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MEMBRANE FILTRATION TECHNOLOGY FOR WATER TREATMENT IN TERMS OF MEMBRANE PERFORMANCE, ENERGY CONSUMPTION, AND COST ASPECTS: A REVIEW

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ABSTRACT

The problems of water quality and its management are a global issue that must be resolved. The membrane filtration technology shows good potential for water treatment to improve water quality, eliminate harmful contaminants, and efficiently restore nutrients. This article aims to comprehensively review membrane filtration, including membrane filtration performance to remove contaminants, energy consumption, cost aspects, and antifouling strategies. Technologies in membrane filtration are microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO). This review systematically evaluates recent advancements in membrane filtration technologies, particularly focusing on membrane performance, energy consumption, and water treatment costs. The data for this review were collected from a comprehensive range of sources, including peer-reviewed journal articles, conference proceedings, and industry reports. The results of this study indicate that the MF/UF system can effectively remove bacteria and be used as a pre-treatment before the NF/RO process. NF/RO system can remove contaminants higher than MF/UF. It can remove almost all contaminants, ions, heavy metals, viruses, and pharmaceutical compounds (PhAC). However, the system is more susceptible to membrane fouling, but adequate pre-treatment can solve these problems. Water treatment with NF and RO offers a good alternative because its operation makes it possible to use lower energy consumption than conventional water treatment. Based on the cost aspect, if the virus and ion contamination are not the main target in the filtering and not for consumption, the MF/UF system is sufficient. It will be more economical than using NF/RO. The findings of this study can provide insight into the effectiveness of membrane filtration technology in water treatment. Future research can develop membrane filtration technology for good performance, low energy consumption, and low cost.

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1. INTRODUCTION

In the past decade, many people have made awareness and progress in water treatment to get high-quality drinking water. However, approximately 663 million people do not get high-quality drinking water. They consume untreated water from wells, springs, and surface water (UNICEF, 2015). The World Economic Forum 2019 also said freshwater scarcity is one of the biggest global problems (Forum, 2019). Thus, water treatment is needed to treat surface water into fresh water that can be consumed. However, if the surface water is not treated or repaired, it can infect consumers with various diseases.

Another problem is poor sanitation, which causes pathogens to contaminate surface and groundwater. Contaminated drinking water can cause consumers to become infected with diseases like diarrhea and vomiting (L. Lin et al., 2022; Shah et al., 2023). Water-borne diseases can be prevented by proper water treatment. It is important to apply low-cost water filtration techniques to treat contaminated water. Generally, conventional activated sludge processes treat water biologically by removing organic substances/ nutrients. According to WHO's water standards, the microfiltration (MF)/ ultrafiltration (UF) process continues to produce high-quality permeated water. The treated water is ready to drink. The next process is a high-pressure membrane process, such as nanofiltration (NF) or reverse osmosis (RO), to remove organic and dissolved ions (Changmai et al., 2020). In a recent study, the NF process was combined with biological processes, and then the NF permeate was processed by RO to obtain water with very high levels of purification (Tay et al., 2018).

However, biologically, water treatment processes are unsuitable for all types of contaminated water due to low treatment efficiency. In addition, biological-based processing is highly dependent on environmental factors such as temperature, variations in feed composition, oxygen levels, etc. (Meena et al., 2019). Biological aerobic-based water treatment requires much energy for aeration. Some organic/ nutrients in contaminated water are converted to CO2, leading to large greenhouse gas emissions (Huang et al. 2017). Some other organic/ nutrients in contaminated water are converted to biomass, which is generally used for biogas production (energy recovery) through anaerobic digestion. However, the efficiency of converting organic/ nutrition into biomass is lower than converting organic/ nutrient into CO2 (Lateef et al. 2013). In addition, the removal of nutrients such as nitrogen (N) and phosphorus (P) during treatment of contaminated water is lower than its recovery.

Research on water treatment using membrane filtration in several types of driving forces (pressure-driven and osmosis-driven) received great attention, especially on improving membrane performance. In a direct membrane filtration system, the membrane effectively rejects organics/ nutrients from contaminated water, so superior permeate quality with a high water recovery ratio was reached. Direct membrane filtration systems generally have a high compactness. The direct membrane process does not involve an additional activated sludge process, which reduces energy consumption. In addition, organic and rejected nutrients enriched at high concentrations can be digested afterward to produce renewable energy (H2, CH4) or become fertilizer (Kimura et al. 2017, Xiong et al. 2019). Thus, the direct membrane process can facilitate water treatment properly.

RO has been used among developed countries such as Saudi Arabia and Israel (Harrington, 2013). This process was implemented in the 1990s to replace distillation due to high energy consumption (Cohen-Tanugi & Grossman 2012). In RO, water is given a high pressure from one side of the membrane. Hydrated sodium and chloride ions will be filtered because the membrane is a very small structural gap through which only water can pass (Economist.com, 2013). In addition, this method can produce an average of 250 million gallons of clean water per day. Several membrane technology applications have proven less efficient in water purification. For example, low salt rejection is a serious problem in carbon nanotube-based membranes, and high-density CNT structures are difficult to produce (Fornasiero et al., 2010). Another problem in water treatment using membrane technology is membrane fouling, especially with high pressure such as NF / RO (Mi et al., 2020). Although there are many studies on membrane technology for water treatment, there is a lack of comprehensive reviews that simultaneously discuss membrane performance, energy consumption, and operational costs in one integrated study.

The problem that needs to be solved in treating contaminated water is finding an efficient process with high performance in removing contaminants, reducing economic costs, and reducing energy consumption for water filtration and antifouling. For this reason, it is necessary to have an in-depth and detailed discussion regarding this matter. To the author's knowledge, there has not been a comprehensive review discussing the issue. This article aims to comprehensively review the filtration membrane that has recently been researched for water treatment. It comprises membrane filtration performance, energy consumption, cost, and antifouling strategies.

2. METHOD

This review systematically evaluates recent advancements in membrane filtration technologies, particularly focusing on membrane performance, energy consumption, and water treatment costs. The data for this review were collected from a comprehensive range of sources, including peer-reviewed journal articles, conference proceedings, and industry reports. Relevant studies were sourced primarily from established academic databases such as ScienceDirect, Wiley Online Library, and Google Scholar. The search terms "membrane filtration," "energy consumption," "cost analysis of membrane filtration systems," and specific filtration technologies like microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) were employed. These resources were carefully selected to ensure a robust and comprehensive analysis of each technology's effectiveness in various water treatment applications.

The performance of each filtration system was assessed by reviewing studies that report the removal efficiency of contaminants, including bacteria, viruses, heavy metals, ions, and pharmaceutical compounds. This performance evaluation was based on key metrics such as permeate flux, rejection rates, and the extent of membrane fouling observed under various operational conditions. For instance, MF and UF membranes were evaluated for their ability to remove larger particles and bacteria. At the same time, NF and RO systems were analyzed for their effectiveness in removing smaller contaminants like dissolved ions and organic compounds. The review also considered the role of pretreatment methods, including integrating low-pressure systems like MF and UF before applying high-pressure systems like NF and RO, as these can significantly impact overall treatment efficiency.

Energy consumption is a critical factor in determining the feasibility and sustainability of membrane filtration systems. This review compared the energy demands of different membrane technologies by analyzing studies that reported power consumption per cubic meter of treated water. Specifically, high-pressure systems like NF and RO, which require significant energy input to achieve the necessary transmembrane pressures, were compared to the more energy-efficient MF and UF systems. The analysis highlighted how membrane material types, operational parameters, and system configurations influence energy consumption. In particular, the review focused on advancements in membrane material design and the potential for energy savings through system efficiency improvements, such as using energy recovery devices and alternative driving forces.

Cost analysis was another central aspect of this review, which examined the capital, operational, and maintenance costs of the four membrane filtration technologies. A life-cycle cost approach was applied to understand the long-term economic viability of each technology. The analysis provided insights into the financial challenges associated with large-scale implementation by reviewing case studies and real-world applications. For example, while MF/UF systems tend to have lower initial capital costs and are more economical in treating non-potable water, NF and RO systems offer superior contaminant removal capabilities despite their higher operational and maintenance costs. Additionally, the review addressed the economic implications of membrane fouling, a significant issue in membrane-based systems. Antifouling strategies, including surface modifications, cleaning protocols, and pretreatment processes, were analyzed to determine their effect on extending membrane life, reducing cleaning costs, and improving overall system performance.

3. RESULTS AND DISCUSSION

3.1. Water Sources

Almost all water sources on Earth come from the ocean in the form of salt water; the other is fresh water found in the soil and ice in Antarctica. Most water supplies on Earth come from the oceans (Stephens et al., 2020). However, not all humans can use seawater directly because water from the ocean has high salt levels, so it must be treated first to separate the salt. The other surface water is fresh water that can be utilized more easily than seawater for daily life. There is a process of seawater intrusion. Seawater entry into freshwater aquifer areas causes a decrease in the quality of fresh water, especially for drinking and clean water needs. Excessive intake of groundwater by a pump causes a decrease in the groundwater interface, which causes seawater intrusion. The increase in seawater also pushes seawater into the inland freshwater aquifer. In addition to the surface water described above, groundwater is used for daily life. Groundwater moves in the soil, which is contained in the spaces between the grains of soil and rock cracks.

