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Review

Membrane Technologies at the Frontier: A Review of Advanced Solutions for Microplastics and Emerging Contaminants in Wastewater

Yousef Tayeh [1], Tharaa M. Al-Zghoul [2], Mohammed J. K. Bashir [3], Motasem Y. D. Alazaiza [4,*] and Salahaldin Abuabdou [5]

[1] Civil Engineering Department, Faculty of Engineering, Islamic University of Gaza, Gaza Strip P.O. Box 108, Palestine; yousef.tayeh@hotmail.com
[2] Department of Civil Engineering, Faculty of Engineering, Tafila Technical University, Tafila 66110, Jordan; tharaaalzghoul@gmail.com
[3] School of Engineering & Technology, Central Queensland University, 120 Spencer St., Melbourne, VIC 3000, Australia; m.bashir@cqu.edu.au
[4] Department of Civil and Construction Engineering, College of Engineering, A'Sharqiyah University, Ibra 400, Oman
[5] Bioengineering School, Universie Libre de Bruxelles, 1050 Bruxelles, Belgium; salahaldin.abuabdou@ulb.be
* Correspondence: my.azaiza@gmail.com

Abstract

Microplastics (MPs) and emerging contaminants (ECs) are increasingly prevalent in environments due to their persistence, toxicity, and resilience against standard wastewater treatment methods. This review presents a comprehensive analysis of contemporary and advanced membrane-based techniques, highlighting their removal efficacy, recovery potential, and fundamental mechanisms such as size exclusion, adsorption, electrostatic interactions, and biodegradation. This review emphasizes the physicochemical properties of MPs, including particle size, shape, polymer type, and hydrophobicity, and their significant impact on membrane performance and fouling behavior. Key findings reveal that membrane fouling is a primary constraint affecting operational efficiency. This study identifies the types of fouling standard, total, intermediate, and cake formation that contribute to flux deterioration and necessitate increased energy expenditures during prolonged operation. Additionally, this research highlights the detrimental effects of mechanical abrasion and scaling on membrane integrity and lifespan. Future prospects for membrane technology are explored, positioning it as a leading solution for sustainable wastewater treatment. Essential directives include the development of intelligent membranes responsive to environmental stimuli, AI-driven monitoring systems, and modular and decentralized treatment units. Moreover, the implementation of circular economy principles is discussed, emphasizing concurrent treatment and resource recovery, such as nutrients, biogas, and clean water. The regulatory and legislative implications of membrane-based treatment are also addressed, underscoring the importance of standardization, performance evaluation, and sustainability. Ultimately, this analysis positions membrane technologies as pivotal instruments in the advancement of intelligent, energy-efficient, and regenerative wastewater management systems.

Keywords: microplastics; pollution; wastewater; emerging contaminant; membrane bioreactor

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Academic Editors: Jonathan Suazo-Hernández, Lizethly Cáceres Jensen and Pamela Sepúlveda Ortiz

Received: 21 January 2026
Revised: 13 February 2026
Accepted: 17 February 2026
Published: 19 February 2026

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1. Introduction

Water is vital for public health, ecosystems, and the growth of important industries like manufacturing and agriculture. However, rapid urbanization, industrialization, and population growth have greatly increased the volume and complexity of wastewater, turning it into a major source of pollution [1,2]. Wastewater contains a wide range of pollutants such as heavy metals, synthetic colors, medicines, pathogenic microbes, and emerging contaminants (ECs) like microplastics (MPs) [3]. If inadequately treated, these contaminants can pose serious risks to aquatic ecosystems and to human health.

In the context of growing freshwater shortage and climate change, effective wastewater treatment has emerged as a crucial element of sustainable water management. The widespread presence of MPs in treated effluents and aquatic systems is one of the most pressing environmental issues that has received attention recently. They are becoming a global problem due to their tenacity, prevalence, and intricate relationships with other contaminants [4–6]. The pervasive identification of MPs in surface water, wastewater, landfill leachate, and drinking water has generated considerable apprehension among researchers and the public. This widespread pollution highlights the urgent necessity for thorough evaluations of the prevalence, behavior, and environmental consequences of MPs as a new category of contaminants [7].

