Chapter 2
Sustainable Wastewater Treatment Using Membrane Technology

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1 Introduction

Water is one of the most important components of life on earth [61]. In many places of the world, water is commonly developed as an economic and social asset. Only around 2.5% of the world's total water content is pure water, which makes up roughly 71% of the overall water content [19]. Fresh water is required to sustain life and the environment afloat. Fresh water resources include rivers, lakes, ponds, ground water, and streams [56]. Around 1% is accessible for human and industrial needs, with the rest being unusable groundwater sources and glaciers [122]. However, due to population growth and industrialization, these resources are decreasing [47]. Climate change, inter-annual climate variability, and its use in energy generation are all factors that contribute to fresh water scarcity and depletion [89]. Fresh water scarcity has become a major environmental concern. It is necessary to recover water from existing wastewater or establish alternative water sources for human consumption to address water scarcity challenges [123]. Waste water treatment, in which water is recovered from industrial waste water, could be a viable solution [49]. Large volumes of wastewater generated by uncontrolled industrialization have been discharged into the environment in recent years without being properly treated. As a result, the water quality of adjacent water bodies has rapidly deteriorated. Chemical precipitation [24], microbial decomposition [125], and physical adsorption are all common methods for removing pollutants from water [69]. Both the environment (i.e. plants,

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animals, ecology, and climate) and humans are harmed by these pollutants. One of the biggest sources of pollution is industrial waste water [30, 122, 123]. Due to the huge quantities of effluent, composition of effluent, and number of industries, waste water treatment has been viewed as a critical priority for environmental protection. Among the toxins present in industrial waste water include heavy metals, dyes, pesticides, herbicides, medications, and other aromatic compounds [95, 100]. These compounds pose a major threat to the environment when they enter the environment. These contaminants are harmless at low concentrations, but their accumulation over time can have dangerous consequences. Toxic compounds are present in mine, petrochemical, textile, and dye effluents, posing a health risk to humans [78, 97].

Several attempts have been made over the years to incorporate various wastewater treatment technologies into this environment, including conventional filtration, coagulation-flocculation, and biological treatment systems, among others [53]. However, membrane technology is one of the wastewater treatment technologies that has witnessed a significant increase in popularity over the last several years [32]. Despite the fact that membrane technology is not a new concept, the varying nature and complexity of wastewater allows for future developments in terms of efficiency, space requirements, energy, permeate quality, and technological capabilities [118].

2 Causes of Water Pollution

Environmental Pollution poses a significant threat to global biodiversity and the human race. The quality of soil, air, and water are impacted by the discharge of industrial effluents into the environment. Domestic, municipal, industrial, and agricultural runoff, sewage from septic tanks, and rainwater are the most common wastes dumped into water channels, lakes, rivers, and streams, respectively [2]. The direct discharge of hazardous chemicals into water from the textile, petrochemical, pharmaceutical industries, refineries, and mining sectors causes water pollution and has major consequences for humans, plants, animals, and aquatic species. Large numbers of pathogenic bacteria and xenobiotic chemicals are disposed of directly in waste water, and even minor physiochemical properties of polluted water pose major health risks to aquatic organisms and people [8].

2.1 Domestic Wastewater

Generally, domestic wastewater can be divided into two basic categories. These are brown wastewater (kitchen, bath, laundry) and the black wastewater (urine, faeces and toilet paper) [7]. It contains low amount of solid usually being 99% of water. It contains millions of bacteria per ml which may cause cholera, dysentery and typhoid fever. It has number of synthetic detergents, resistant to biodegradation.

2.2 Municipal Wastewater

Municipal wastewater, composed mainly of urban wastewater intended to be removed from communities, is also regarded as a renewable resource from which water, materials, and energy can be recovered [80].

2.3 Industrial Wastewater

Industrial wastewater encompasses any sewage from any producing, manufacturing, processing, institutional, commercial, agricultural, or other operations when the sewage discharged includes considerable quantities of wastes of non-human origin, excluding domestic sewage and uncontaminated water [52]. Industrial sewage also includes polluted water from cooling or condensing systems and air-conditioning systems from any of the preceding operations, without limiting any of the foregoing [20].

2.4 Agricultural Runoff

Soil washed off fields is the most common source of agricultural water contamination [3]. Rainwater picks up soil particles (sediment) and deposits them in nearby lakes and streams. A buildup of silt in the water can veil it, lowering the amount of sunlight reaching aquatic plants. Pesticides and fertilizers used in agriculture, as well as organic livestock wastes, antibiotics, silage effluents, and processing wastes from plantation crops, can contaminate both groundwater and surface water [59, 113].

2.5 Sewage from Septic Tank

A septic tank is an underground container composed of concrete, fiberglass, or plastic into which sewage (domestic wastewater) flows for primary treatment, which includes settling and anaerobic solids and organics reduction [28].

2.6 Rainwater

Rainwater carries bacteria, parasites, viruses, and toxins that can make people sick, and it's been connected to disease epidemics. Especially when rain follows several days of dry weather, dirt and germs might be washed into the roof's collected rainwater [119].

3 Common Steps Involved in Wastewater Treatment

Before the water is released into the environment, wastewater treatment is a procedure in which impurities or pollutants are removed from the aqueous phase using a variety of physical and chemical techniques. Residential and nonresidential wastewater can be treated in a variety of ways; most wastewater is first sent to a municipal sewage treatment plant [43]. These treatment plants can remove a large amount of the contaminant if they are correctly constructed and operated [37].

Wastewater from homes, businesses, and storm runoff must transit through multiple steps before becoming potable, in order to provide all of the water required [1]. We will acquire a greater grasp of the effort that goes into generating safe drinking water for everyone if we understand the three stages of wastewater treatment systems. To generate treated wastewater, a variety of techniques are used, which can be divided into three categories: primary, secondary, and tertiary [88].

3.1 Pre-treatment

Although there are three basic processes, there is one crucial step that must take place before any of them can begin. This is known as the pre-treatment stage, and it entails removing contaminants from the wastewater that may otherwise harm or block the pipes. Sanitary items, nappies, plastic, leaves, and other big objects are often removed during this operation [35].