It is called water gap or fissure water. Water that fills the pore layers of the Earth under the water table is usually called groundwater. Surface water quality is influenced by groundwater and water that flows above the surface due to the full capacity of soil infiltration (runoff). During the rainy season, the phenomenon is reversed, where surface water affects groundwater quality (McLachlan et al., 2017).

The interaction between groundwater and surface water has important implications for the quantity and quality of water and ecological health. The presence of geological, hydrological, and biogeochemical heterogeneity in groundwater and surface water is difficult to characterize through direct observation. It has caused many problems, one of which is flooding. For example, high urbanization can increase surface runoff and prevent groundwater filling during the rainy season. Agricultural activities can also reduce the storage of rainwater on the ground. These phenomena can affect surface water in complex ways that depend on many aspects, including plant type, soil type, and climate (Han et al. 2017, Hocking & Kelly 2016). For example, more natural organic content is expected in humic waters than non-humic waters. Therefore, the permissible variation of dissolved organic carbon (DOC) concentration depends on the type of water (DEFRA, 2014).

3.2. Water Problems

Water source treatment and clean water supply are the main challenges of the 21st century (Zheng et al., 2023). Contaminants in water can pose significant risks to the environment and human health, so the efficient disposal of these contaminants is very important (Cai et al. 2018, Trinh et al. 2018, Wu et al. 2018). The problem in water is eutrophication. Eutrophication is excess nutrients in water or water pollution by excessive nutrition. Water pollution is contaminated or affected water by organic or inorganic substances (Zhou et al. 2020). This problem happens around the world, both in freshwater and seawater ecosystems. Eutrophication is caused by many things, such as human behavior that is not friendly to the environment and nutrient emissions by companies or industries thrown into the water (Jarvie et al., 2018). Nutrient wastes in water can be from industry (Rachbauer et al., 2024), agricultural fertilizers (Chen et al. 2019, Huang et al. 2017), and husbandry waste (Barcellos et al., 2019). Water that contains many nutrients, such as phosphorus and nitrogen, can trigger the growth of phytoplankton and algae. It also increases aquatic productivity (Lin et al. 2020). If there is a large increase, algae will bloom, which can harm the life of organisms in the waters. Eutrophication will threaten the water ecosystem more in the dry and rainy seasons (Zhang et al. 2017). Increasing temperature, changes in rainfall patterns, and changing hydrodynamics in the dry season contribute to eutrophication's acceleration (Lu et al., 2019).

Another problem caused by eutrophication is the appearance of cyanobacteria in water. These microorganisms can produce and release oxygen (Demoulin et al., 2019) and also produce toxins that are harmful to many high-level organisms such as fish, cattle, and humans (Conklin et al. 2020, D'Agostino et al. 2019, Wisniewska et al. 2019). Thus, it is important to treat wastewater that is contaminated with many nutrients and disinfect water to deactivate bacteria (Rajendran et al., 2018)c. The main water sources in households, agriculture, and industry are lakes and reservoirs. These are susceptible to environmental changes because they have low flow velocity or stagnation. Eutrophication can cause significant problems. Nutrition and Natural Organic Matter (NOM) can be removed by processes such as activated sludge (Rajendran et al., 2018) and sand filtration (Kulkarni et al. 2019, Xu et al. 2019). At the same time, removing microorganisms produced in the water because of the many nutrients can use membrane technology (Chang et al. 2019, Hylling et al. 2019; de Vries et al. 2020).

Another problem that can affect water quality is the presence of heavy metals in the water. Heavy metals in water can produce short-term contamination derived from anthropogenic activities (Sarah et al., 2019). These activities include coal burning, mining, pesticide use, battery production, welding, etc. Over time, ecosystems usually adapt to cope with increasing levels of these heavy metals (Paul, 2017). When organisms absorb heavy metals and metalloids, especially Cadmium (Cd), Zinc (Zn), Lead (Pb), and Arsenic (As), they are not easily excreted (Y. Xu et al., 2019). Therefore, they ultimately bioaccumulate in the food chain (Hao et al., 2019; Sarah et al., 2019). For example, pollution caused by heavy metals in mining is a widespread problem worldwide (Qiao et al., 2020). However, pollution also appears around sediments that are not exploited, such as swamps. These areas are contaminated with many pollutants, such as Cu, Zn, and As, with concentrations exceeding the provisions of the WHO. High concentrations of heavy metals can occur in surface water, sediment, and surface soil.

3.3. Water Treatment

WHO issued a recommendation regarding contaminant parameters that must be followed so that the water sources are safe for consumption. Water treatment aims to produce water whose quality depends on the treatment process (J. A. Silva, 2023). In developed countries, water is treated in wastewater treatment plants (WWTP) and drinking water treatment plants (DWTP), which implement various pre-treatment steps, including coarse and fine filtration, sedimentation, coagulation/circulation, various filtration methods, activated sludge, primary disinfectants, and residues, etc. (Yang et al., 2017).

Each method usually removes certain groups of pollutants. For example, the activated sludge removes NOM, NO3, and PO4 from wastewater (Keene et al., 2017). Coagulation and fluctuation remove ionic/ colloidal materials such as clay particles and dissolved metals (Zaharia et al., 2024). The oxidation of organic matter contributes to the release of carbon dioxide into the atmosphere, which endangers the environment. Heavy metal waste can be removed from wastewater using granular activated carbon (GAC) (Bilardi et al. 2018, Eeshwarasinghe, et al. 2019; Mohammad-pajooh et al. 2018). However, high process optimization is required to achieve optimal cleaning (Sounthararajah et al., 2015). RO can be used as an alternative to metal removal. The high pressure used in RO causes higher power consumption (Vital et al., 2018). UF and NF systems can also remove heavy metals and metalloids (Lam et al., 2018). MF, UF, NF, and RO filtration systems can be used to remove contaminants such as bacteria, viruses, and other dissolved metals (Krystynik & Tito 2017, Moussa et al. 2017, Sillanpää et al. 2018).

3.4. Membrane Filtration Methods

Contaminants in water cannot be removed effectively with conventional treatments. They can pose significant risks to both the environment and human health. Contaminants have to be removed effectively. Membrane filtration is a good technique for removing many contaminants in water (Abdel-Shafy & Abdel-Shafy, 2017; Veréb et al., 2019). This technology makes it possible to improve the purification of contaminated water and produce a higher quality permeate than conventional treatment. The advantages of membrane technology as a new approach in wastewater treatment are modular design, automated methods, pore size flexibility, great resistance to many types of contaminants, and good permeate quality (Ezugbe & Rathilal, 2020).

A filtering membrane is a separation technique that uses a membrane in several phases. A filtration membrane consists of a single layer of material, a membrane that allows water to pass through. Technologies including membrane filtration are MF, UF, NF, and RO, which filter 0.5 - 5 μm particles for MF, 0.005 - 0.5 μm particles for UF, and 0.0007 - 0.005 μm particles for NF. RO can eliminate almost all contaminants in water (Global 2012). RO and NF are very effective for removing dissolved ions and organic solutes. However, operating RO and NF membranes requires high pressure (6-70 bar). In contrast, UF and MF membranes require lower pressures (0.3 - 5 psi) than others. UF and MF are ineffective in maintaining dissolved ions and organic solutes (Diallo, 2014).

Membranes are usually made of woven fibers (Phiri et al., 2019), ceramics (Mestre et al., 2019; Myat et al., 2018; Rasouli et al., 2019), and polymeric materials (Norouzi et al., 2019; Veréb et al., 2019; Zaouk et al., 2020). Ceramic membranes have advantages in terms of thermal, chemical, and mechanical stability and longer usage times (Tai et al., 2019). There are several types of polymeric membranes, including polyethersulfone (PES), polyacrylonitrile (PAN), and polytetrafluoroethylene (PTFE). PES has excellent mechanical and chemical resistance, high stability, easy manufacturing, and good environmental durability (Yin & Zhou 2015). PAN has good hydrophilicity, membrane surface roughness, and a strong antibacterial effect (Li et al. 2019). PTFE has exceptional chemical resistance and high porosity (Wei et al., 2017).

They can also be modified to improve performance before being applied in water purification. They can be used to reduce impurities (Nidhi et al. 2019), purify oil emulsions (Veréb et al., 2019), and improve the removal of specific pollutants, such as arsenic (Chatterjee & De 2017), Mg and Ca (Zaouk et al., 2020), bacteria (Li et al. 2019). There is no general agreement on the most beneficial polymer material for filtering contaminants in water. Membrane technology can follow environmental standards and can ensure the reuse of wastewater. Thus, a thorough discussion of water treatment with membrane technology is very interesting to investigate so that the characteristics of each membrane can be known.

3.5. Low Pressure Membrane Filtration (MF dan UF)

MF cannot remove small particles, unlike UF and NF. However, MF effectively removes bacteria (Hellinga et al., 2019; Thuy & Boontawan, 2017). MF can be used in domestic water recycling systems (Choobar et al., 2019; Manouchehri & Kargari, 2017). In addition, many MF technology activities are wastewater treatment from the textile industry (Manni et al., 2020) and soy sauce improvement process (Guo et al., 2020). Low-pressure membranes (MF and UF) can also be applied as a pretreatment system for high-pressure membranes (NF and RO) (Changmai et al., 2020; Tawalbeh et al., 2018; X. Zhang et al., 2020). The aim is to reduce the possibility of ineffectiveness in the NF/RO process because it can eliminate the potential of pollutants such as bacteria (Hellinga et al., 2019) and improve the stability of NF/RO performance (Al-Mashharawi et al., 2013). In the pretreatment cycle, MF can remove bacterial cells, while other dissolved impurities, such as proteins, colloids, dyes, and salts, will be removed in the NF process (Thuy & Boontawan 2017).

