD. It also provides high permeate flux with low operating pressure and cost.	Li *et al.* (2020)
6	Granular Activated Carbon with ultra filtration/microfiltration	Drinking water	Cross flow velocity at 0.5 m/s	Shows high COD removals (70%)	Stoquart *et al.* (2012)
7	Forward osmosis with ultrafiltration in which sodium polyacrylate is sandwiched	Seawater and surface water	Pressure was 30 psig	Rejection rate is 99.8%	Emadzadeh *et al.* (2019)
8	Polysulfone membrane with photo catalytic properties	Rubber wastewater	Permeate flux of 80 l m^{-2} h^{-1}, temp. 60 – 70 °C	Rejection were increased by up to 95.83%	Kusworo *et al.* (2021)
9	Micro filtration in combination with forward osmosis and membrane distillation	Fracking wastewater	Pressure 0.28 bar, time 12 h, stirring rate 500 rpm	Solute rejection ~99.99%	Islam *et al.* (2019)
10	MCM-41 adsorbent with ultrafiltration	Synthetic wastewater	Pressure 1 bar, temp. 25 °C	Dye removal 97%, permeate flux 39 l/h m^2	Alardhi *et al.* (2020)
11	Nanofiltration/reverse osmosis with advance oxidation process	Pharmaceutical wastewater	Pressure for UF 1 bar, pressure for RO 60–80 bar	99.9% removal efficiency of p-methoxyphenol	Rosman *et al.* (2018)

(*Continued.*)

Table 1 | Continued

Sr. No.	Hybrid membranes	Effluent	Operating conditions	Result and observations	References
12	Coagulation/ flocculation with microfiltration/ ultrafiltration	Synthetic vegetable oil refinery wastewater and real vegetable oil refinery wastewater	Flow rate 3,000 l/h, temp. 1.2 bar	The hybrid process was able to remove 99.97, 93.7 and 94.1% of turbidity, COD and TOC respectively	Khouni *et al.* (2020)
13	N_2–CO_2 selective membrane	CO_2	Pressure 1 bar, 13% CO_2 and 87% N_2	90% recovery of CO_2	Ren *et al.* (2020)
14	Ultrafiltration/ Nanofiltration/ Reverse osmosis with zeo liquid discharge technology	Pigment wastewater	Feed flow rate of 10 $m^3 \cdot h^{-1}$ and operating pressure of 0.5–1.0 bar	Rejection ratio –81.8%	Xiao *et al.* (2020)
15	Ultrasound with adsorption, and membrane ultrafiltration	Real wastewater	Constant flux of 150 l/m^2 h	Particulate rejection: 90%	Naddeo *et al.* (2020)

CASE STUDIES PERTAINING TO COST ANALYSIS OF THE HMP

One critical and significant criterion in deciding whether or not hybrid membrane systems are economically viable in water treatment and desalination facilities is the cost. So in order to understand how HMPs are more beneficial in comparison to conventional processes, a few case studies are listed in order to validate the abovementioned statement.

Case study 1

In the first case study, a small-scale, photovoltaic (PV)-driven hybrid nano filtration (NF) and reverse osmosis (RO) membrane system for brackish water treatment is being investigated (Semiat *et al.* 2003). Now, common technological assumptions, specifications, and design factors for PV-assisted RO and NF membrane systems were taken into account for estimating the cost of water production (Garg & Joshi 2014).

The following products were included in the package: (1) investment in capital costs, (2) costs of maintenance and operation, and (3) other expenses and operational costs (Garg & Joshi 2014).

The PV–RO system in most AC-powered desalination processes includes a battery backup to manage the input energy toward the membrane module. A 28-Ah battery capacity with a 4 kWh/day (Rs.8,000/kWh) requirement and 3 days of autonomy have been used to assess the cost of water production with battery storage (Garg & Joshi 2014). The schematic of this case study is shown in Figure 1.

Tables 2–4 depicts the capital cost, cost for maintenance and operation, as well as other expenses associated with the process. In Table 2, cost estimation has been conducted among three different types of membrane systems, i.e., hybrid, NF, and RO, respectively. Initially, capital expenditure for the hybrid membrane system is relatively high as compared to conventional methodologies.