3.2 Primary Treatment

The first of the three processes is to separate the organic waste and sludge from the rest of the water [86]. Allowing wastewater to pass through massive settling tanks, where particles sink to the bottom and grease and oils rise to the top, accomplishes this. Heavier substances sink to the bottom, whereas lighter solids rise to the top due to gravity. To remove even more sediments, chemicals might be used as coagulants [91]. Oils and grease are skimmed off the top of the surface on a regular basis, and sludge is scraped into the centre of the floor with massive scrapers. The water is then pumped away while the rest is treated in a secondary treatment facility [61].

3.3 Secondary Treatment

The removal of soluble organic matter solids that escaped primary treatment is part of secondary treatment. It can also handle smaller suspended solids [91].

Secondary treatment methods include:

- Bioreactors
- Filter beds
- Aerated ponds
- Activated sludge
- Rotating biological contactors

The best way to remove organic impurities is to use a membrane bioreactor, which uses a biological process in which microorganisms devour the organic matter for energy. Solids are formed when bacteria replicate. After that, the solids are filtered by the membrane, which produces effluent [14, 92].

The key benefit of this method is that it does not require the use of a secondary solids clarifier or filter system. The biological process in the reactor is integrated with the physical separation of solids in one technique [117].

Filter beds, aerated ponds, biofilters, activated sludge, and rotating biological contactors are some of the other secondary treatment options. Membrane bioreactors, on the other hand, are the most efficient and modern technology [124].

Secondary-treated water can be discharged into the environment without causing harm to aquatic life or ecosystems.

3.4 Tertiary Treatment

Water is disinfected to the highest standards through tertiary treatment, also known as polishing. This step is required to generate water that has specific requirements, such as technical waters, as well as to treat wastewater for public water systems [46].

Tertiary treatment methods include:

- UV disinfection
- Chemical disinfection

UV disinfection does not necessitate the use of chemicals and can be used instead. This elimination has the need for an additional additive filtering stage. Although ultraviolet light has no effect on the pH, look, taste, or odor of water, it can destroy microbes [58]. Bacterial control is usually achieved using UV light wastewater treatment, which prevents organisms from replicating. It's also capable of removing chlorine, chloramines, ozone, and bromine, making it excellent for generating ultrapure technical waters [95].

The addition of a chemical to the water is required for chemical disinfection. Chlorine is the most frequent. Chlorination destroys bacteria and viruses, but it has the drawback of necessitating a stage of dichlorination before being released into the environment. Iodine is another chemical that is used to disinfect water. When it comes to killing viruses and bacteria, this is just as powerful as chlorine [93] (Fig. 1).

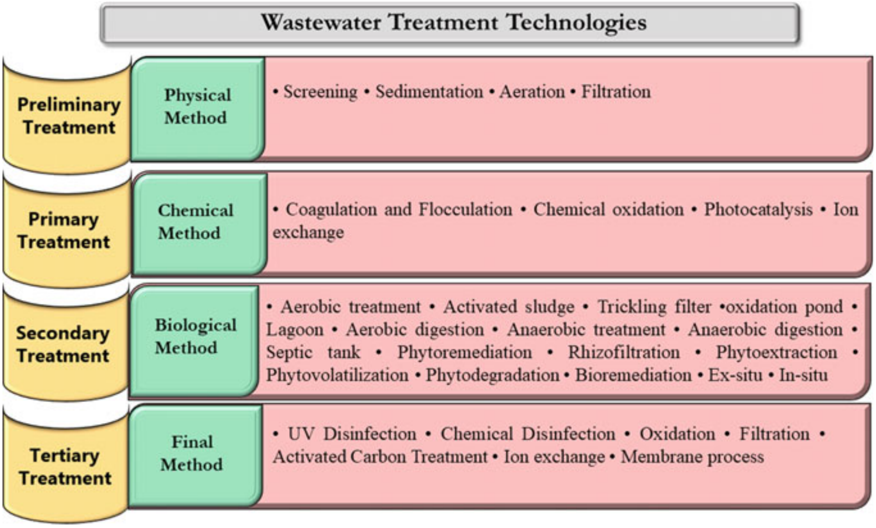

Fig. 1 Traditional wastewater treatment steps

4 Techniques Available for Wastewater Treatment

Various wastewater treatment methods have been used to remove toxic contaminants from the water.

4.1 Physical Methods

Physical events, rather than biological or chemical changes, are used in wastewater treatment systems to finish the removal process. Physical methods include screening, sedimentation, and filtration. To remove oil and grease particles, sand filters are sometimes employed in the oil water separation process [104].

4.1.1 Screening

Screening is the initial step in a physical wastewater treatment system. This technique comprises eliminating large non-biodegradable and floating particles from a wastewater treatment plant, such as rags, papers, plastics, tins, containers, and wood [103]. If these pollutants are removed efficiently, the downstream plant and equipment will be safeguarded from potential damage and pipe jams. The two most frequent methods of wastewater screening are coarse and fine screening.

4.1.2 Sedimentation

Gravity settling isolates particles from a fluid in this procedure. Due to the decrease in water velocity throughout the water treatment process, the particle in suspension remains stable in quiescent conditions, after which the particles settle by gravity force [43, 101]. In the sedimentation process, particle size is extremely important. The residual time for particle settling can be described as settling velocity. Sedimentation is used to reduce the concentration of solids before coagulation to reduce the amount of coagulants used in the coagulation process. In the treatment of dirty water, three main forms of sedimentation can be used.

Type 1—Particles settle at a constant velocity and sticking or flocculation does not occur.

Type 2—Due to change of particle size constantly it affects settling velocity and the particles Flocculate.

Type 3—High concentration of particles settle down. Two distinct zones such as sludge zone and clear zone were formed.

Some chemicals become adsorbed on the suspended material during organic chemical sedimentation. Pollutants with a higher density than water deviate from the fluid streamline flow and settle at the bottom. Solid particles undergo physical and hydrodynamic processes as a result of shear forces in the water stream, which affect the aggregation process and solid removal efficiency [87]. Gravity sedimentation, flocculation, and thickening all affect sedimentation efficiency.