The materials used in MF/UF membrane technology are ceramics, polymers, and woven fabrics. These materials can be modified with other materials, such as titanium dioxide (TiO_2) nanoparticles or polyvinylpyrrolidone, to improve hydrophilicity and disinfection (Carpintero-tepole et al. 2017). The MF process can also be integrated with pre-coagulation (Almojjly et al., 2019; Hao et al., 2019; Hassan et al., 2019). This process can remove chemical compounds, waste oil, and ARGs (Antibiotic resistance genes) from the water. ARGs have been considered pollutants that appear in WWTP wastes. It is because of the potential risks to human health and ecological safety when reused. The results show that the integrated process can reduce the absolute abundance of total ARGs and eARGs from waste. The integrated process performs well in removing common pollutants (for example, organic carbon and dissolved phosphate) from waste to improve water quality. The integrated process reduces membrane impurities more than MF as a single process. Pre-coagulation and MF integration is an advanced wastewater treatment technology that can remove ARG (especially eARG) from WWTP waste for reuse. Another integration is electrocoagulation (EC), which is followed by the MF process (Changmai et al., 2020). This is effectively used to remove metal (Mn and Fe) contaminants.

Other recent research is the manufacture of filtration membranes from natural magnesite (Manni et al., 2020). Magnesite added with clay is optimized to be a ceramic membrane as an MF membrane for filtering wastewater in the textile industry. The integration is intended to increase mechanical strength and reduce sintering temperatures. The experimental results show that the magnesite membrane effectively cleans textile wastewater. The filtration results show that the membrane efficiently removes all turbidity from textile wastewater (99.9%) while eliminating chemical oxygen demand (COD) by 69.7%.

UF is a selective separation process that purifies water, such as proteins, carbohydrates, and enzymes (Global 2012). UF is also very effective in removing microorganisms in wastewater, especially protozoa (Cryptosporidium) and bacteria (Escherichia coli) (Ferrer et al., 2015). However, the pore size is not small enough to eliminate norovirus (Yasui et al., 2016), adenovirus (Z. Yin et al., 2015), rotavirus (Qiu et al., 2015), and bacteriophages (Ferrer et al., 2015). Virus removal can be improved by using coagulation as a pretreatment for UF (Lee et al. 2017). The efficiency of coagulation can be dramatically improved by optimizing the pH. Coagulation as a pretreatment in UF can also reduce fouling drastically (Racar et al., 2019).

Regarding fouling, UF and MF are vulnerable to fouling even though it is less severe than NF or RO. Recent research shows that Novel Polyetherimide composite membranes in UF can effectively antifouling (Sathya et al., 2020). Antifouling in the study was observed using model pollutants such as bovine serum albumin, humic acid, and real textile wastewater. Polysulfone-based UF membranes with dopamine and Nisin are also very effective in overcoming fouling (Kim et al., 2018). Nisin, a low molecular weight antimicrobial peptide, is immobilized on the surface of the UF membrane. The resulting Nisin-containing UF membrane shows good fouling resistance and flux recovery ability.

3.6. High Pressure Membrane Filtration (NF dan RO)

NF can be used to remove solutes greater than RO. The size of the contaminant removed is in the range between UF and RO. NF effectively removes particles between sizes of 100 and 1000 Da (Z. Li et al., 2013). Despite these advantages and the application in this case, drinking water production, wastewater treatment, the food industry, the chemical and pharmaceutical industries, and many other industries, there are an inhibit the application of NF and RO on a large scale, namely fouling (Mi et al., 2020; F. C. Silva, 2018; X. Zhu et al., 2020). Fouling can reduce membrane performance due to particle accumulation and microbial growth on the membrane surface (Peña et al., 2013). RO membranes are more susceptible to fouling than NF membranes (Foureaux et al., 2019). Fouling can be reduced by adequate pre-treatment. This pre-treatment is in the form of conventional pre-treatment (coagulation, flocculation, sedimentation) or pre-treatment MF and UF. However, pre-treatment cannot eliminate all microorganisms that pollute the membrane (Badruzzaman et al., 2019). Most membrane installations must be cleaned to remove recalcitrant bio-films and maintain product quality (Beyer et al., 2017).

Many recent studies discuss antifouling in high-pressure filtration membranes. Nanocomposite membranes with natural clay bentonites are used in the polyamide selective layer as flux enhancers and antifouling agents in NF and RO systems (Nidhi Maalige et al., 2019). Sulfonated clays are induced in the polyamide selective layer through a modified interface polymerization method. Incorporating these nanoparticles results in the formation of membranes with enhanced flux, rejection of many contaminants, and the induction of anti-impurities in conventional polyamide layers. Other studies on developing antifouling NF membranes include zwitterionic functionalized monomers (Mi et al., 2020). The zwitterionic membrane structure can be adjusted for separation performance and antifouling properties. The developed membrane shows antifouling performance with a flux recovery ratio of 94.9%. Antifouling can be solved by infusing goethite-tannic acid nanoparticles (Saniei et al., 2020). Nanoparticles are synthesized through the phase inversion method. Membranes modified by 0.5% by weight of nanoparticles showed the best performance in overcoming fouling.

NF and RO can remove most solutes and produce stable and clean water. NF and RO have become interesting things in water treatment. Improved material design has led to advances in membrane functionality (permeability and selectivity) and membrane applicability (mechanical and chemical stability) (Salman et al., 2022). In a single purification step, NF and RO provide options to eliminate most impurities, such as hardness, color, and disinfection products (Werber et al., 2016). Other advantages include low purchase costs and space requirements, and NF/RO systems can be easily upgraded and operated continuously and automatically (S. Lin & Elimelech, 2015). This explains that NF and RO membrane filtration has become the most important technology for seawater desalination.

NF is less effective in filtering ions from water than RO, but operating and maintenance costs can be lower (Golpour & Pakizeh, 2017; Moraes et al., 2018). This is because it has lower TMPs (Transmembrane Pressure), producing water flows with the same permeate. For certain contaminants, such as pharmaceutical compounds (PhAC), NF generally shows better eliminating ability than UF but less than RO (Foureaux et al., 2019; Licona et al., 2018). UF, NF, and RO can be chemically adjusted to enhance the removal of specific contaminants. For example, NF can remove pharmaceutical compounds with a pressure of 20 bar and pH 5. The situation can reject the nonionic compound acetaminophen and caffeine more than 90%. As for the anionic compound of the mother-proven, dipiron and diclofenac, using a pH of 5 or 7 (Licona et al., 2018).

Based on membrane performance, the NF/RO system can remove almost all contaminants (A. S. C. Chen et al., 2020; Gholami et al., 2020; Peydayesh et al., 2019). Hybrid NF membrane with Polyethyleneimine is the recent research in water treatment. Hybrid membranes have superior performance in removing Zn (99.06%), Mg (97.36%), Cd (96.72%), Cu (95.84%), Ca (95.25%), Ca (95.25%), Ni (94.63%), and Pb (93.39%) (Peydayesh et al., 2019). Hybrid membranes also show good antifouling properties. Membrane fouling can be overcome by reducing the surface roughness of the membrane, as well as surface energy. Most fouling adsorption occurs on the valley surface membrane. For certain parameters, for example, pH = 2, pressure = 10 bar, and permeate recovery rate = 45%, can remove 94% sulfate contaminants, 98% calcium, 85% As III, and 75% As V with reusable permeates accordingly WHO standards (Reis et al., 2019). Using sulfonated poly-equipped NF as a new interlayer polymer can reject 99.7% Na_2SO_4 at pressure = 10 bar (Y. Zhu et al., 2020).

Water treatment with NF and RO offers an attractive alternative because its operation uses lower energy consumption than conventional treatment. This has had an impact in the last decade, when NF and RO took over the market share in water treatment. RO is a membrane separation process that offers more energy savings than conventional separation processes (Dong et al., 2020). Energy efficiency can be a critical consideration for industrialization due to significant long-term savings in energy costs (S. Lin & Elimelech, 2015). The minimum energy requirement in the conventional distillation process is 225 kJ/mol; pervaporation requires 75 kJ/mol. In contrast, the minimum energy requirement for RO with membrane organosilica is lower than that for conventional distillation or pervaporation, which is 2.3 kJ/mol (Dong et al., 2020). These results indicate that RO has great potential to separate organic solvent mixtures and is efficient in energy consumption. Membranes have excellent selectivity, superior solvent resistance, and adequate mechanical strength.