There are historical roots to the extent of plastic contamination. An estimated 367 million metric tons (MT) of plastic were manufactured worldwide in 2020 as a result of the exponential growth in mass production of plastics since the 1950s [8,9]. MPs are small particles of polymeric materials with sizes of up to 5 mm [4,10,11] that can be found in almost every area of the environment, including the human food chain, soil, sediment, groundwater, surface water, and air [12]. They have been detected in landfill leachate [13,14], surface water [7,15,16], drinking water and groundwater [17–19], tap waters [20], bottled waters [21], air [22], and food [23].

In addition to their physical harm, MPs are dangerous because they transport dangerous materials. Numerous chemical additives, including plasticizers, flame retardants, and colors, are added during the plastic production process. Heavy metals, polybrominated diphenyl ethers (PBDEs), polychlorinated biphenyls (PCBs), polyfluoroalkyl substances (PFAS), medications, and personal care items are among the pollutants that MPs can adsorb and transfer once they are released into the environment [24]. They are more likely to bioaccumulate and biomagnify in food webs due to their small size and surface characteristics, which enable them to pass through biological barriers.

Furthermore, the physicochemical properties of MPs' dimensions, morphology, density, and polymer composition exhibit significant variability and affect their environmental interactions. MPs typically manifest as fibers, pieces, spheres, and films, exhibiting colors that include black, white, red, green, blue, and translucent [25]. These characteristics influence their settling velocities, transport routes, and likelihood of interaction with biota. Research indicates that MPs are intricate particles whose characteristics change with environmental exposure, influencing their degradation rates, sorption capacity, and ecological outcomes [26]. Recent research has revealed that even routine use of plastic containers, such as filling plastic bottles with water, can result in the release of nanoscale plastic particles into the liquid. Due to their small size, these particles can penetrate biological barriers, enter the human body, and accumulate in tissues, including the brain, raising serious toxicological and neurological concerns [27,28].

Because of their harmful impact on a variety of creatures, MPs are a major threat to aquatic ecosystems. Their detrimental effects on fish, crustaceans, algae, mussels, and rotifers have been verified by studies [29,30]. Numerous negative effects of MPs on marine organisms have been demonstrated in laboratory experiments. These effects include the fol-

lowing: decreased filtration rates, DNA damage, and neurotoxicity in bivalves [31], altered swimming behavior [32], increased mortality [33], and developmental abnormalities [34]. These biological responses threaten the integrity of aquatic ecosystems and the sustainability of food resources. Even more concerning, MPs have been found in human heart tissue [35], lungs and blood [36,37]. To mitigate the release of MPs into the environment, wastewater treatment plants (WWTPs) play a pivotal role.

Recent advancements in membrane-based technologies offer promising solutions for the effective removal of MPs and ECs. Pressure-driven membrane systems such as reverse osmosis (RO), ultrafiltration (UF), nanofiltration (NF), and microfiltration (MF) utilize mechanisms, including size exclusion, electrostatic repulsion, and adsorption, to achieve high removal efficiencies [38,39]. These technologies have demonstrated significant success in both pilot-scale and full-scale applications and are well-suited for integration into the tertiary treatment stages of WWTPs.

Membrane bioreactors (MBRs), which combine membrane filtration with biological degradation processes, have shown remarkable efficacy in the removal of persistent pollutants, including MPs, with reported removal rates reaching up to 99.9% [40,41]. By synergistically integrating bioremediation with membrane separation, MBRs enhance effluent quality, reduce the need for chemical additives, and minimize the overall treatment footprint [42–44]. However, challenges such as membrane fouling, the potential for secondary MPs release from infrastructure, and the economic viability of large-scale implementation continue to impede widespread adoption [45,46].

Therefore, beyond environmental considerations, micro- and nanoplastics represent a growing medical and public health issue. This study focuses on the characterization and implications of plastic particle fragmentation, with particular emphasis on their potential biological interactions and health hazards. This review also aims to provide a comprehensive analysis of both conventional (MF, UF, NF, RO) and advanced membrane systems (nanocomposites, membranes (MBRs), hybrids) specifically for the removal of MPs from wastewater alongside resource recovery. Given the increasing prevalence of MPs and their significant environmental and health risks, this study addresses the urgent need for effective treatment solutions. By systematically evaluating recent advancements in membrane technologies, this review highlights their effectiveness, potential operational challenges, and opportunities for integration into existing wastewater treatment systems. The contributions of this study are multifaceted. First, it synthesizes current research on membrane performance regarding MP removal, outlining the mechanisms that enhance their efficiency and reliability. Second, it identifies critical knowledge gaps and proposes innovative strategies to address challenges such as membrane fouling and the risk of secondary MP release. Ultimately, this review aims to guide future research and promote the development of sustainable wastewater treatment solutions that effectively mitigate the impacts of MP.