4.1.3 Filtration

Filtration is the process of removing contaminants according to their size. Water can be reused for a variety of applications after pollutants are removed from wastewater. Depending on the impurities in the water, different types of filters are utilized in the method. Particle filtration and membrane filtration are the two main forms of wastewater filtration [5]. Particle filtering is the primary process in the wastewater treatment technique. It's made to get rid of solids that are bigger than one micron in size. The particle shape, size, texture, density, and quantity all influence the type of filter employed in the filtration process. The two primary types of filters used in the filtration of polluted water are bag and cartridge filters [81]. Solid wastes are confined inside bags in bag filters, and the filtration media includes activated carbon, nylon, and other materials [59]. The wastewater is poured into the bags, which trap the solid particles while allowing the liquid to flow. Bag filters are best for small-scale wastewater treatment since they produce less solid waste than cartridge filters. In comparison to other filter systems, bag filters collect less total waste. Cartridge filters catch solid particles outside of the filter media. Polluted water enters the filter vessel at the top, flows through the filter medium, which traps solids, and then exits through the lower section. There are three types of cartridge filters: disposable, back washable, and cleanable. The constraints of using cartridge filters are difficulties in air reversal and filter material selection [35]. Filtration can be used to remove suspended particles, particulate matter, microorganisms like bacteria and viruses, as well as other chemical pollutants.

A membrane process is a method of filtering or removing particles from water using a membrane barrier. At the cellular level, each action necessitates a different layer that acts as a filter or separates water from contaminants [53]. Depending on the pore size and cell size, different materials are employed to distinguish the membrane

Microfilteration (MF),
Ultrafilteration (UF),
Nanofilteration (NF),
Advanced/ Forward Osmosis (FO) and
Reverse osmosis (RO).

4.2 Chemical Methods

Chemical treatments are used in addition to physical or biological approaches to reduce the discharge of pollutants and wastewater into water bodies [99]. Different chemical procedures for the conversion into end products or the removal of pollutants are used for the safe disposal of contaminants. Some of the chemical methods are

- Coagulation and Flocculation
- Chemical oxidation
- Photocatalysis
- Ion exchange.

4.2.1 Coagulation and Flocculation

In industrial wastewater treatment, coagulation and flocculation are essential for solid–liquid separation. The addition of specific compounds known as coagulants to the coagulation process destabilizes colloidal suspensions by neutralizing their charges, resulting in the aggregation of smaller particles [68].

In some cases, flocculants are used to speed up particle aggregation and improve the efficiency of settlement. Various coagulants/ flocculants have different properties due to structural differences such as functional groups, charge, ionic strength, and molecular weight [64].

Coagulants neutralize the negative electrical charge on particles, which destabilizes the forces keeping colloids apart [29]. Coagulants for water treatment are made up of positively charged molecules that neutralize the charge in the water when combined. In order to remove suspended solids from water, inorganic coagulants, organic coagulants, or a combination of both are commonly utilized [112].

Flocculants gather the destabilized particles causing them to clump together and fall out of solution.

4.2.2 Chemical Oxidation

Chemical oxidation diminishes the wastewater's biological oxygen demand and may reduce the toxicity of some contaminants. Some contaminants are converted to carbon dioxide, water, and biosolids during secondary treatment. For disinfection, chemical oxidation is commonly utilized [11, 15].

4.2.3 Photocatalysis

The photocatalysis technique is an advanced oxidation method for removing persistent organic pollutants and bacteria from water. Solid, semiconductive catalysts generate active oxygen forms on their surfaces during photocatalysis when exposed to light of the appropriate wavelength [16, 17]. The oxidation and reduction of substances adsorbed on the catalyst surface are carried out by these oxygen forms. The main objective of photocatalysis using TiO_2 as a semiconductive catalyst is to carry out a sequence of redox reactions on the catalyst surface. It is only associated with the characteristics of electrons in the outer molecular orbital. When a photon energy (hν) larger than or equal to the valence to the band gap energy (TR) of TiO_2 is exposed onto the catalytic surface [23]. Semiconductive photocatalysis using UV or sun radiation has proven to be a viable approach for both mineralization and disinfection of organic molecules. The process's integration with other treatment procedures creates a viable alternative to conventional water and wastewater treatment technologies.

4.2.4 Ion Exchange

The ion exchange technique is used to replace ions or ions in wastewater treatment [57]. Contaminants and changed structures that have the same type of electrical charging can be either harmful or beneficial. Water that is too hard to clean with is difficult to use and frequently leaves a greyish residue. Water hardness is caused by ions such as calcium and magnesium. Positively charged sodium ions are added to the water in the form of dissolved sodium chloride salt to soften it [60]. The sodium ions take the place of hard calcium and magnesium ions, and the free sodium ions are simply discharged into the water. However, after softening a considerable amount of water, the softening solution may get clogged with calcium and magnesium ions, necessitating a sodium ion recharge [9].

4.3 Biological Methods

Biological operations are crucial in the wastewater treatment process. These biochemical activities can be classified based on three factors: the biological environment, the type of the biological environment, nature of biological transformation and reactor configuration [94]. This is the process by which dissolved and suspended organic chemical elements are eliminated through biodegradation, with the addition of microorganisms in an optimal proportion to mimic the natural self-purification process. Microorganisms can breakdown organic substances in wastewater using two different biological processes called biological oxidation and biosynthesis [40].

Although biological wastewater treatment appears to be a simple and easy process on the surface, it is a complex process involving biochemistry and biology. Natural mechanisms are employed to aid in the dissolution of organic elements. In order to break down the organic wastes, biological treatments uses common cellular processes that bank on small organisms, bacteria, and nematodes [85].

Biological methods include (i) aerobic treatment, (ii) anaerobic treatment, (iii) phytoremediation, (iv) bioremediation.

4.3.1 Aerobic Treatment

Aerobic wastewater treatment processes include simple septic or aerobic tanks, and oxidation ditches; surface and spray aeration; activated sludge; oxidation ditches, trickling filters; pond and lagoon-based treatments; and aerobic digestion. Biological treatment procedures include constructed wetlands and other types of filtration. While the wastewater is being treated, diffuse aeration systems can be used to enhance oxygen transport and reduce smells [75]. As beneficial bacteria and other organisms breakdown organic components in wastewater, aeration produces oxygen.

Aerobic microorganisms require oxygen to support their metabolic activity. Special aeration equipment provides oxygen to the effluent in the form of air during effluent treatment [108]. Bacteria transform organic compounds into carbon dioxide and biomass using dissolved oxygen. Furthermore, aerobic microorganisms convert ammonified organic nitrogen compounds to nitrate by oxidising ammonium and nitrite (nitrification). A sufficient amount of nutrients in relation to the amount of biomass, a specific temperature and pH regime, and the absence of toxic substances are all important factors in the success of an aerobic process [22].