There is a recent study in which solar energy operates the NF/RO system to treat brackish water, so it is suitable for consumption (Richards et al., 2015; Shen et al., 2016, 2019). The main performance parameters investigated are flux, fluoride retention, and specific energy consumption (SEC). The research compares 1×4 inch module, one element in 4 inches NF/RO (BW30), to a 3 × 2.5-inch module, three elements in 2.5-inch NF/RO (BW30, BW30LE, and NF90) (Shen et al., 2019). The results show that the 1 × 4-inch module's overall performance is superior to the 3 × 2.5-inch module. The 3 × 2.5-inch module performance decreases significantly from the first element to the third element. It is because of an increase in feed concentration and a decrease in net driving pressure. All of them can follow WHO drinking water recommendations related to fluoride content. The NF90 membrane showed good performance, balanced productivity, and permeate quality. There are 1582 L of clean drinking water produced with specific energy consumption averaging 1.6 kWh/m3 for one day (Shen et al., 2016). Solar-powered membrane systems equipped with modules provide a good solution to overcoming the drinking water problem in rural areas.

3.7. Cost Aspects in Water Treatment

The operational and maintenance costs of MF, UF, NF, and RO technologies vary greatly. They depend on the variability of several factors, including plant capacity, assumptions, and scale at the time of the study. However, in general, they can be compared in terms of capital, operational, and maintenance costs.

Suppose viruses and ion contamination are not the main targets. In that case, the filtering system can only use MF/UF by providing acceptable quality efficiencies and is more economical than using a combination of MF/UF and NF/RO. For example, Chlorella minutissima can be removed using MF on a pilot scale. Certain variability in the MF process affects operational costs. A pressure of 1.95 bar, 1.0 g DCW/L initial biomass concentration, 0.70 kWh, 25 0C, and a membrane area of 3.8 m^2 need operating costs of 2.86 kWh/kg of biomass. Changes in certain operating variability can reduce operational costs significantly to 1.27 kWh/kg of biomass with a pressure parameter of 1.95 bar, 2.0 g DCW/L initial biomass concentration, 0.46 kWh, 20^{o}C and membrane area 7.6 m^2 (Gerardo et al., 2015).

The results of previous studies indicate that water treatment with MF/UF is more economical than conventional processes (Al-Malack, 2003). The MF crossflow process can produce reliable permeate quality. Meanwhile, in conventional processes, water quality depends largely on operational factors. The operational difficulties of the MF/UF process are also less than those of the conventional process. Capital costs from conventional water treatment processes are

65% greater than using MF/UF, while annual operating and maintenance costs are 21% lower. Based on predictions, after MF/UF is used for 40 years, it will be 8% more efficient than conventional processes.

Based on the study, the NF system has a capex (capital expense) estimated at US$ 551,250.00 and an opex (operating expense) ranging from US$ 0.364 to 0.446 per cubic meter of wastewater for an estimated membrane life of 1 - 5 years. Industry can save more than US$ 99,000 per year by reusing permeates. It can reduce water consumption around 551,880 m^3 per year (Reis et al., 2019). The bioreactor-NF system on a pilot scale records unit costs per m^3 of wastewater treatment for US$ 2.57, not including labor costs (Li et al. 2020). If implemented at full scale, the results will show a better efficiency of wastewater treatment, which has good quality for reuse (He et al., 2013). The NF process shows very good potential in waste treatment and waste reuse.

In other studies, NF/RO works well by rejecting an average of 94.5 – 99% of the metal and giving a residual concentration of 0.01 – 0.77 g/L for Cu and Ni and 0.7 – 5.7 μg/L for Zn. Operational costs consist of energy demand (47%), membrane replacement (37%) and for others (16%). NF/RO reliably removes metals below 6 μg/L with an operating cost of 18 p/m^3 (Garcia et al., 2013). NF/RO technology is increasing globally because there are always continuous improvements to significant cost reductions. These advances include membrane properties, module design, process design, initial feeds, energy recovery devices, and operational strategies focused on reducing energy consumption (Peña et al., 2013; Rahimpour et al., 2010).

4. CONCLUSION

The MF/UF system can serve as an effective pre-treatment for the NF/RO process, particularly for removing bacteria. Moreover, MF/UF membranes can be modified to enhance their performance, improving filtration. In contrast, the NF/RO system can eliminate a broader range of contaminants than MF/UF, including ions, heavy metals, viruses, and pharmaceutical compounds (PhAC). However, NF/RO membranes are more susceptible to fouling, which can be mitigated through antifouling strategies, such as developing NF membranes with zwitterionic functionalized monomers. RO, in particular, is highly effective for seawater treatment, providing high-quality water suitable for consumption. Additionally, water treatment using NF and RO systems presents a promising alternative due to their ability to operate with lower energy consumption than conventional water treatment methods. However, cost considerations play a significant role, as the water treatment process using a single MF/UF system is more economical than a combined MF/UF and NF/RO process, though the latter cannot remove all types of contaminants as effectively as NF/RO. This review highlights the need for further research into low-cost antifouling membranes and the integration of renewable energy to support the sustainable implementation of NF/RO systems. Policymakers and engineers should consider these insights when designing scalable, context-appropriate water treatment solutions.

REFERENCES

Abdel-Shafy, H. I., & Abdel-Shafy, S. H. (2017). Membrane technology for water and wastewater management and application in Egypt. *Egyptian Journal of Chemistry*, *60*(3), 347–360. https://doi.org/10.21608/EJCHEM.2017.3480

Al-Malack, M. H. (2003). Technical and economic aspects of crossflow microfiltration. *Desalination*, *155*(1), 89–94. https://doi.org/10.1016/S0011-9164(03)00242-X

Al-Mashharawi, S. K., Ghaffour, N., Al-Ghamdi, M., & Amy, G. L. (2013). Evaluating the efficiency of different microfiltration and ultrafiltration membranes used as pretreatment for Red Sea water reverse osmosis desalination. *Desalination and Water Treatment*, *51*, 617–626. https://doi.org/10.1080/19443994.2012.699449

Almojjly, A., Johnson, D. J., Mandale, S., & Hilal, N. (2019). Optimisation of the removal of oil in water emulsion by using ceramic microfiltration membrane and hybrid coagulation/sand filter-MF. *Journal of Water Process Engineering*, *27*, 15–23. https://doi.org/10.1016/j.jwpe.2018.11.007

Badruzzaman, M., Voutchkov, N., Weinrich, L., & Jacangelo, J. G. (2019). Selection of pretreatment technologies for seawater reverse osmosis plants: A review. *Desalination*, *449*, 78–91. https://doi.org/10.1016/j.desal.2018.10.006

Barcellos, D., Queiroz, H. M., Nóbrega, G. N., de Oliveira Filho, R. L., Santaella, S. T., Otero, X. L., & Ferreira, T. O. (2019). Phosphorus enriched effluents increase eutrophication risks for mangrove systems in northeastern Brazil. *Marine Pollution Bulletin*, *142*, 58–63. https://doi.org/10.1016/j.marpolbul.2019.03.031

Beyer, F., Laurinonyte, J., Zwijnenburg, A., Stams, A. J. M., & Plugge, C. M. (2017). Membrane Fouling and Chemical Cleaning in Three Full-Scale Reverse Osmosis Plants Producing Demineralized Water. *Journal of Engineering (United Kingdom)*, *2017*, 1–14. https://doi.org/10.1155/2017/6356751

Bilardi, S., Calabrò, P. S., Greco, R., & Moraci, N. (2018). Selective removal of heavy metals from landfill leachate by reactive granular filters. *Science of the Total Environment*, *644*, 335–341. https://doi.org/10.1016/j.scitotenv.2018.06.353

Cai, Y., Chen, D., Li, N., Xu, Q., Li, H., He, J., & Lu, J. (2018). A smart membrane with antifouling capability and switchable oil wettability for high-efficiency oil/water emulsions separation. *Journal of Membrane Science*, *555*, 69–77. https://doi.org/10.1016/j.memsci.2018.03.042

Carpintero-tepole, V., Brito-de, E., & Torrestiana-sánchez, B. (2017). Microfiltration of oil in water (O/W) emulsions: Effect of membrane microstructure and surface properties. *Chemical Engineering Research and Design*, *126*, 286–296. https://doi.org/10.1016/j.cherd.2017.08.023

Chang, H., Liu, B., Wang, H., Zhang, S. Y., Chen, S., Tiraferri, A., & Tang, Y. Q. (2019). Evaluating the performance of gravity-driven membrane filtration as desalination pretreatment of shale gas flowback and produced water. *Journal of Membrane Science*, *587*, 117187. https://doi.org/10.1016/j.memsci.2019.117187

Changmai, M., Das, P. P., Mondal, P., Pasawan, M., Sinha, A., Biswas, P., Sarkar, S., Purkait, M. K., Das, P. P., Mondal, P., Pasawan, M., Sinha, A., & Biswas, P. (2020). Hybrid electrocoagulation – microfiltration technique for treatment of nanofiltration rejected steel industry effluent. *International Journal of Environmental Analytical Chemistry*, 1–22. https://doi.org/10.1080/03067319.2020.1715381

Chatterjee, S., & De, S. (2017). Adsorptive removal of arsenic from groundwater using chemically treated iron ore slime incorporated mixed matrix hollow fiber membrane. *Separation and Purification Technology*, *179*, 357–368. https://doi.org/10.1016/j.seppur.2017.02.019

Chen, A. S. C., Wang, L., Sorg, T. J., & Lytle, D. A. (2020). Removing arsenic and co-occurring contaminants from drinking water by full-scale ion exchange and point-of-use/point-of-entry reverse osmosis systems. *Water Research*, *172*, 115455. https://doi.org/10.1016/j.watres.2019.115455