2. Characteristics of MPs in Wastewater

2.1. Sources and Pathways of MPs

The adverse effects of plastic pollution were initially recognized through observations of visible debris, such as floating bottles and plastic bags, which frequently caused entanglement and injury to wildlife [47].

MPs infiltrate wastewater systems via several direct and indirect routes, creating a multifaceted pollution landscape.

Point sources, such as WWTPs, industrial effluents, and healthcare facilities, play a significant role in contaminating aquatic environments [48]. Conversely, non-point sources,

including urban runoff, atmospheric deposition, and agricultural drainage, introduce these pollutants into water bodies in a more diffuse manner [48].

Agricultural runoff can carry pesticides and fertilizers, while plastic pollution primarily arises from consumer products and improper waste management. Understanding these pathways is crucial for developing effective management strategies and implementing appropriate control measures. Recent studies indicate that urban environments, characterized by high population density and extensive infrastructure, exacerbate the contamination of water systems with both MPs and ECs. This necessitates a multi-faceted approach to monitoring and remediation [48].

2.2. Types, Sizes, and Shapes of MPs

MPs can be classified based on their size and shape, significantly influencing their environmental behavior and toxicity. In response, so-called rapidly degradable plastics were developed, often through the incorporation of additives such as starch. However, subsequent studies demonstrated that these materials may fragment into micro- and nanoplastics, increasing their dispersion in aquatic environments and posing additional risks [49].

Generally, MPs are defined as plastic particles ranging from 1 μm to 5 mm in length [50], while "nanoplastics" refer to particles smaller than 1 μm, and various studies have set their upper size limits of 1000 nm or 100 nm [50]. These size categories are critical for understanding ecological impacts, as smaller particles may be more readily ingested by aquatic organisms. The United Nations categorizes plastic waste into several size groups: megaplastics (>1 m), macroplastics (1–25 mm), mesoplastics (5–25 mm), MPs (5 mm–1 μm), and NPs (<0.1 μm) [51,52], as shown in Figure 1.

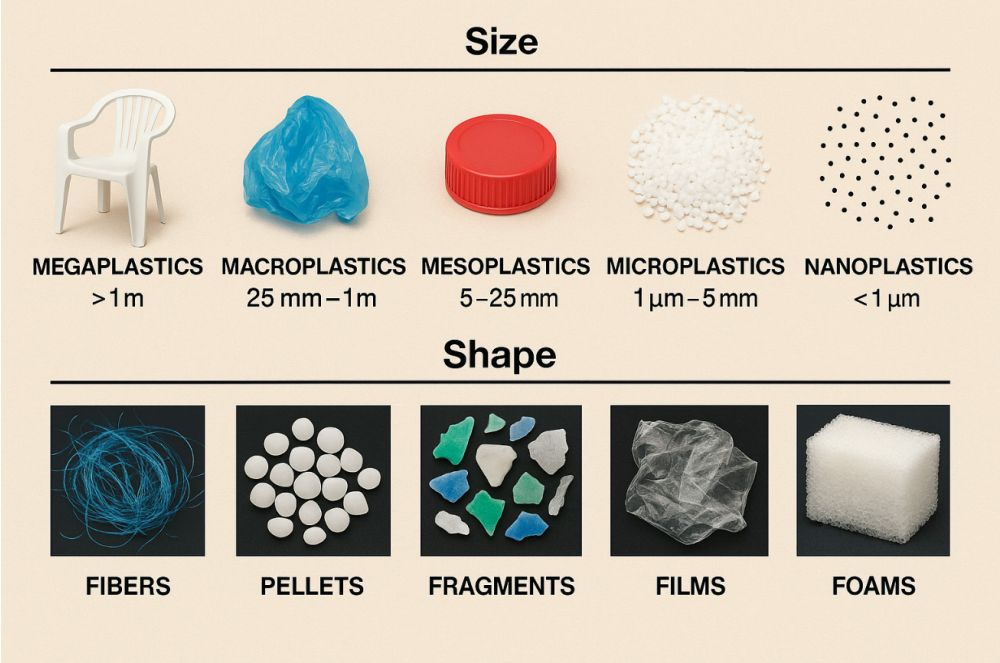


Figure 1. Visual Classification of Plastic Pollution: Dimensional Ranges and Typical Morphologies of Plastic Particles in the Environment [53].