4.3.2 Anaerobic Treatment

It is a slow process that can take up to three months to occur due to excessive decay [15, 45]. There could be an unpleasant odor that needs to be addressed in order to eliminate water waste. Bacteria are used in anaerobic treatment to assist organic material to decompose in an oxygen-free environment [27]. Anaerobic procedures are employed in lagoons and septic tanks, but the most well-known anaerobic treatment is anaerobic digestion, which is used to treat food and beverage effluent, as well as municipal wastewater, chemical effluent, and agricultural waste [31].

One of the most robust areas of resource recovery is energy recovery, which is driven by anaerobic digestion. Anaerobic digestion is utilised to produce biogas, which is mostly constituted of methane, in this type of energy recovery, also known as waste-to-energy. Operators can use it to create energy, which will help them reach their goal of being energy net zero, or even turn waste streams into revenue streams [126].

4.3.3 Phytoremediation

Phytoremediation is a cheaper and feasible sustainable method for removal of pollutants. At the same time, it is environmentally beneficial, and it has no negative impact on people who live and work in the surrounding area because it cleans the environment with plants [72]. Aquatic plants are important in biological wastewater treatment systems because they may be employed for phytoremediation using processes like rhizofiltration, phytoextraction, phytovolatilization, phytodegradation, and phytotransformation. The period of exposure, the concentration of pollutants, environmental factors (pH, temperature), and plant features (species, root system etc.) all play a role in pollutant eradication. However, it is worth noting, that other aquatic plant species have been successfully used in the wastewater phytoremediation process [25].

Various plant species have endogenous qualities that can help to clean up water contamination. The ability of plants to accumulate various metals (essential or non-essential) is the basic principle underpinning phytoextraction [54]. Phytoremediation of wastewater is a new low-cost method for removing harmful metal ions from industrial wastewater that is still in its early stages of development. Heavy metals such as cadmium and lead are not easily absorbed by microorganisms [1, 109]. These poisons would be the ideal treatment option if they were bioaccumulated by normal plant metabolism. Aquatic plants have an excellent deal of ability to reduce harmful metals, BOD, and total solids in wastewater. It is also a cost-effective, aesthetically beautiful technology that conserves the ecosystem in situ [26, 130].

4.3.4 Bioremediation

Bioremediation is a method of removing nutrients from wastewater by using naturally occurring microorganisms and other features of the natural environment [115]. Single-celled organisms grow until they reach a specific size, at which point they divide into two. This type of endeavour opens the door to environmentally and economically sound treatment options. Due to the extensive time and planning required for efficient treatment, wastewater treatment and bioremediation is a cost-effective method. Bioremediation is a technique for restoration of ecological damage by enhancing the ability of some living organisms (for example, plants, fungi, and bacteria, for instance) to remove, breakdown, or change hazardous organic molecules into harmless or less dangerous metabolic products [10]. Hydrogeologic conditions, the pollutant, microbial ecology, and other geographical and temporal considerations all have a role in a successful, cost-effective microbial bioremediation programme. The pollutants are used as nutrition or energy sources by the introduced microorganisms in any bioremediation procedure. Some common microorganisms used in the process of remediation are *Acromobacter, Alcaligenes, Arthrobacter, Bacillus, Cinetobacter, Corneybacterium, Flavobacterium, Micrococcus, Mycobacterium, Nocardia, Pseudomonas, Vibrio, Rhodococcus* and *Sphingomonas* species [33].

The two main types of bioremediation are in situ bioremediation and ex situ bioremediation. The term in situ bioremediation refers to cleaning up a contaminated site right where it happened. The removal of contaminated material from its original location to be treated elsewhere is known as ex situ. There are various technologies used, Bioaugmentation, Biostimulation, Bioreactors, Fungal Remediation, Phytoremediation, Electrobiorremediation, Leaching, Chelation, Methylation and Precipitation [41] (Table 1).

5 Polymeric Membrane for Pollution Remediation

Membrane (MBR) technology has become a crucial component in water reclamation schemes due to the possibility of providing water of high quality (e.g. as particle-free permeate from membrane bioreactors, removal of microbiological contaminants) [65]. Polymeric membranes are commonly used for water treatment, such as agro-food, textile, and petroleum industry waste streams, or for the removal of pollutants from drinking water, allowing the concentrate to be treated or discharged and, as a result, reducing contaminants discharged directly or indirectly into wastewater [96]. Obtaining a remediated effluent is also a cost-effective method. It is cost-effective and environmentally friendly for usage in remote areas [76]. A membrane is a selectively restrictive barrier that separates two phases by preventing component mobility [129] (Fig. 2).

Membranes can be classified as isotropic or anisotropic based on their properties. Isotropic membranes are composed of compatible materials and same physical structure. They can be microporous, which implies they have large permeation fluxes, or nonporous (dense), which means their applicability is severely limited due to low permeation fluxes [79]. On the other hand, anisotropic membranes are made up of multiple layers with varied structures and compositions that are non-uniform over the membrane region. A thin selective layer is supported by a thicker, highly permeable layer in these membranes.

Table 1 Different wastewater control techniques and their advantages and disadvantages

Sl. No.	Wastewater control techniques	Advantages	Disadvantages
1	*Physical methods*		
(i)	Screening	1. It removes objects like rags, paper, plastics, and metals 2. It prevents damage and clogging of downstream equipment, piping, and appurtenances [104]	1. Damage to other process equipment 2. Reduction in efficiency of the whole system [103]
(ii)	Sedimentation	1. No energy requirement 2. Excellent reproducibility [101]	1. Selective process 2. Lacks precision [87]
(iii)	Filtration	Autoclaving can be done in some cases [5]	Clogging of filters may occur [35]
2	*Chemical methods*		
(i)	Coagulation-flocculation	1. Used for fine particle removal 2. Removes metals, colour and turbidity [68]	1. Multiple process step 2. Toxic if improperly used 3. High sludge production [112]
(ii)	Chemical oxidation	1. Do not introduce new hazardous substances into water 2. All organic materials and can remove some heavy metals 3. No sludge production as with chemical or biological processes [11]	1. Relatively high capital and operating/maintenance costs 2. Complex chemistry tailored to specific contaminants [15]
(iii)	Photocatalysis	1. Environmental friendly 2. Complete degradation of pollutants 3. No secondary pollution [16]	1. High cost 2. Complex catalysis [23]
(iv)	Ion exchange	1. Possible to regenerate resin 2. Zero hardness can be achieved 3. Rapid separation process 4. Small area requirement [57]	1. Pre-treatment is required in most of the effluents 2. Ionic competition 3. Fouling of matrix [60]