- The comparative findings for each membrane system design have been illustrated, with alternative interpretations and conclusions offered in the following.
- As shown in Table 3, the PV-hybrid system's water production cost (₹.99.81/m^3) is 1.6 times lower than PV–NF (Rs.158.46/m^3) and 4 times lower than PV–RO (₹.400.49/m^3) (Garg & Joshi 2014).
- Furthermore, by expanding the capacity of the membrane system and offering greater subsidies on solar systems as an incentive to its users, this cost might be further decreased (Garg & Joshi 2014).

On the basis of Table 4, we can conclude that as per the government subsidy on water production cost, the price of treating 1 m^3 of water decreases from 80.03 to 35.25 INR/m^3 for the hybrid system. For NF, the price of treating 1 m^3 water decreases from 154.44 to 42.69 INR/m^3; in RO, the price of treating 1 m^3 water decreases from 309.58 to 107.90 INR/m^3.

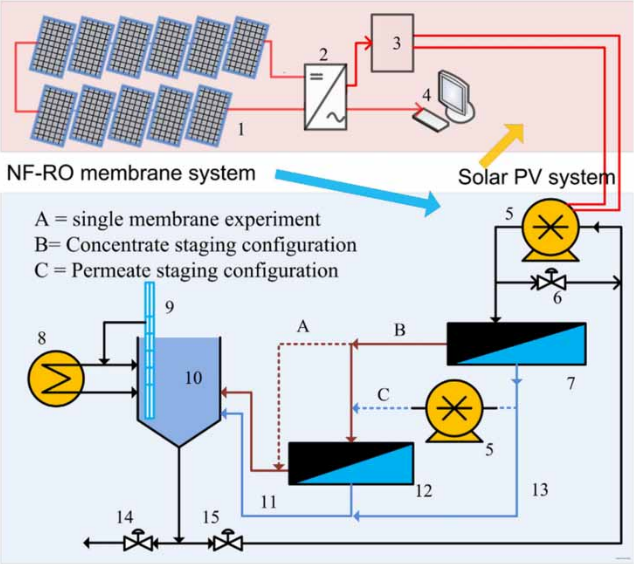

Figure 1 | Various experimental setups for single and hybrid PV–NF/RO membranes: PV modules (number 1), DC–AC inverter (number 2), AC distribution board (number 3), and data logging system (number 4). Number 5 indicates a high-pressure pump. Number 6 represents a gate valve. Number 7 is the number of the NF module. Number 8 denotes a smart thermostat, number 9 denotes a digital thermometer, number 10 denotes a feed water tank, number 11 denotes a concentration stream, number 12 denotes a RO module, number 13 denotes a filtrate flow, and numbers 14 and 15 denote valves (Garg & Joshi 2014).

Table 2 | The expenditure of a photovoltaic membrane system in terms of investment

	Hybrid	NF	RO
Cost of membrane system			
High-pressure pump	15,000	15,000	15,000
High-pressure connecting pipes	5,000	5,000	5,000
Membrane housing	5,000	2,500	2,500
NF/RO membranes	10,000	5,000	5,000
Feed/permeate tank	2,000	2,000	2,000
Temperature control unit	2,000	2,000	2,000
Membrane system installation cost	5,000	5,000	5,000
Total cost of RO system	44,000	31,500	31,500
PV system component wise cost			
PV module (11 × 140 W)	84,233	84,233	84,233
AC distribution board	8,294	8,294	8,294
Solar inverter (3 KW)	102,512	102,512	102,512
Copper cable	12,282	12,282	12,282
Super earthing kit			
Module moulting structure	23,979	23,979	23,979
Installation charges, freight, and insurance of PV system	25,700		25,700
Total cost of PV system	257,000		257,000
Total capital cost	301,000	288,500	288,500

Garg & Joshi (2014).

Table 3 | The expenditure of a photovoltaic membrane system in terms of investment

	PV–Hybrid	PV–NF	PV–RO
Membrane replacement cost per year, $A1$	5,000	2,500	2,500
Annual amortized capital cost, $A2$	21,357	20,470	20,470
O and M annual cost, $A3 = A2 \times 0.2$	4,271.34	4,093.96	4,093.96
Annual operating cost $C = (A1 + A2 + A3)$	30,628.03	27,063.74	27,063.74
Unit production cost $= C/(f \times P)$, Rs/m^3	99.81	158.46	400.49

Garg & Joshi (2014).