Chen, Z., Huang, T., Huang, X., Han, X., Yang, H., Cai, Z., Yao, L., Han, X., Zhang, M., & Huang, C. (2019). Characteristics, sources and environmental implications of atmospheric wet nitrogen and sulfur deposition in Yangtze River Delta. *Atmospheric Environment*, *219*, 116904. https://doi.org/10.1016/j.atmosenv.2019.116904

Choobar, B. G., Shahmirzadi, M. A. A., Kargari, A., & Manouchehri, M. (2019). Journal of Environmental Chemical Engineering Fouling mechanism identi fi cation and analysis in micro fi ltration of laundry wastewater. *Journal of Environmental Chemical Engineering*, *7*, 103030. https://doi.org/10.1016/j.jece.2019.103030

Cohen-Tanugi, D., & Grossman, J. C. (2012). Water desalination across nanoporous graphene. *Nano Letters*, *12*(7), 3602–3608. https://doi.org/10.1021/nl3012853

Conklin, K. Y., Stancheva, R., Otten, T. G., Fadness, R., Boyer, G. L., Read, B., Zhang, X., Sheath, R. G., State, C., Oaks, S. T., Rd, V., & Marcos, S. (2020). Molecular and morphological characterization of a novel dihydroanatoxin-a producing Microcoleus species (cyanobacteria) from the Russian River. *Harmful Algae*, *93*, 101767. https://doi.org/10.1016/j.hal.2020.101767

D'Agostino, P. M., Boundy, M. J., Harwood, T. D., Carmichael, W. W., Neilan, B. A., & Wood, S. A. (2019). Re-evaluation of paralytic shellfish toxin profiles in cyanobacteria using hydrophilic interaction liquid chromatography-tandem mass spectrometry. *Toxicon*, *158*, 1–7. https://doi.org/10.1016/j.toxicon.2018.11.301

de Vries, H. J., Stams, A. J. M., & Plugge, C. M. (2020). Biodiversity and ecology of microorganisms in high pressure membrane filtration systems. *Water Research*, *172*, 115511. https://doi.org/10.1016/j.watres.2020.115511

DEFRA. (2014). Water Framework Directive implementation in England and Wales: new and updated standards to protect the water environment. In *Department for Environment Food and Rural Affairs*. https://doi.org/10.1016/j.jengtecman.2009.06.008

Demoulin, C. F., Lara, Y. J., Wilmotte, A., Javaux, E. J., Cornet, L., François, C., & Baurain, D. (2019). Free Radical Biology and Medicine Cyanobacteria evolution : Insight from the fossil record. *Free Radical Biology and Medicine*, *140*, 206–223. https://doi.org/10.1016/j.freeradbiomed.2019.05.007

Diallo, M. S. (2014). Water Treatment by Dendrimer-Enhanced Filtration: Principles and Applications. In *Nanotechnology Applications for Clean Water: Solutions for Improving Water Quality: Second Edition* (Second Edi, pp. 227–239). Elsevier Inc. https://doi.org/10.1016/B978-1-4557-3116-9.00015-9

Dong, G., Nagasawa, H., Yu, L., Guo, M., & Kanezashi, M. (2020). Energy-efficient separation of organic liquids using organosilica membranes via a reverse osmosis route. *Journal of Membrane Science*, *597*, 117758. https://doi.org/10.1016/j.memsci.2019.117758

Economist.com. (2013). *Graphene and desalination*. https://www.economist.com/babbage/2013/04/04/allo-allo

Eeshwarasinghe, D., Loganathan, P., & Vigneswaran, S. (2019). Simultaneous removal of polycyclic aromatic hydrocarbons and heavy metals from water using granular activated carbon. *Chemosphere*, *223*, 616–627. https://doi.org/10.1016/j.chemosphere.2019.02.033

Ezugbe, E. O., & Rathilal, S. (2020). Membrane technologies in wastewater treatment: A review. *Membranes*, *10*(89), 1–28. https://doi.org/10.3390/membranes10050089

Ferrer, O., Casas, S., Galvan, C., Lucena, F., Bosch, A., Galofre, B., Mesa, J., Jofre, J., & Bernat, X. (2015). Direct ultrafiltration performance and membrane integrity monitoringby microbiological analysis. *Water Research*, *83*, 121–131. https://doi.org/10.1016/j.watres.2015.06.039

Fornasiero, F., In, J. Bin, Kim, S., Park, H. G., Wang, Y., Grigoropoulos, C. P., Noy, A., & Bakajin, O. (2010). PH-tunable ion selectivity in carbon nanotube pores. *Langmuir*, *26*(18), 14848–14853. https://doi.org/10.1021/la101943h

Forum, W. E. (2019). *The Global Risks Report (14th Edition)*.

Foureaux, A. F. S., Reis, E. O., Lebron, Y., Moreira, V., Santos, L. V., Amaral, M. S., & Lange, L. C. (2019). Rejection of pharmaceutical compounds from surface water by nanofiltration and reverse osmosis. *Separation and Purification Technology*, *212*, 171–179. https://doi.org/10.1016/j.seppur.2018.11.018

Garcia, N., Moreno, J., Cartmell, E., Rodriguez-Roda, I., & Judd, S. (2013). The cost and performance of an MF-RO/NF plant for trace metal removal. *Desalination*, *309*, 181–186. https://doi.org/10.1016/j.desal.2012.10.017

Gerardo, M. L., Zanain, M. A., & Lovitt, R. W. (2015). Pilot-scale cross-flow microfiltration of Chlorella minutissima: A theoretical assessment of the operational parameters on energy consumption. *Chemical Engineering Journal*, *280*, 505–513. https://doi.org/10.1016/j.cej.2015.06.026

Gholami, S., López, J., Rezvani, A., Vatanpour, V., & Cortina, J. L. (2020). Fabrication of thin-film nanocomposite nanofiltration membranes incorporated with aromatic amine-functionalized multiwalled carbon nanotubes. Rejection performance of inorganic pollutants from groundwater with improved acid and chlorine resistance. *Chemical Engineering Journal*, *384*, 123348. https://doi.org/10.1016/j.cej.2019.123348

Global engineering. (2012). *Membrane Filtration: Reverse Osmosis, Nanofiltration, Ultrafiltration and Microfiltration*. 1–12. https://www.gea.com/en/binaries/membrane-filtration-ultrafiltration-nanofiltration-microfiltration-reverse-osmosis-gea_tcm11-34841.pdf

Golpour, M., & Pakizeh, M. (2017). Development of a new nanofiltration membrane for removal of kinetic hydrate inhibitor from water. *Separation and Purification Technology*, *183*, 237–248. https://doi.org/10.1016/j.seppur.2017.04.011

Guo, H., Li, Z., Huang, J., Zhou, R., Wu, C., & Jin, Y. (2020). Microfiltration of Soy Sauce: Efficiency, Resistance and Fouling Mechanism at Different Operating Stages. *Separation and Purification Technology*, 116656. https://doi.org/10.1016/j.seppur.2020.116656

Han, D., Currell, M. J., Cao, G., & Hall, B. (2017). Alterations to groundwater recharge due to anthropogenic landscape change. *Journal of Hydrology*, *554*, 545–557. https://doi.org/10.1016/j.jhydrol.2017.09.018

Hao, Z., Chen, L., Wang, C., Zou, X., Zheng, F., Feng, W., Zhang, D., & Peng, L. (2019). Heavy metal distribution and bioaccumulation ability in marine organisms from coastal regions of Hainan and Zhoushan, China. *Chemosphere*, *226*, 340–350. https://doi.org/10.1016/j.chemosphere.2019.03.132

Harrington, K. (2013). *New Graphene Desalination Requires Nearly 100 Times Less Energy*.

https://www.aiche.org/chenected/2013/09/new-graphene-desalination-requires-nearly-100-times-less-energy

Hassan, S. S. M., Abdel-shafy, H. I., & Mansour, M. S. M. (2019). Removal of pharmaceutical compounds from urine via chemical coagulation by green synthesized ZnO- nanoparticles followed by microfiltration for safe reuse. *ARABIAN JOURNAL OF CHEMISTRY*, *12*(8), 4074–4083. https://doi.org/10.1016/j.arabjc.2016.04.009

He, Y., Wang, X., Xu, J., Yan, J., Ge, Q., Gu, X., & Jian, L. (2013). Application of integrated ozone biological aerated filters and membrane filtration in water reuse of textile effluents. *Bioresource Technology*, *133*, 150–157. https://doi.org/10.1016/j.biortech.2013.01.074

Hellinga, A., Grote, C., Büning, D., Ulbricht, M., Wessling, M., Polakovic, M., & Thom, V. (2019). Influence offlow alterations on bacteria retention during microfiltration. *Journal of Membrane Science*, *575*, 147–159. https://doi.org/10.1016/j.memsci.2019.01.021

Hocking, M., & Kelly, B. F. J. (2016). Groundwater recharge and time lag measurement through Vertosols using impulse response functions. *Journal of Hydrology*, *535*, 22–35. https://doi.org/10.1016/j.jhydrol.2016.01.042

Huang, B. C., Guan, Y. F., Chen, W., & Yu, H. Q. (2017). Membrane fouling characteristics and mitigation in a coagulation-assisted microfiltration process for municipal wastewater pretreatment. *Water Research*, *123*, 216–223. https://doi.org/10.1016/j.watres.2017.06.080