(continued)

Table 1 (continued)

Sl. No.	Wastewater control techniques	Advantages	Disadvantages
3	*Biological methods*		
(i)	Aerobic treatment	1. Simplicity of activity 2. Limits creation of odor 3. Decreases pathogens and fats 4. A more prominent number of microbes types can be utilized for Processing [75]	1. Cost expensive 2. Maintenance problem [22]
(ii)	Anaerobic treatment	1. Produces renewable energy 2. Less environmental pollution [15]	1. High capital cost 2. Odor nuisance [27]
(iii)	Phytoremediation	1. Low capital requirement 2. Low energy requirement 3. Environmental friendliness [1]	1. Limited to shallow contaminant 2. Phyto-toxicity of contaminants 3. Slower than conventional methods [26]
(iv)	Bioremediation	1. Natural process 2. Onsite treatment 3. Cost-effective process 4. Complete destruction [41]	1. Slow process 2. Heavy metals are not expelled 3. Bioremediation site must have soil with high penetrability 4. Considerable gaps exist in the comprehension of microbial Environment [41]

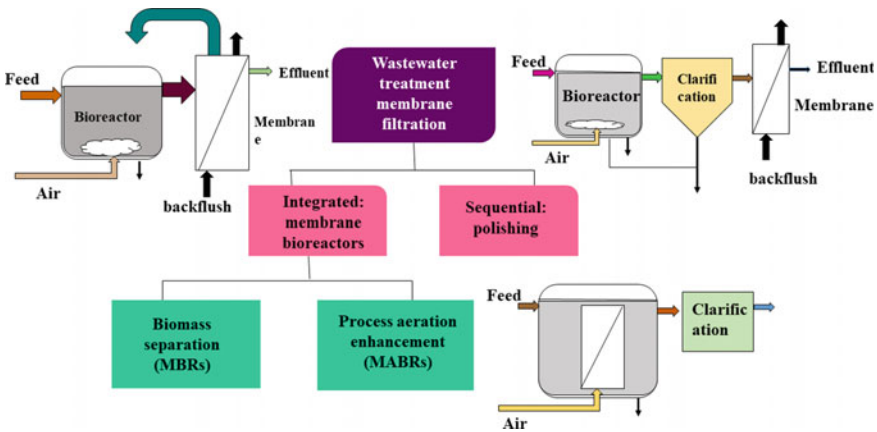

Fig. 2 Membrane filtration in wastewater treatment

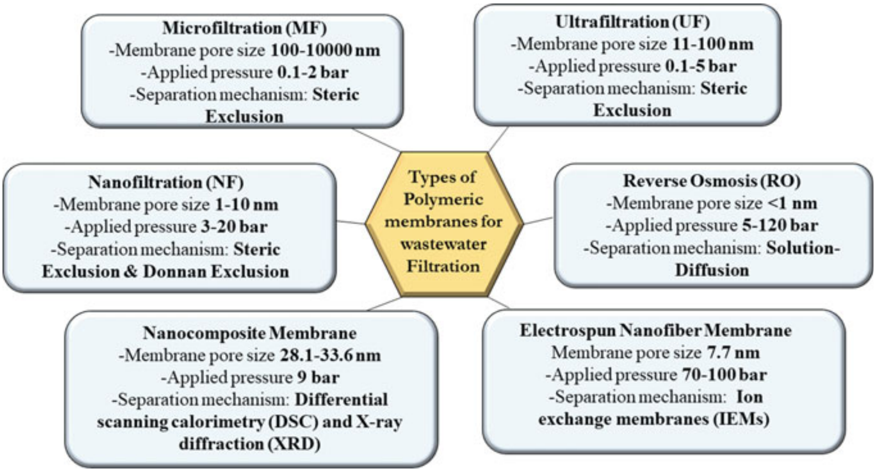

Fig. 3 Types of polymeric membranes for wastewater treatment

Membranes are classed as organic or inorganic based on their material composition. Synthetic organic polymers are used to create organic membranes. Synthetic organic polymers are almost solely used to make membranes for pressure-driven separation processes (microfiltration, ultrafiltration, nanofiltration, and reverse osmosis) [74]. Polyethylene (PE), polytetrafluorethylene (PTFE), polypropylene, and cellulose acetate are examples of these materials. Ceramics, metals, zeolites, and silica are used to create inorganic membranes. Aside from that, adsorption is the most widely used method for removing pollutants from water due to its low cost, wide range of adsorbents, and convenience of application. Adsorbents such as magnetic nanoparticles, activated carbon, nanotubes, and polymer nanocomposites have been used to remove a variety of contaminants, including heavy metals, which are exceedingly dangerous even at low concentrations [38]. The adsorption mechanism in the membrane separation process is based on the hydrophobic interactions between the membrane and the solute (analyte). Increased rejection occurs as the membrane's pore size diminishes as a result of these interactions. How well materials travel through the membrane is determined by the size of the pore and the molecules. As a result, a variety of membrane processes with various separation methods have been created. Organic membranes are among them [84] (Fig. 3).

5.1 Membrane Processes

5.1.1 Microfiltration

Microfiltration (MF) is a physical filtration technique that separates microorganisms and suspended particles from process liquids by passing a polluted fluid through a particular pore-sized membrane [102]. MF is a pressure-driven separation method that can be used to concentrate, purify, or separate macromolecules, colloids, and suspended particles from a solution [4]. Microfiltration is accomplished using membranes with pore sizes ranging from 0.1 to 10 µm. All microorganisms are removed via microfiltration membranes [18]. Even though viruses are smaller than the holes of a microfiltration membrane, the method only collects a percentage of the viral contamination. This is due to the fact that viruses can bind to bacterial biofilms. Microfiltration can be utilised in a variety of water treatment processes when particles larger than 0.1 mm in diameter need to be removed from a liquid [21].

5.1.2 Ultrafiltration

The method of water purification known as ultrafiltration (UF) involves pushing water through a semi-permeable membrane [98] Water and low-molecular-weight solutes pass through to the permeate side of the membrane, while suspended particles and high-molecular-weight solutes remain on the retentate side [13].

UF can eliminate most organic compounds and viruses, as well as a range of salts. It has gained popularity since it produces consistent water quality regardless of the source water, has a small physical footprint, removes 90–100 percent of pathogens, and requires no chemicals except for cleaning membranes [66].