Table 4 | Effect caused by subsidy on per m^3 water production cost

Effect of subsidy on per cubic meter water production cost	Subsidized water production cost	30%	40%	50%	60%	70%	80%	90%
Hybrid	97.28	80.03	70.52	63.47	56.42	49.36	42.31	35.25
NF	154.44	122.49	106.06	93.39	80.71	68.04	55.37	42.69
RO	390.32	309.58	268.06	236.03	204	171.96	139.93	107.90

Garg & Joshi (2014).

Case study 2

The desire to lower the amount of energy used in the seawater RO process has driven researchers to design novel hybrid systems (Bhojwani *et al.* 2019). In this case study, reverse electro dialysis and electro dialysis are linked with RO to form a hybrid system. Each process model is put to the test and cost analysis is done (Bhojwani *et al.* 2019) (as shown in Figure 2).

A proven simulation tool was used to evaluate the performance and cost savings of two coupled processes: (A) RED–RO ((assisted) reverse electro dialysis–RO) and (B) ED–RO (electro dialysis–RO). Changing various design characteristics and operating circumstances, as well as evaluating several cost scenarios, were used to conduct a sensitivity analysis (Bhojwani *et al.* 2019).

In the electro-membrane pre-desalting process, the (A) RED-RO consumes less energy than a stand-alone SWRO over a wide range of external voltage. In the 'reference' cost scenario, a maximum cost saving of 7.5% could be achieved, thus

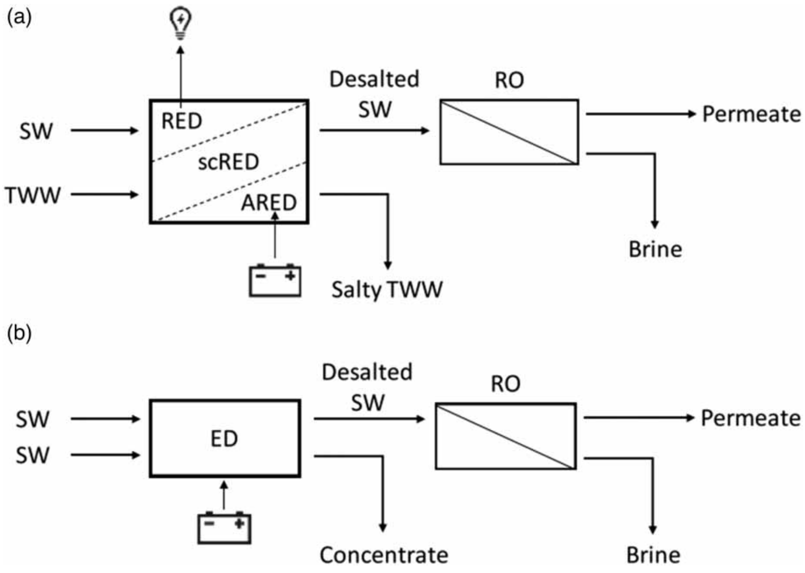

Figure 2 | Schematic diagram representing possible IMS with RO (RED-RO and ED-RO, respectively) (Bhojwani *et al.* 2019).

lowering the capital cost (Bhojwani *et al.* 2019). The highest cost savings may be increased to 24.6% in an optimistic cost scenario with low RED/ED plant costs comparable to IEMs prices (10 €/m^2) and high energy costs (0.3 €/kWh) (Bhojwani *et al.* 2019). As a result, (A) RED-RO connection is advantageous, particularly, in terms of IEM cost reduction (Bhojwani *et al.* 2019).

Case study 3

In this study, using powdered activated carbon/coagulation/ceramic microfiltration (PAC/cMF) addresses the increased removal of pharmaceutical compounds (PhCs), a family of increasing concern pollutants, and effluent organic matter (EfOM) in water reclamation (Viegas *et al.* 2020).