Huang, J., Xu, C. chun, Ridoutt, B. G., Wang, X. chun, & Ren, P. an. (2017). Nitrogen and phosphorus losses and eutrophication potential associated with fertilizer application to cropland in China. *Journal of Cleaner Production*, *159*, 171–179. https://doi.org/10.1016/j.jclepro.2017.05.008

Hylling, O., Nikbakht Fini, M., Ellegaard-Jensen, L., Muff, J., Madsen, H. T., Aamand, J., & Hansen, L. H. (2019). A novel hybrid concept for implementation in drinking water treatment targets micropollutant removal by combining membrane filtration with biodegradation. *Science of the Total Environment*, *694*, 133710. https://doi.org/10.1016/j.scitotenv.2019.133710

Jarvie, H. P., Smith, D. R., Norton, L. R., Edwards, F. K., Bowes, M. J., King, S. M., Scarlett, P., Davies, S., Dils, R. M., & Bachiller-Jareno, N. (2018). Phosphorus and nitrogen limitation and impairment of headwater streams relative to rivers in Great Britain: A national perspective on eutrophication. *Science of the Total Environment*, *621*, 849–862. https://doi.org/10.1016/j.scitotenv.2017.11.128

Keene, N. A., Reusser, S. R., Scarborough, M. J., Grooms, A. L., Seib, M., Santo Domingo, J., & Noguera, D. R. (2017). Pilot plant demonstration of stable and efficient high rate biological nutrient removal with low dissolved oxygen conditions. *Water Research*, *121*, 72–85. https://doi.org/10.1016/j.watres.2017.05.029

Kim, J. joo, Kim, K., Choi, Y. S., Kang, H., Kim, D. M., & Lee, J. C. (2018). Polysulfone based ultrafiltration membranes with dopamine and nisin moieties showing antifouling and antimicrobial properties. *Separation and Purification Technology*, *202*, 9–20. https://doi.org/10.1016/j.seppur.2018.03.033

Kimura, K., Honoki, D., & Sato, T. (2017). Effective physical cleaning and adequate membrane flux for direct membrane filtration (DMF) of municipal wastewater: Up-concentration of organic matter for efficient energy recovery. *Separation and Purification Technology*, *181*, 37–43. https://doi.org/10.1016/j.seppur.2017.03.005

Krystynik, P., & Tito, D. N. (2017). Key process parameters affecting performance of electro-coagulation. *Chemical Engineering and Processing: Process Intensification*, *117*, 106–112. https://doi.org/10.1016/j.cep.2017.03.022

Kulkarni, P., Raspanti, G. A., Bui, A. Q., Bradshaw, R. N., Kniel, K. E., Chiu, P. C., Sharma, M., Sapkota, A., & Sapkota, A. R. (2019). Zerovalent iron-sand filtration can reduce the concentration of multiple antimicrobials in conventionally treated reclaimed water. *Environmental Research*, *172*, 301–309. https://doi.org/10.1016/j.envres.2019.02.012

Lam, B., Déon, S., Morin-Crini, N., Crini, G., & Fievet, P. (2018). Polymer-enhanced ultrafiltration for heavy metal removal: Influence of chitosan and carboxymethyl cellulose on filtration performances. *Journal of Cleaner Production*, *171*, 927–933. https://doi.org/10.1016/j.jclepro.2017.10.090

Lateef, S. K., Soh, B. Z., & Kimura, K. (2013). Direct membrane filtration of municipal wastewater with chemically enhanced backwash for recovery of organic matter. *Bioresource Technology*, *150*, 149–155. https://doi.org/10.1016/j.biortech.2013.09.111

Lee, S., Ihara, M., Yamashita, N., & Tanaka, H. (2017). Improvement of virus removal by pilot-scale coagulation-ultrafiltration process for wastewater reclamation: Effect of optimization of pH in secondary effluent. *Water Research, 114,* 23–30. https://doi.org/10.1016/j.watres.2017.02.017

Li, J. H., Zhang, H., Zhang, W., & Liu, W. (2019). Nanofiber membrane of graphene oxide/polyacrylonitrile with highly efficient antibacterial activity. *Journal of Biomaterials Science, Polymer Edition*, *30*(17), 1620–1635. https://doi.org/10.1080/09205063.2019.1652793

Li, K., Liu, Q., Fang, F., Wu, X., Xin, J., Sun, S., Wei, Y., Ruan, R., Chen, P., Wang, Y., & Addy, M. (2020). Influence of nanofiltration concentrate recirculation on performance and economic feasibility of a pilot-scale membrane bioreactor-nanofiltration hybrid process for textile wastewater treatment with high water recovery. *Journal of Cleaner Production*, *261*, 121067. https://doi.org/10.1016/j.jclepro.2020.121067

Li, Z., Feng, X., Li, G., Bi, X., Zhu, J., & Qin, H. (2013). Distributions , sources and pollution status of 17 trace metal / metalloids in the street dust of a heavily industrialized city of central China. *Environmental Pollution*, *182*, 408–416. https://doi.org/10.1016/j.envpol.2013.07.041

Licona, K. P. M., Geaquinto, L. R. d. O., Nicolini, J. V., Figueiredo, N. G., Chiapetta, S. C., Habert, A. C., & Yokoyama, L. (2018). Assessing potential of nanofiltration and reverse osmosis for removal of toxic pharmaceuticals from water. *Journal of Water Process Engineering*, *25*, 195–204. https://doi.org/10.1016/j.jwpe.2018.08.002

Lin, G., Li, K., Liang, S., Li, Y., Su, Y., & Wang, X. (2020). Compound eutrophication index: An integrated approach for assessing ecological risk and identifying the critical element controlling harmful algal blooms in coastal seas. *Marine Pollution Bulletin*, *150*, 110585. https://doi.org/10.1016/j.marpolbul.2019.110585

Lin, L., Yang, H., & Xu, X. (2022). Effects of Water Pollution on Human Health and Disease Heterogeneity: A Review. *Frontiers in Environmental Science, 10,* 1–16. https://doi.org/10.3389/fenvs.2022.880246

Lin, S., & Elimelech, M. (2015). Staged reverse osmosis operation: Configurations, energy efficiency, and application potential. *Desalination*, *366*, 9–14. https://doi.org/10.1016/j.desal.2015.02.043

Lu, X., Lu, Y., Chen, D., Su, C., Song, S., Wang, T., Tian, H., Liang, R., Zhang, M., & Khan, K. (2019). Climate change induced eutrophication of cold-water lake in an ecologically fragile nature reserve. *Journal of Environmental Sciences*, *75*, 359–369. https://doi.org/10.1016/j.jes.2018.05.018

Manni, A., Achiou, B., Karim, A., Harrati, A., Sadik, C., Ouammou, M., Younssi, S. A., & Bouari, A. El. (2020). New low-cost ceramic microfiltration membrane made from natural magnesite for industrial wastewater treatment. *Journal of Environmental Chemical Engineering*, 103906. https://doi.org/10.1016/j.jece.2020.103906

Manouchehri, M., & Kargari, A. (2017). Water recovery from laundry wastewater by the cross flow microfiltration process: A strategy for water recycling in residential buildings. *Journal of Cleaner Production*, *168*, 227–238. https://doi.org/10.1016/j.jclepro.2017.08.211

McLachlan, P. J., Chambers, J. E., Uhlemann, S. S., & Binley, A. (2017). Geophysical characterisation of the groundwater–surface water interface. *Advances in Water Resources*, *109*, 302–319. https://doi.org/10.1016/j.advwatres.2017.09.016

Meena, R. A. A., Yukesh Kannah, R., Sindhu, J., Ragavi, J., Kumar, G., Gunasekaran, M., & Rajesh Banu, J. (2019). Trends and resource recovery in biological wastewater treatment system. *Bioresource Technology Reports*, *7*, 100235. https://doi.org/10.1016/j.biteb.2019.100235

Mestre, S., Gozalbo, A., Lorente-ayza, M. M., & Sánchez, E. (2019). Journal of the European Ceramic Society Low-cost ceramic membranes : A research opportunity for industrial application. *Journal of the European Ceramic Society*, *39*(12), 3392–3407. https://doi.org/10.1016/j.jeurceramsoc.2019.03.054

Mi, Y. F., Xu, G., Guo, Y. S., Wu, B., & An, Q. F. (2020). Development of antifouling nanofiltration membrane with zwitterionic functionalized monomer for efficient dye/salt selective separation. *Journal of Membrane Science*, *601*(3), 117795. https://doi.org/10.1016/j.memsci.2019.117795

Mohammad-pajooh, E., Turcios, A. E., Cuff, G., Weichgrebe, D., Rosenwinkel, K. H., Vedenyapina, M. D., & Sharifullina, L. R. (2018). Removal of inert COD and trace metals from stabilized landfill leachate by granular activated carbon (GAC) adsorption. *Journal of Environmental Management*, *228*, 189–196. https://doi.org/10.1016/j.jenvman.2018.09.020

Moraes, I. V. M. d., Rabelo, R. S., Pereira, J. A. d. L., Hubinger, M. D., & Schmidt, F. L. (2018). Concentration of hydroalcoholic extracts of graviola (Annona muricata L.) pruning waste by ultra and nanofiltration: Recovery of bioactive compounds and prediction of energy consumption. *Journal of Cleaner Production*, *174*, 1412–1421. https://doi.org/10.1016/j.jclepro.2017.11.062

Moussa, D. T., El-Naas, M. H., Nasser, M., & Al-Marri, M. J. (2017). A comprehensive review of electrocoagulation for water treatment: Potentials and challenges. *Journal of Environmental Management*, *186*, 24–41. https://doi.org/10.1016/j.jenvman.2016.10.032

Myat, D. T., Roddick, F., Puspita, P., Skillman, L., Charrois, J., Kristiana, I., Uhl, W., Vasyukova, E., Roeszler, G., Chan, A., Zhu, B., Muthukumaran, S., Gray, S., & Duke, M. (2018). Effect of oxidation with coagulation and ceramic microfiltration pre-treatment on reverse osmosis for desalination of recycled wastewater. *Desalination*, *431*, 106–118. https://doi.org/10.1016/j.desal.2017.10.029

Nidhi Maalige, R., Aruchamy, K., Mahto, A., Sharma, V., Deepika, D., Mondal, D., & Nataraj, S.