The structure of Ultrafiltration membrane can be symmetric or asymmetric. A symmetric membrane's thickness (porous or nonporous) might range from 10 to 200 µm. The entire membrane thickness determines the resistance to mass transfer. When the thickness of the membrane is reduced, the rate of penetration increases [128]. Ultrafiltration membranes have an asymmetric structure that consists of a dense top-layer or skin with a thickness of 0.1–0.5 µm, which is supported by a porous sub-layer with a thickness of 50 to 150 µm. Ultrafiltration membranes have pore sizes ranging from 0.1 to 0.01 µm, although "molecular weight cut-off" (MWCO) is now one of the finest terms to characterize them [50]. These membranes combine a dense membrane's high selectivity with a thin membrane's high penetration rate. Ultrafiltration membranes must be cleaned on a regular basis to avoid fouling from solids, scaling, and microbiological agents including bacteria and algae. Contaminants that have been separated and condensed in the UF retentate must be discarded [67] (Fig. 4).

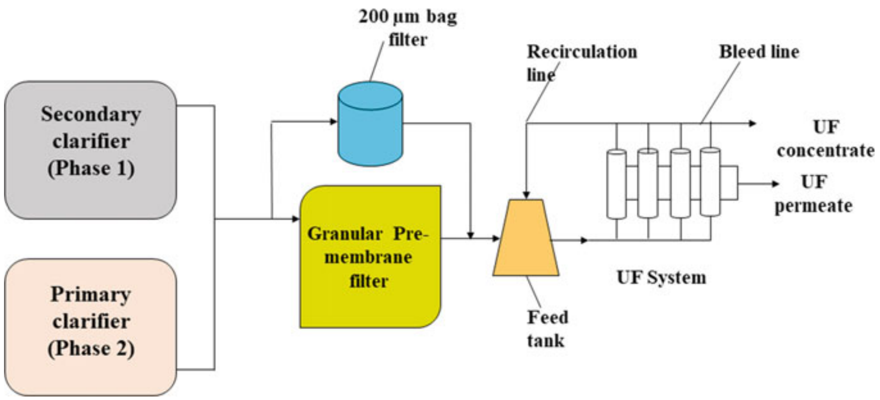

Fig. 4 Wastewater treatment by ultrafiltration technique

Application

- Wastewater and industrial process water treatment and recycling
- Removal of particulates and macromolecules
- In existing water treatment plants, augmenting or replacing secondary and tertiary filtering stages.
- Capable of exceeding regulatory standards of water quality, achieving 90–100% pathogen removal.

5.1.3 Nanofiltration

In terms of its ability to reject molecular or ionic species, nanofiltration is a pressure-driven membrane technique that falls in between ultrafiltration and reverse osmosis [121]. The nanofiltration (NF) membrane technique is a popular method for removing organic matter, colour, odor, taste, residual disinfectant levels, and trace herbicides from vast bodies of water. The properties of NF, which include a 1–5 nm pore size and a 7–30 operating pressure, are utilized to separate low molecular weight solutes such as lactose, glucose, and salt, as well as hardness, dye, and heavy metals [110]. Colloids, organic composites with reduced molecular mass, and divalent salts are all filtered out by an NF membrane. In comparison to RO, higher flux can be achieved with NF, which operates at low pressures of 8–30 bar, resulting in lower process operating costs. The two operating processes that control transport through the NF membrane are the sieving mechanism and the Donnan effect. NF can replace reverse osmosis (RO) in a variety of applications due to its low operating pressure and increased permeate flux (Fig. 5).

Application: In industry, pharmaceuticals, water purification, wastewater treatment, biotechnology, and brackish water desalination, nanofiltration is becoming more widespread. In industry, the NF process is used to separate colours in the textile sector, recover metal, and treat effluent from olive mills [116]. In comparison

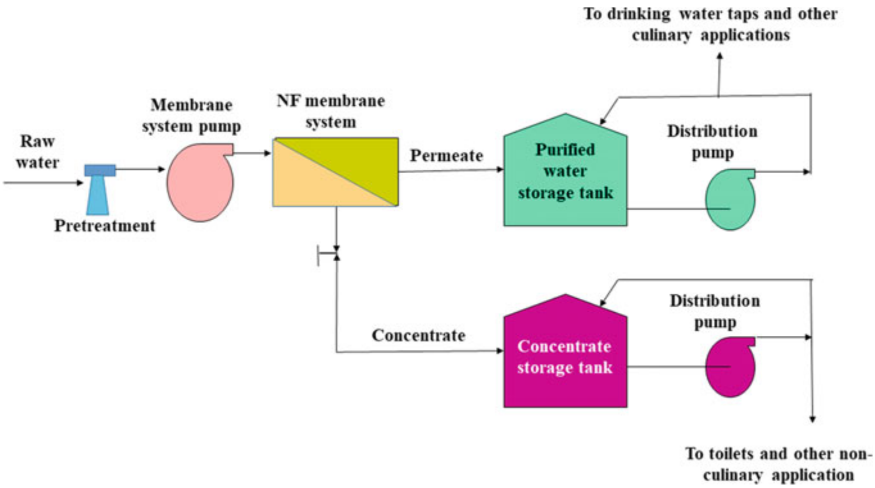

Fig. 5 Wastewater treatment by nanofiltration technique

to a conventional physicochemical approach, NF and RO integration effectively eliminated soluble monovalent and divalent ions from OME (olive mill effluent). NF was also employed in the treatment of coke wastewater, pulp and paper, oily wastewater treatment in the oil and petroleum industries, and the elimination of acid sulphate from mine water [83]. There were also many applications on domestic sector, e.g. treatment of municipal wastewater, Leachate, car wash wastewater, and restaurant effluent. When compared to aerobic and anaerobic procedures, chemical coagulation and electrocoagulation, and electroflotation, NF-90 effectively reduces BOD 5 and increases conductivity by over 80%.

5.1.4 Reverse Osmosis

For wastewater reclamation plants, reverse osmosis (RO) membranes provide a cost-effective water purifying alternative. Total dissolved solids, heavy metals, organic pollutants, viruses, bacteria, and other dissolved contaminants have all been demonstrated to be greatly reduced by RO membranes [114]. It's a pressure-driven method for removing dissolved solids and tiny particles, only water molecules can pass through by RO [70]. The pressure delivered to the RO must be high enough for the water to overcome the osmotic pressure. The pore structure of RO membranes is significantly tighter than UF i.e., smaller than 0.1 nm and they convert hard water to soft water, and they are practically capable of eliminating all particles, bacteria and organics, it requires less maintenance [111].