The operational circumstances that were evaluated, as well as the design specifications listed in Table 5, were used in the cost analysis. This approach was chosen because of the greater removals obtained with PAC dosage to a contact tank, and a 15-min contact duration was evaluated. The factory was expected to run 24 h a day, 365 days a year. Plant downtime of 40 min per day for backwash, 35 min per day for CEB, and 18 min per day for regular maintenance and cleaning-in-place were calculated based on the pilot demo, and a plant lifespan of 40 years was assumed (Viegas *et al.* 2020).

The pilot testing allowed assessing the performance and obtaining the key design parameters of the configurations tested. The values obtained for Fe/MF and PAC dosage testing periods are shown in Table 5. When the same PAC and PAC dose (15 mg/L) were employed, the latter included both Fe/PAC in-line/MF and PAC tank/Fe/MF setups. Comparable interfacial pressure and fouling rates—0.37 bar and 139 mbar/h for Fe/MF vs. 0.40 bar and 116 mbar/h when dosing PAC – were seen for the Fe/MF and the PAC dosage settings. The outcomes permitted it to be determined that there was no place for PAC-driven membrane fouling or pore-clogging since the amount of dissolved organic material in the effluent throughout both demonstration sessions was comparable. The schematic of this setup is shown in Figure 3.

Table 6 shows the components and their lifetimes taken into account when calculating capital expenditure costs (CAPEX), whereas Table 7 shows the operating expenditure costs (OPEX). The annualized expenses of equipment replacement were

Table 5 | Effectiveness and important design characteristics of Fe/MF and PAC dosage setups

Parameter	Fe/MF (30 days)	Fe/PAC In-line/MF PAC Tank/Fe/MF (5 days)
Water recovery rate (%)	98	98
Inlet pressure (bar)	0.43	0.46
Transmembrane pressure (TMP, bar)	0.37	0.40
Fouling rate (mbar/h)	139	116
Specific flux (lmh/bar)	296	261

Viegas *et al.* (2020).

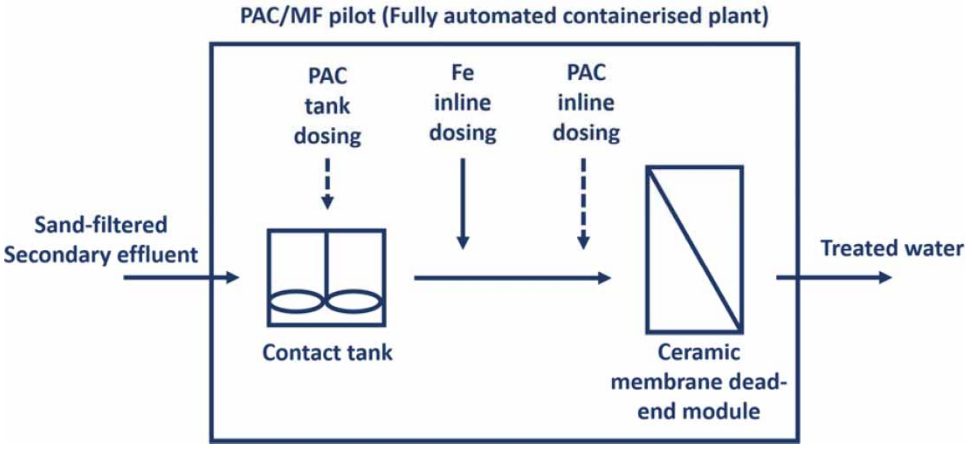

Figure 3 | Schematic diagram of the PAC/cMF process (Viegas *et al.* 2020).

Table 6 | Assets and their lifespan are taken into account when determining capital expenditure cost (CAPEX)

Components	Lifespan (years)
Membranes	20
Pipes and valves	20
Instrumentation and control	8
Tanks and frames	14
Chemically enhanced backwashing (CEB) skid	15
Feed, backwash, CEB, and PAC dosing pumps	10
Miscellaneous equipment	14

Viegas *et al.* (2020).

Table 7 | The financial analysis taken into account w.r.t. operating expenditures (OPEX)

OPEX	Cost
Energy cost for pumping and mixing	0.08 £/kWh
Personnel costs (annual cost)	20 k£/worker
Chemical reagent costs	
PAC	2.95 £/kg
Coagulant	1.4 £/kg Fe
Sodium hypochlorite solution	0.416 £/kg
Sulphuric acid solution	0.130 £/kg
Maintenance	1.5% of the total capital cost

Viegas *et al.* (2020).

included in OPEX. There were no fees for land acquisition or construction taken into account. OPEX and total production cost with respect to plant flow rate is shown in Figure 4.