In terms of shape, MPs can be further divided into fibers, foam, film, pellets, and fragments [54], as shown in Figure 2.

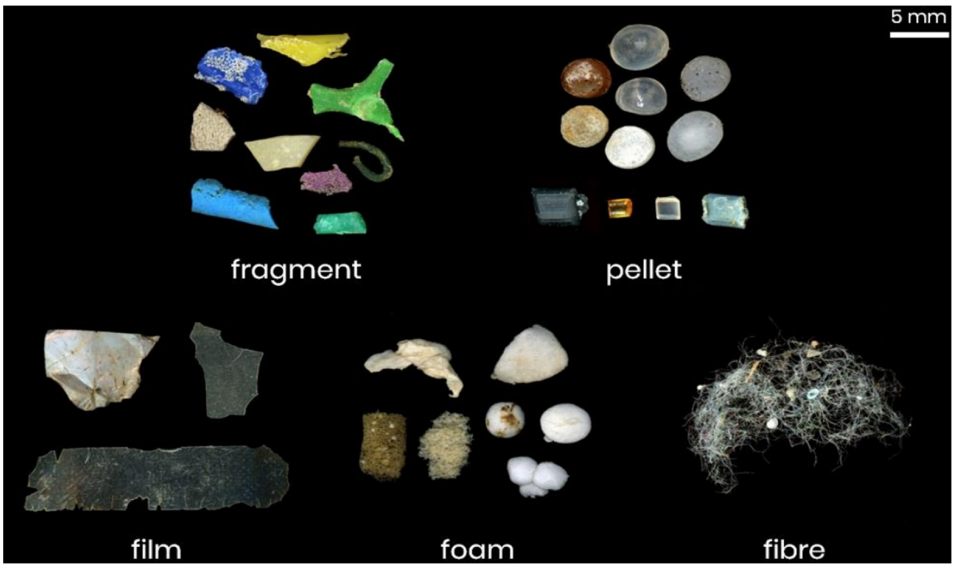


Figure 2. Various shapes of MPs [55].

Fibers are elongated particles, often resulting from the degradation of textiles, while pellets are nearly spherical and commonly used in manufacturing. Particles that are elongated and have lengths far greater than their width and thickness are called fibers [53]. Foam refers to porous, lightweight particles commonly found in products such as packaging materials and insulation. These particles are typically irregular in shape and can vary greatly in size. Foam microplastics can break down into smaller pieces, increasing their prevalence in water systems and their potential for ingestion by marine life [54]. Film consists of thin, flat sheets of plastic that can come from various sources, including plastic bags and food packaging. Films tend to have a large surface area relative to their volume, which can enhance their interaction with pollutants in the environment. Their flat nature allows them to be easily transported by wind and water currents [54]. Pellets have the same scale for length, width, and thickness, making them nearly spheroidal. Fragments are flat, uneven particles that are similar in size in length and width but have a somewhat lesser thickness [53].

ECs encompass a broad spectrum of substances, including pharmaceuticals, personal care products, pesticides, industrial chemicals, and heavy metals. These ECs are characterized by their diverse chemical properties, which determine their solubility, volatility, and persistence in the environment [56]. For instance, many pharmaceuticals are hydrophilic, allowing them to easily dissolve in water [57], while compounds like per- and polyfluoroalkyl substances (PFAS) are hydrophobic and highly resistant to degradation [58]. This diversity necessitates a comprehensive approach to understanding their impact and management.

2.3. Transport and Distribution in the Environment

The transport and distribution of MPs in the environment are crucial for understanding their ecological impacts [59]. These processes are influenced by various physical and chemical properties of both MPs, which significantly affect their behavior and distribution in aquatic systems. A Danish study using non-target screening found that common reusable plastic water bottles released over 400 distinct chemical compounds into tap water after 24 h, and that this number increased to more than 3500 compounds after dishwasher washing, including substances derived from the plastic and from dishwasher detergent, many of which are of unknown or potentially harmful biological activity [60]. These findings underscore that everyday use and cleaning practices can significantly enhance human

exposure to leached compounds from plastic materials, adding to concerns about health risks beyond environmental pollution.