Application:

- Treatment and recycle of wastewater generated from metal finishing and plating operations.
- Printed circuit board and semiconductor manufacturing (treatment and recycle of rinse waters used in electroplating processes).
- Automotive manufacturing (treatment and recycle of water used for cleaning and painting).
- Food and beverage (concentration of wastewater for reuse and reduction of BOD prior to discharge).
- Groundwater and landfill leachate (removal of salts and heavy metals prior to discharge).

5.1.5 Nanocomposite Membranes

Nanocomposite membranes for water treatment are a promising modified version of traditional polymeric membranes with three primary characteristics: enhanced permeation, improved rejection, and reduced fouling [62]. Nanoparticle materials (the filler) are introduced into a macroscopic sample material (the matrix) to create nanocomposite membranes. Before membrane casting, nanoparticles can be deposited on the membrane surface or disseminated in the polymer solution [71]. Polymer-nanocomposite membranes, also known as mixed matrix membranes (MMMs), are created by incorporating secondary components known as fillers into the main polymeric matrix. Polymer-based nanocomposite membranes have gotten a lot of interest recently among diverse nanocomposites [105]. Phase inversion (PI), interfacial polymerization (IP), physical coating, electrospinning and cross-linking, self-assembly, layer-by-layer assembly, and chemical grafting are some of the processes used to disperse nanoparticles (NPs), nanotubes, nanofibers, or nanosheets into the polymer matrix. The incorporation of engineered nanoparticles including metal oxides (Al_2O_3, TiO_2, SiO_2, ZnO, MgO, Fe_2O_3, and zeolite), metals (Cu, Ag), carbon-based materials (graphene, carbon nanotube (CNT), carbon nanofibers (CNFs)), and nanofiber polymers (polyurethane, polylactic acid, polyethylene oxide) in polymer matrices imparts tunable physicochemical properties and unique functionalities to the membranes [63]. Nanocomposite membranes have developed as viable water purification technology, giving improved hydrophilicity, thermal and mechanical stability, permeability, targeted degradation, solute rejection, and magnetic, antibacterial, and anti-fouling capabilities over traditional polymeric membranes. Polymeric membranes are still a popular choice because of their low relative cost, wide range of pore sizes, design flexibility, and scalability [44].

Different types of Nanocomposites and their applications

- **Metal Nanocomposite**: Polymer-supported nanosilver exhibits antibacterial capabilities of polyurethane, and cellulose acetate impregnated nanosilver-fiber composites have good Gram-positive and negative bacteria inhibitory activity.

Polyurethane foam dispersion nanoparticles have proven to be efficient antibacterial filters [34]. Nanosilver was also employed to create cost-effective microfilters for managing drinking water, which is very important in unreachable regions.

- **Metal oxide Nanocomposite**: Metal oxide nanocomposite (MONC) are frequently employed as adsorbents, photocatalysts, and devices to combat pollution issues. For the elimination of various organic and inorganic contaminants, MONC is combined with graphene, silica, other oxides, carbon nanotube (CNT), and polymers [127].
- **Carbon Nanocomposite**: The cationic dyes were removed from aqueous solutions using a magnetic multi-wall carbon nanotube (MMWCNT) nanocomposite as an adsorbent. The MMWCNT nanocomposite was made up of multi-wall CNTs that were still alive and iron oxide nanoparticles (IONPs) [6]. The use of MMWCNT nanocomposite adsorbent to remove Methylene Blue (MB), neutral red, and brilliant cresyl blue was purposeful.
- **Polymer Nanocomposite**: PNCs (polymer nanocomposites) are a superior type of tool in which nanoparticles are dispersed in a polymer matrix, resulting in novel materials with distinct physical and chemical properties. Polymers are unique nanomaterial supports because they often have tunable porosity topologies, high mechanical qualities, and chemically attached functional groups [48]. PNCs are looking for materials that work well in water and wastewater treatment. Contaminant adsorption by PNC is one of several treatment strategies that is considered an advanced instrument in water treatment technology. PNCs can be made by fusing nanoparticles to polymer structures or by attaching polymers to nanoparticles [82].

5.1.6 Electrospun Nanofiber Membrane

An electrospun nanofibrous membrane (ENM) is a membrane made by electrospinning that possesses appealing properties [42]. Electrospun nanofibrous membranes (ENMs) are a cutting-edge membrane technology that outperforms traditional membranes in terms of flux and rejection rate. Electrospinning is a new and unique fabrication approach that produces nanofibrous nonwovens using a simple nanofiber production technology [39]. Electrospinning has opened up new and exciting possibilities in a variety of fields, including the environment, catalysts, energy, and health. Electrospun nanofibers' unique properties make them a good fit for a variety of additional applications, such as functionalized composite constructions, electrode materials for batteries and energy devices like solar cells, protective apparel, food and agriculture, and tissue engineering [51]. After considering this, it's worth noting that the applications for electrospun nanofibers are virtually unlimited. After that, the use of electrospun nanofibers as a scaffold for TFC (thin-film composite) membranes in pressure- and osmotic-membrane processes is discussed. The use of electrospun nanofibrous membranes in the thermally-driven MD (membrane distillation) process for water treatment, as well as performance improvement schemes [12] (Fig. 6; Tables 2 and 3).

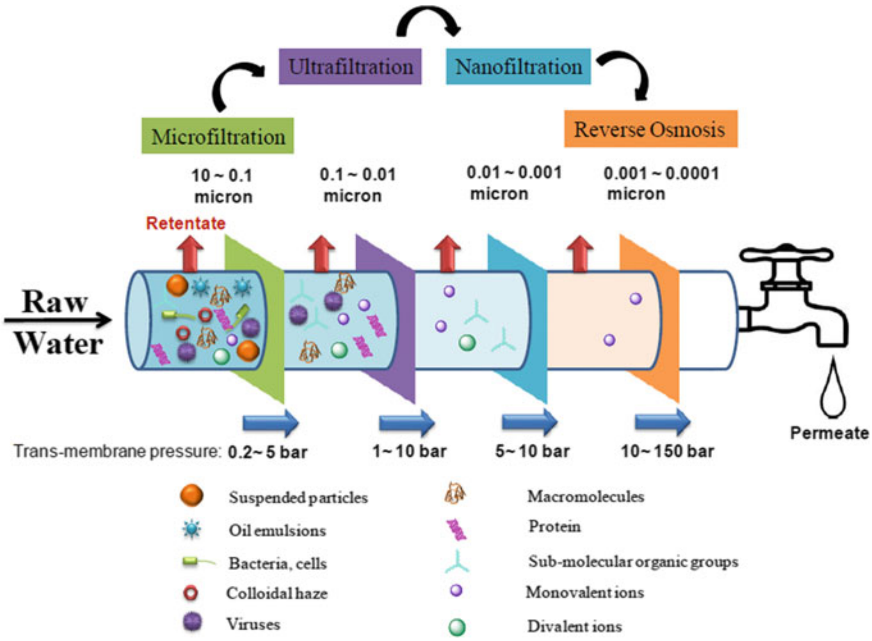

Fig. 6 Schematics of membrane water treatment system (Adapted from [73])