Table 6 shows the components and their lifetimes taken into account for determining CAPEX, and Table 7 shows the OPEX. OPEX comprised the annualized expenses of replacing the equipment. Development and land reclamation expenditures were not taken into account.

For the Fe/MF and PAC/Fe/MF processes, operational costs, capital costs, and the total cost of production for processing the WWTP sand-filtered secondary effluent investigated are displayed as a function of plants fluid velocity (Viegas *et al.* 2020)

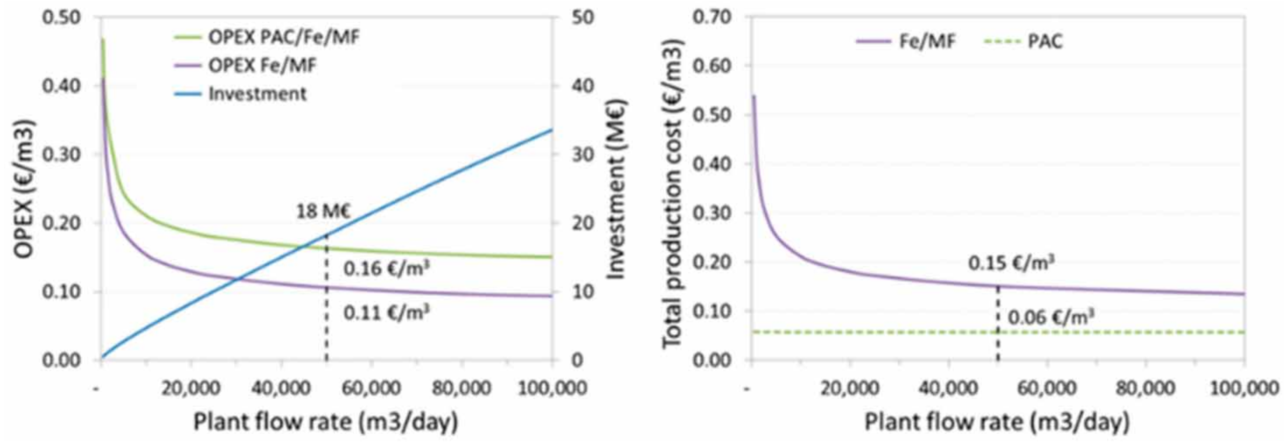

Figure 4 | Investment and operating costs for both membrane processes taken into account (Viegas *et al.* 2020).

When utilizing Fe/ceramic MF, the primary expenditures are linked with equipment and membrane replacement (50%), capital (30%), and chemicals (16%). The operational cost changes when PAC is introduced, i.e., for PAC/Fe/ceramic MF, the reagent cost rises and surpasses the replacement costs, accounting for 39 vs. 36% for the latter; and the proportional contribution of capital expenses falls from 30 to 21% (Viegas *et al.* 2020).

Summary and benefits of the HMP

The combination of treatment approaches used in hybrid membrane processes is thought to give a chance to go beyond the boundaries of traditional procedures (Hube *et al.* 2020).

The benefits are listed as follows:

- HMP can be used to increase the flux of permeate.
- Its helps in improving removal efficiency and producing cleaner products.
- It reduces membrane fouling.
- It is cost-effective compared to conventional processes.

Pretreatment before the membrane process, for example, is one sort of hybrid process that can increase the flow of the membrane unit, which has a favorable impact on productivity and efficiency (Hube *et al.* 2020). Pathways for developing HMP can be seen in Figure 5.