K. (2019). Low operating pressure nanofiltration membrane with functionalized natural nanoclay as antifouling and flux promoting agent. *Chemical Engineering Journal*, *358*, 821–830. https://doi.org/10.1016/j.cej.2018.10.087

Norouzi, M., Sharifnezhad, H., & Hosseini, S. G. (2019). Preparation and modification of polyethersulphone MF/UF membrane by TiO2 nanoparticles for pre-treatment of Pink water. *International Journal of Environmental Analytical Chemistry*, *100*(2), 175–188. https://doi.org/10.1080/03067319.2019.1634700

Paul, D. (2017). Research on heavy metal pollution of river Ganga: A review. *Annals of Agrarian Science*, *15*(2), 278–286. https://doi.org/10.1016/j.aasci.2017.04.001

Peña, N., Gallego, S., del Vigo, F., & Chesters, S. P. (2013). Evaluating impact of fouling on reverse osmosis membranes performance. *Desalination and Water Treatment*, *51*(4–6), 958–968. https://doi.org/10.1080/19443994.2012.699509

Peydayesh, M., Mohammadi, T., & Bakhtiari, O. (2019). Water desalination via novel positively charged hybrid nanofiltration membranes filled with hyperbranched polyethyleneimine modified MWCNT. *Journal of Industrial and Engineering Chemistry*, *69*, 127–140. https://doi.org/10.1016/j.jiec.2018.09.007

Phiri, I., Young, K., Woo, J., San, W., Hern, S., Myoun, J., Jung, H., & Si, À. (2019). Journal of Industrial and Engineering Chemistry Simultaneous complementary oil-water separation and water desalination using functionalized woven glass fi ber membranes. *Journal of Industrial and Engineering Chemistry*, *73*, 78–86. https://doi.org/10.1016/j.jiec.2018.12.049

Qiao, D., Wang, G., Li, X., Wang, S., & Zhao, Y. (2020). Pollution, sources and environmental risk assessment of heavy metals in the surface AMD water, sediments and surface soils around unexploited Rona Cu deposit, Tibet, China. *Chemosphere*, *248*, 125988. https://doi.org/10.1016/j.chemosphere.2020.125988

Qiu, Y., Lee, B. E., Neumann, N., Ashbolt, N., Craik, S., Maal-Bared, R., & Pang, X. L. (2015). Assessment of human virus removal during municipal wastewater treatment in Edmonton, Canada. *Journal of Applied Microbiology*, *119*(6), 1729–1739. https://doi.org/10.1111/jam.12971

Racar, M., Dolar, D., Farkaš, M., Milčić, N., Špehar, A., & Košutić, K. (2019). Rendering plant wastewater reclamation by coagulation, sand filtration, and ultrafiltration. *Chemosphere*, *227*, 207–215. https://doi.org/10.1016/j.chemosphere.2019.04.045

Rachbauer, L., Granda, C. B., Shrestha, S., Fuchs, W., Gabauer, W., Singer, S. W., Simmons, B. A., & Urgun-Demirtas, M. (2024). Energy and nutrient recovery from municipal and industrial waste and wastewater - A perspective. *Journal of Industrial Microbiology and Biotechnology*, *51*, 1–14. https://doi.org/10.1093/jimb/kuae040

Rahimpour, A., Jahanshahi, M., Mortazavian, N., Madaeni, S. S., & Mansourpanah, Y. (2010). Preparation and characterization of asymmetric polyethersulfone and thin-film composite polyamide nanofiltration membranes for water softening. *Applied Surface Science*, *256*(6), 1657–1663. https://doi.org/10.1016/j.apsusc.2009.09.089

Rajendran, V., Nirmaladevi D, S., Srinivasan, B., Rengaraj, C., & Mariyaselvam, S. (2018). Quality assessment of pollution indicators in marine water at critical locations of the Gulf of Mannar Biosphere Reserve, Tuticorin. *Marine Pollution Bulletin*, *126*, 236–240. https://doi.org/10.1016/j.marpolbul.2017.10.091

Rasouli, Y., Abbasi, M., & Hashemifard, S. A. (2019). Fabrication, characterization, fouling behavior and performance study of ceramic microfiltration membranes for oily wastewater treatment. *Journal of Asian Ceramic Societies*, *7*(4), 476–495. https://doi.org/10.1080/21870764.2019.1667070

Reis, B. G., Araújo, A. L. B., Vieira, C. C., Amaral, M. C. S., & Ferraz, H. C. (2019). Assessing potential of nanofiltration for sulfuric acid plant effluent reclamation: Operational and economic aspects. *Separation and Purification Technology*, *222*, 369–380. https://doi.org/10.1016/j.seppur.2019.04.048

Richards, B. S., Capão, D. P. S., Früh, W. G., & Schäfer, A. I. (2015). Renewable energy powered membrane technology : Impact of solar irradiance fluctuations on performance of a brackish water reverse osmosis system. *SEPARATION AND PURIFICATION TECHNOLOGY*, *156*(2), 379–390. https://doi.org/10.1016/j.seppur.2015.10.025

Salman, M., Yaseen, M., & Shakir, M. (2022). Recent Developments in Membrane Filtration for Wastewater Treatment. In *Industrial Wastewater Treatment*. https://doi.org/https://doi.org/10.1007/978-3-030-98202-7_1

Saniei, N., Ghasemi, N., Zinatizadeh, A. A., Zinadini, S., Ramezani, M., & Derakhshan, A. A. (2020). Preparation and characterization of a novel antifouling nano filtration poly ethersulfone (PES) membrane by embedding goethite-tannic acid nanoparticles. *Separation and Purification Technology*, *241*(6), 116646. https://doi.org/10.1016/j.seppur.2020.116646

Sarah, R., Tabassum, B., Idrees, N., Hashem, A., & Abd_Allah, E. F. (2019). Bioaccumulation of heavy metals in Channa punctatus (Bloch) in river Ramganga (U.P.), India. *Saudi Journal of Biological Sciences*, *26*, 979–984. https://doi.org/10.1016/j.sjbs.2019.02.009

Sathya, U., Nithya, M., & Keerthi. (2020). Fabrication and characterisation of fine-tuned Polyetherimide (PEI)/WO3 composite ultrafiltration membranes for antifouling studies. *Chemical Physics Letters*, *744*, 137201. https://doi.org/10.1016/j.cplett.2020.137201

Shah, A., Arjunan, A., Baroutaji, A., & Zakharova, J. (2023). A review of physicochemical and biological contaminants in drinking water and their impacts on human health. *Water Science and Engineering*, *16*(4), 333–344. https://doi.org/10.1016/j.wse.2023.04.003

Shen, J., Jeihanipour, A., Richards, B. S., & Schäfer, A. I. (2019). Renewable energy powered membrane technology : Experimental investigation of system performance with variable module size and fluctuating energy. *Separation and Purification Technology*, *221*, 64–73. https://doi.org/10.1016/j.seppur.2019.03.004

Shen, J., Richards, B. S., & Schäfer, A. I. (2016). Renewable Energy Powered Membrane Technology : Case Study of St . Dorcas Borehole in Tanzania Demonstrating Fluoride Removal via Nanofiltration / Reverse Osmosis. *Separation and Purification Technology*, *170*, 445–452. https://doi.org/10.1016/j.seppur.2016.06.042

Sillanpää, M., Ncibi, M. C., Matilainen, A., & Vepsäläinen, M. (2018). Removal of natural organic matter in drinking water treatment by coagulation: A comprehensive review. *Chemosphere*, *190*, 54–71. https://doi.org/10.1016/j.chemosphere.2017.09.113

Silva, F. C. (2018). Fouling of Nanofiltration Membranes. In *Nanofiltration* (pp. 119–131). https://doi.org/10.5772/intechopen.75353

Silva, J. A. (2023). Wastewater Treatment and Reuse for Sustainable Water Resources Management: A Systematic Literature Review. *Sustainability (Switzerland)*, *15*(14), 1–31. https://doi.org/10.3390/su151410940

Sounthararajah, D. P., Loganathan, P., Kandasamy, J., & Vigneswaran, S. (2015). Adsorptive removal of heavy metals from water using sodium titanate nanofibres loaded onto GAC in fixed-bed columns. *Journal of Hazardous Materials*, *287*, 306–316. https://doi.org/10.1016/j.jhazmat.2015.01.067