6 Conclusion

With the rapid increase in population, increased industrialization, urbanization, and vast agriculture techniques, the demand for clean and safe water is increasing over the world. Water is currently being decontaminated and purified using a variety of procedures. Manufacturing plants, refineries, and industrial effluent wastewater is typically treated at the on location sites. Biological waste treatment plants separate waste matter by using biological materials and bacteria. On the other hand, physical waste treatment plants treat wastewater using synthetic responses in the same way that physical processes do. Physical wastewater treatment plants are commonly used to treat wastewater from factories, industries, and manufacturing organisations. While biological treatment systems are ideal for treating wastewater from households and business premises. Mechanical methods are used as a preliminary stage of wastewater treatment. The various types of membrane technology will play an increasingly essential role in water and wastewater control in industry. Polymeric membranes are employed on an industrial scale for water desalination and wastewater treatment due to their ease of manufacture and fascinating separation performance. An improvement of the NF and RO performance in the removal of heavy metals could be achieved by incorporating nanomaterials. Water flux and heavy metal rejection can both be improved with nanocomposite membranes. Electrospinning is a versatile

Table 2 Some features of pressure-driven membranes (adapted [36])

Membrane process	Particle size (nm)	*MWCO (kilo Dalton)	Retained diameters (µm)	Pressure required (bar)	Membrane Type	Average permeability (L/m^2 h bar)	Solutes retained
Microfiltration	100–10,000	100–500	10^{-1}–10	1–3	Porous, asymmetric or symmetric	500	Suspended particles (bacteria, fat, oil, colloids, organics, microparticles)
Ultrafiltration	1–100	20–150	10^{-3}–1	2–5	Micro porous, asymmetric	150	Macro and micromolecules (proteins, pigments, oils, sugar, organics, microplastics)
Nanofiltration	1–10	2–20	10^{-3}–10^{-2}	5–15	Tight porous, asymmetric, thin film composite	10–20	Divalent cations and anions, lactose, sucrose
Reverse osmosis	<1	0.2–2	10^{-4}–10^{-3}	15–75	Semi porous, asymmetric, thin film composite	5–10	Monovalent ions and all contaminants

* MWCO = Molecular weight cutoff

Table 3 Advantages and disadvantages of membrane-based technologies

Sl. No.	Membrane based processes	Advantages	Disadvantages
1	Microfiltration (MF)	• It is capable of removing impurities from water without the use of harsh or costly chemicals • Its larger pore size makes it excellent for a 'first pass' filtration [4]	• Its enormous pore size makes it impossible to distinguish tiny materials from water [18]
2	Ultrafiltration (UF)	• It removes all particulates as well as any microbes that may have contaminated the water • There are no chemicals employed in the process, no pollutants are emitted into the environment [13] • It requires less operating pressure and uses less energy than nanofiltration or reverse osmosis	• Soluble materials will not be filtered • The odor of the water still remains the same • Neither humans nor animals should drink the water produced during this method. This is because the method does not separate solubles, which could be damaging to our health [107]
3	Nanofiltration (NF)	• The hard water is cleansed of viruses, organic components, and valence ions. It is an efficient method for softening hard water • Salt content and dissolved matter content (TDS) in brackish water are reduced; heavy metals, nitrates, and sulphates are reduced [55]	• Soluble elements cannot be separated from the water • Higher energy consumption than UF and MF (0.3–1 kWh/m^3) • Some extremely polluted waterways require pre-treatment [90] • Nanofiltration membranes cost slightly more than reverse osmosis membranes [26]

(continued)

Table 3 (continued)

Sl. No.	Membrane based processes	Advantages	Disadvantages
4	Reverse osmosis (RO)	• Pollutants such as lead, pesticides, fluoride, pharmaceuticals, arsenic, and other contaminants can be removed from water using reverse osmosis devices, making the human body sick. Lead poisoning can result in brain damage and anaemia [17] • A semi-permeable membrane is used in the RO water purification process to extract pollutants from water, leaving it clean and pure for drinking. Its high-pressure technique contributes to the purification process as a positive feature	• While a RO water purifier removes dissolved contaminants, it also removes natural minerals like iron, magnesium, calcium, and sodium, which are necessary for human health and can lead to a mineral shortage. Water becomes de-mineralized as natural minerals are eliminated, affecting the taste and making it bland [106] • RO water purifier does not kill waterborne disease-causing bacteria and viruses. There high probability that microorganisms can pass through RO membrane [111]
5	Nanocomposite membranes	• The advantages of this separation method are high removal capacity, operational flexibility, and cost-effectiveness [82] • They're lighter than traditional composites because they can achieve high levels of stiffness and strength with significantly less high-density material [120]	• Due to their intrinsic hydrophobicity, they are prone to fouling • They also have a low chlorine resistance [77]
6	Electrospun nanofiber membrane	• Nanofiber membranes with a large surface area have several advantages over cast film [113] • Fibers with diameters size of nanometer to few microns; relatively inexpensive technique; high aspect ratio; enhanced mechanical properties	• They undergo several difficulties in making a large volume of scaffold [51]

technology that makes producing nanofibers facile. Nanofiber membranes (ENMs) have gotten a lot of interest because of their large specific surface area and excellent pore interconnectivity, and they appear to be very promising for wastewater treatment. In any case, by enhancing the pore size, porosity, and mechanical strength of ENMs, various problems should be considered and overcome. As a result, the application of membrane technology for wastewater management appears to be highly promising and could have a great future, but a serious and focused effort by the scientific community and government agencies is required.

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