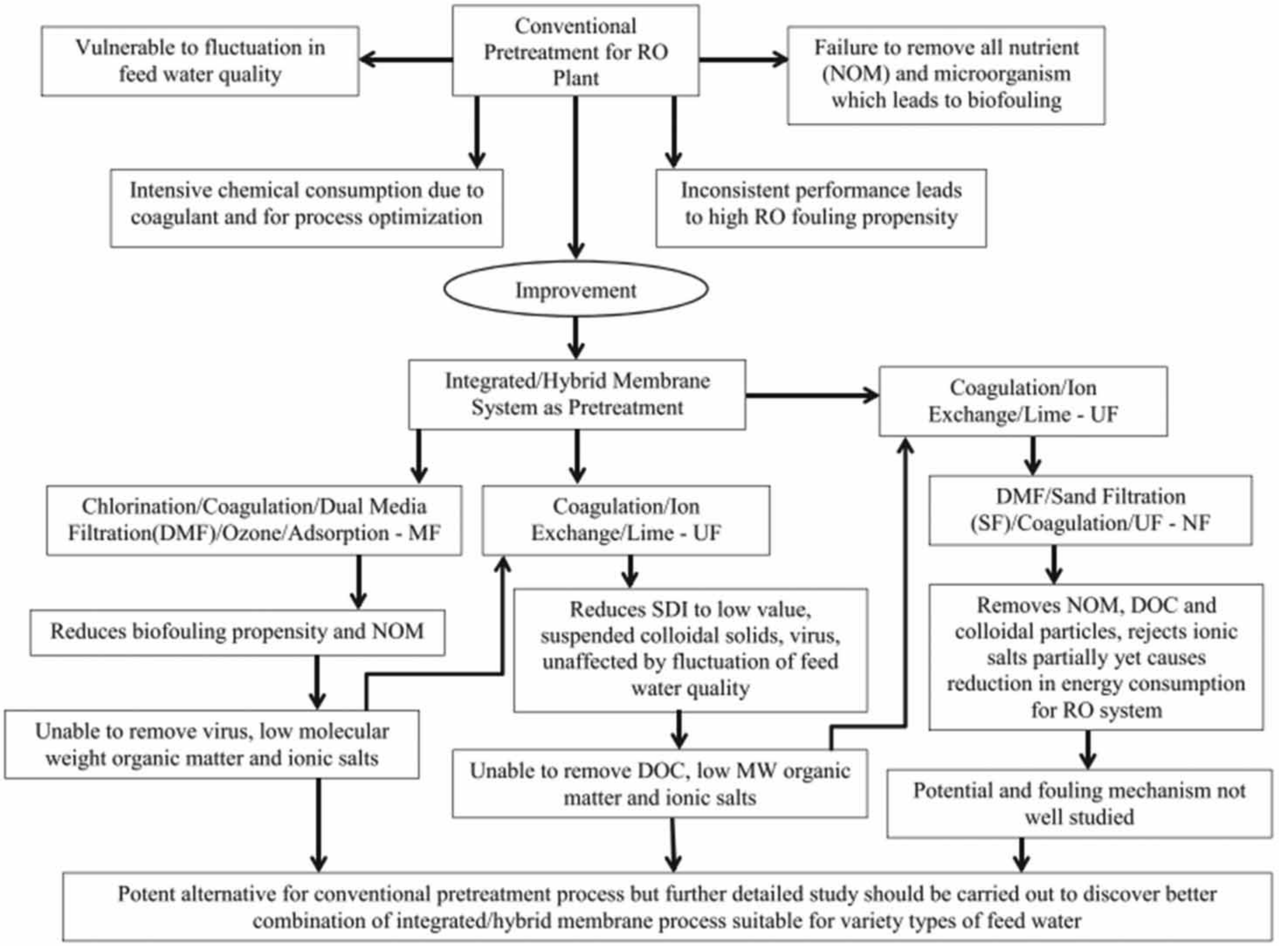

Figure 5 | Pathways for developing a HMP for use as a precursor for a SWRO plant (Hube *et al.* 2020).

Recommendations

The following charts show the efforts that can be made now and in the future, to increase the adoption of membrane processes in the drinking water production business. These may be broken down into two categories (as shown in Figure 6). The first one is membrane fouling, while the latter is the expense of energy use and the environmental effect (Ang *et al.* 2015). There are numerous avenues of study that may be undertaken to lessen the problem of membrane fouling, such as:

- The usage and invention of novel additives that not only minimize harmful byproducts in the feed water, but are also innocuous to the membranes or would have minimal negative impacts on them.
- Membrane production and modification to develop new versions of membranes with improved capacity to reject toxicants, strong resilience to fouling operations, high resistivity to synthetic chemicals, and the ability to function at lower pressures without reducing the flux rate.
- The development of extremely effective integrated/hybrid systems with high yield, low energy consumption, and fewer fouling issues.