Stephens, G. L., Slingo, J. M., Rignot, E., Reager, J. T., Hakuba, M. Z., Durack, P. J., Worden, J., & Rocca, R. (2020). Earth's water reservoirs in a changing climate. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *476*(2236). https://doi.org/10.1098/rspa.2019.0458

Tai, Z. S., Abd Aziz, M. H., Othman, M. H. D., Mohamed Dzahir, M. I. H., Hashim, N. A., Koo, K. N., Hubadillah, S. K., Ismail, A. F., A Rahman, M., & Jaafar, J. (2019). Ceramic Membrane Distillation for Desalination. *Separation & Purification Reviews*, 1–40. https://doi.org/10.1080/15422119.2019.1610975

Tawalbeh, M., Al Mojjly, A., Al-Othman, A., & Hilal, N. (2018). Membrane separation as a pre-treatment process for oily saline water. *Desalination*, *447*, 182–202. https://doi.org/10.1016/j.desal.2018.07.029

Tay, M. F., Liu, C., Cornelissen, E. R., Wu, B., & Chong, T. H. (2018). The feasibility of nanofiltration membrane bioreactor (NF-MBR)+reverse osmosis (RO) process for water reclamation: Comparison with ultrafiltration membrane bioreactor (UF-MBR)+RO process. *Water Research*, *129*, 180–189. https://doi.org/10.1016/j.watres.2017.11.013

Thuy, N. T. H., & Boontawan, A. (2017). Production of very-high purity succinic acid from fermentation broth using microfiltration and nanofiltration-assisted crystallization. *Journal of Membrane Science*, *524*, 470–481. https://doi.org/10.1016/j.memsci.2016.11.073

Trinh, T. A., Li, W., Han, Q., Liu, X., Fane, A. G., & Chew, J. W. (2018). Analyzing external and internal membrane fouling by oil emulsions via 3D optical coherence tomography. *Journal of Membrane Science*, *548*, 632–640. https://doi.org/10.1016/j.memsci.2017.10.043

UNICEF. (2015). *Progress on sanitation and drinking water: 2015 update and mdg assessment*. World Health Organization and United Nations Children's Fund.

Veréb, G., Végh, J., Kertész, S., Beszédes, S., Hodúr, C., & László, Z. (2019). Effects of Pre-ozonation on Membrane Filtration of Oil-in-water Emulsions Using Different Polymeric (PES, PAN, PTFE) Ultrafilter Membranes. *Ozone: Science and Engineering*, 1–14. https://doi.org/10.1080/01919512.2019.1652567

Vital, B., Bartacek, J., Ortega-Bravo, J. C., & Jeison, D. (2018). Treatment of acid mine drainage by forward osmosis: Heavy metal rejection and reverse flux of draw solution constituents. *Chemical Engineering Journal*, *332*, 85–91. https://doi.org/10.1016/j.cej.2017.09.034

Wei, W., Sun, M., Zhang, L., Zhao, S., Wu, J., & Wang, J. (2017). Underwater oleophobic PTFE membrane for efficient and reusable emulsion separation and the influence of surface wettability and pore size. *Separation and Purification Technology*, *189*, 32–39. https://doi.org/10.1016/j.seppur.2017.07.074

Werber, J. R., Osuji, C. O., & Elimelech, M. (2016). Materials for next-generation desalination and water purification membranes. *Nature Reviews Materials*, *1*(5), 16018. https://doi.org/10.1038/natrevmats.2016.18

Wisniewska, K., Lewandowska, A. U., & Sliwinska-Wilczewska, S. (2019). The importance of cyanobacteria and microalgae present in aerosols to human health and the environment – Review study. *Environment International*, *131*, 104964. https://doi.org/10.1016/j.envint.2019.104964

Wu, J., Wei, W., Li, S., Zhong, Q., Liu, F., Zheng, J., & Wang, J. (2018). The effect of membrane surface charges on demulsification and fouling resistance during emulsion separation. *Journal of Membrane Science, 563,* 126–133. https://doi.org/10.1016/j.memsci.2018.05.065

Xiong, J., Yu, S., Hu, Y., Yang, Y., & Wang, X. C. (2019). Applying a dynamic membrane filtration (DMF) process for domestic wastewater preconcentration: Organics recovery and bioenergy production potential analysis. *Science of the Total Environment*, *680*, 35–43. https://doi.org/10.1016/j.scitotenv.2019.05.080

Xu, D., Bai, L., Tang, X., Niu, D., Luo, X., Zhu, X., Li, G., & Liang, H. (2019). A comparison study of sand filtration and ultrafiltration in drinking water treatment: Removal of organic foulants and disinfection by-product formation. *Science of the Total Environment*, *691*, 322–331. https://doi.org/10.1016/j.scitotenv.2019.07.071

Xu, Y., Li, J., Zhang, X., Wang, L., Xu, X., Xu, L., Gong, H., Xie, H., & Li, F. (2019). Data integration analysis: Heavy metal pollution in China's large-scale cattle rearing and reduction potential in manure utilization. *Journal of Cleaner Production, 232,* 308–317. https://doi.org/10.1016/j.jclepro.2019.05.337

Yang, L., She, Q., Wan, M. P., Wang, R., Chang, V. W. C., & Tang, C. Y. (2017). Removal of haloacetic acids from swimming pool water by reverse osmosis and nanofiltration. *Water Research*, *116*, 116–125. https://doi.org/10.1016/j.watres.2017.03.025

Yasui, N., Suwa, M., Sakurai, K., Suzuki, Y., Kobayashi, K., Takabatake, H., Lee, S. T., & Tanaka, H. (2016). Removal characteristics and fluctuation of norovirus in a pilot-plant by an ultrafiltration membrane for the reclamation of treated sewage. *Environmental Technology*, *37*(21), 2791–2801. https://doi.org/10.1080/09593330.2016.1164760

Yin, J., & Zhou, J. (2015). Novel polyethersulfone hybrid ultrafiltration membrane prepared with SiO2-g-(PDMAEMA-co-PDMAPS) and its antifouling performances in oil-in-water emulsion application. *Desalination*, *365*, 46–56. https://doi.org/10.1016/j.desal.2015.02.017

Yin, Z., Tarabara, V. V., & Xagoraraki, I. (2015). Human adenovirus removal by hollow fiber membranes: Effect of membrane fouling by suspended and dissolved matter. *Journal of Membrane Science*, *482*, 120–127. https://doi.org/10.1016/j.memsci.2015.02.028

Zaharia, C., Musteret, C. P., & Afrasinei, M. A. (2024). The Use of Coagulation–Flocculation for Industrial Colored Wastewater Treatment—(I) The Application of Hybrid Materials. *Applied Sciences (Switzerland)*, *14*(5). https://doi.org/10.3390/app14052184

Zaouk, L., Massé, A., Bourseau, P., Taha, S., Rabiller-Baudry, M., Jubeau, S., Teychené, B., Pruvost, J., & Jaouen, P. (2020). Filterability of exopolysaccharides solutions from the red microalga Porphyridium cruentum by tangential filtration on a polymeric membrane. *Environmental Technology (United Kingdom)*, *41*(9), 1167–1184. https://doi.org/10.1080/09593330.2018.1523234

Zhang, W., Jin, X., Liu, D., Lang, C., & Shan, B. (2017). Temporal and spatial variation of nitrogen and phosphorus and eutrophication assessment for a typical arid river — Fuyang River in northern China. *Journal of Environmental Sciences (China), 55,* 41–48. https://doi.org/10.1016/j.jes.2016.07.004

Zhang, X., Liu, C., Yang, J., Zhu, C., Zhang, L., & Xu, Z. (2020). Nanofiltration membranes with hydrophobic microfiltration substrates for robust structure stability and high water permeationflux. *Journal of Membrane Science*, *593*, 117444. https://doi.org/10.1016/j.memsci.2019.117444

Zheng, Y., Vanderzalm, J., Hartog, N., Escalante, E. F., & Stefan, C. (2023). The 21st century water quality challenges for managed aquifer recharge: towards a risk-based regulatory approach. *Hydrogeology Journal*, *31*(1), 31–34. https://doi.org/10.1007/s10040-022-02543-z

Zhou, Y., Wang, L., Zhou, Y., & Mao, X. zhong. (2020). Eutrophication control strategies for highly anthropogenic influenced coastal waters. *Science of the Total Environment*, *705*. https://doi.org/10.1016/j.scitotenv.2019.135760

Zhu, X., Tang, X., Luo, X., Cheng, X., Xu, D., Gan, Z., Wang, W., Bai, L., Li, G., & Liang, H. (2020). Toward enhancing the separation and antifouling performance of thin-film composite nanofiltration membranes: A novel carbonate-based preoccupation strategy. *Journal of Colloid and Interface Science*, *571*, 155–165. https://doi.org/10.1016/j.jcis.2020.03.044

Zhu, Y., Dou, P., He, H., Lan, H., Xu, S., Zhang, Y., He, T., & Niu, J. (2020). Improvement of permeability and rejection of an acid resistant polysulfonamide thin-film composite nanofiltration membrane by a sulfonated poly(ether ether ketone) interlayer. *Separation and Purification Technology*, *239*, 116528. https://doi.org/10.1016/j.seppur.2020.116528