The following recommendations can be explored for concerns involving the environment and cost:

- Development of renewable and clean energy resources that can lessen reliance on non-renewable forms of energy, while also being environmentally benign (less pollution). It is expected that, as a result of government initiatives encouraging the use of renewable energy sources, energy prices will be decreased, and hence, water cost can be reduced.
- The employment of cutting-edge new equipment in the facility should be explored. To minimize squandering energy, devices that can recover energy from concentrated brine can be employed. Furthermore, devices with high energy conversion rates can minimize energy waste while maintaining or improving performance.
- Minerals that can be extracted from brine solution can be used. Advanced technology that can recover important minerals while also treating the waste's detrimental components before it is released into the environment should be researched and developed.

Ultimately, the design of integrated/hybrid membrane systems and membrane variation should be coordinated such that flaws in one may be corrected for utilizing other approaches. The development of integrated/hybrid processes should not be limited to already known treatment processes; instead, new creative approaches should be tested to uncover the potential of new integrated/hybrid membrane systems that can solve the difficulties that water treatment facilities confront. Water

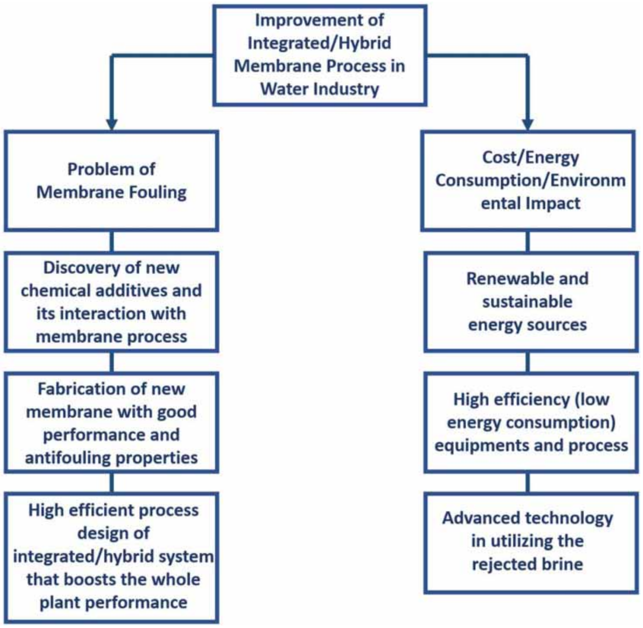

Figure 6 | Potential improvements that can be adopted by the HMP for water treatment (Ang *et al.* 2015).

shortage would undoubtedly benefit from the combination of fault-free hybrid membrane systems and enhanced membrane module design for industries (Ang *et al.* 2015).

CONCLUSION

HMPs have been shown to be superior to conventional membrane processes in terms of water treatment and desalination. On the other side, every water treatment/RO desalination unit might require a distinct type of preparation and composition. This is because the purity of both input water and the characteristics of water to be generated impact the efficacy and complexity of integrated membrane systems. Exquisite groundwater simply demands rudimentary coagulation–NF process to provide potable water; however, poor-quality seawater demands more extensive preparation prior to joining the RO system, which can be seen in the IMS varieties depicted above. Before integrated/hybrid membrane solutions could be built, membrane fouling mechanisms should be examined and understood. In most cases, interactions between contaminants or contaminants inside the water, membranes, and additions like coagulation factors and antiscalants are poorly understood. Extensive investigation and advanced analysis are required to evaluate and investigate the reasons for fouling caused by interactions among the three substrates mentioned previously. For every specific freshwater industrial use, resolving the fouling issue culminates in more sophisticated and accurate integrated membrane systems. As a consequence, not only will the plant's overall expenditure be lower, but it would also help to minimize energy consumption and eliminate excessive waste. We were indeed able to identify the significant benefits we have over traditional water treatment methods, such as cost-effectiveness, reduced energy usage than traditional processes, and so on.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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