2.3.1. Behavior of MPs

Upon entering the environment, MPs are influenced by physical, chemical, and biological transport processes. Their dimensions, morphology, density, and buoyancy influence their dispersion in aquatic environments [61]. The density of MPs has a significant impact on their dispersal. Generally, MPs with densities lower than that of saltwater tend to float, allowing them to accumulate on the water's surface [62]. This floating behavior facilitates their transport across considerable distances by wind and ocean currents. Conversely, MPs with higher densities typically settle in benthic habitats, integrating into the sediment and potentially being ingested by bottom-dwelling organisms.

An important principle in froth flotation is the ability for a certain material to float, which is highly dependent on its density. In the case of plastic, the majority of their densities are higher than that of water, meaning that they would naturally sink. The densities of polyvinyl chloride (PVC), acrylonitrile butadiene styrene (ABS), polyethylene terephthalate (PET), polymethyl methacrylate (PMMA), and polystyrene (PS) are roughly 1.50, 1.20, 1.40, 1.20, and 1.05 g/cm^3, respectively [63]. While froth flotation is not solely dependent on particle density, it does favor particles with higher densities as it increases the probability of collision and adhesion to the bubbles [64]. Since PVC is the plastic with the highest density, it is most favorable for froth flotation.

Depositions on the seafloor, water column suspension, and surface drifting are examples of transport mechanisms. Non-buoyant MPs are found around coastal regions and deep-sea floors because they frequently build large amounts of biofilm or are composed of thick materials [65]. In aquatic conditions, MPs frequently experience biofilm formation due to microbial colonization by fungi, algae, and bacteria [66]. Due in major part to plastics' lower density than seawater, which allows them to stay afloat, the prevalence of plastic debris in surface water samples taken from the open ocean reached a worrisome 88% [67].

2.3.2. Distribution of Emerging Contaminants (ECs)

ECs encompass a wide range of substances, including pharmaceuticals, personal care products, pesticides, and industrial chemicals [68]. Understanding their distribution in aquatic environments is essential for assessing their ecological impact and potential risks to human health. Unlike MPs, which primarily rely on physical properties like density and buoyancy for transport, ECs exhibit a variety of transport mechanisms influenced by their chemical properties [59].

Many ECs are hydrophilic, meaning they readily dissolve in water [69]. This property promotes their widespread dispersal throughout aquatic systems [69]. For instance, pharmaceuticals often enter water bodies through wastewater discharges, agricultural runoff, and leachate from landfills, leading to their dilution and diffusion in surface waters [70]. This hydrophilic behavior can result in a more uniform distribution of ECs in the water column, as they tend to remain dissolved and can travel significant distances [70].

Conversely, hydrophobic ECs have a tendency to adhere to particulate matter, including sediments and MPs [69]. This interaction is crucial as it affects their bioavailability, or the extent to which they can be absorbed by organisms [69]. When hydrophobic contaminants bind to particles, they can become more concentrated in specific areas, such as sediment layers, thereby increasing the potential for bioaccumulation in benthic organisms. This accumulation can have cascading effects throughout the food web, as higher trophic levels may ingest contaminated prey [69].

The transport mechanisms of ECs occur through several pathways. As previously mentioned, they can dissolve in water, allowing them to be transported over long distances. Additionally, they can adsorb onto suspended particles, which enhances their mobility in aquatic environments. This adsorption process is influenced by various factors, including the nature of the particles, the chemical structure of the ECs, and environmental conditions such as temperature and pH [69].

The mobility of ECs raises significant concerns regarding their potential bioaccumulation in aquatic organisms. Bioaccumulation refers to the process by which organisms accumulate contaminants in their tissues at concentrations higher than those found in their environment. This phenomenon can lead to toxic effects on aquatic life, impacting growth, reproduction, and overall health. Furthermore, as these organisms are consumed by predators, the contaminants can biomagnify through the food chain, posing risks to larger animals, including humans.

2.4. Primary and Secondary MPs and ECs

MPs enter the environment through numerous sources, primarily driven by human activities. Significant contributors include land-based activities, wastewater effluents, and air deposition [51]. Road runoff, landfills, air transportation, textile shedding, tourism, maritime vessels, aquaculture, recreational activities, synthetic fertilizers, artificial turf, and plastic waste from shipping operations, including bottles and packaging, are some of the main causes [51,71,72].

Several researchers have begun to consider sub-scale plastics fragmentation, which depends on where they come from; as such, MPs are divided into primary and secondary categories, as shown in Figure 3 [11].

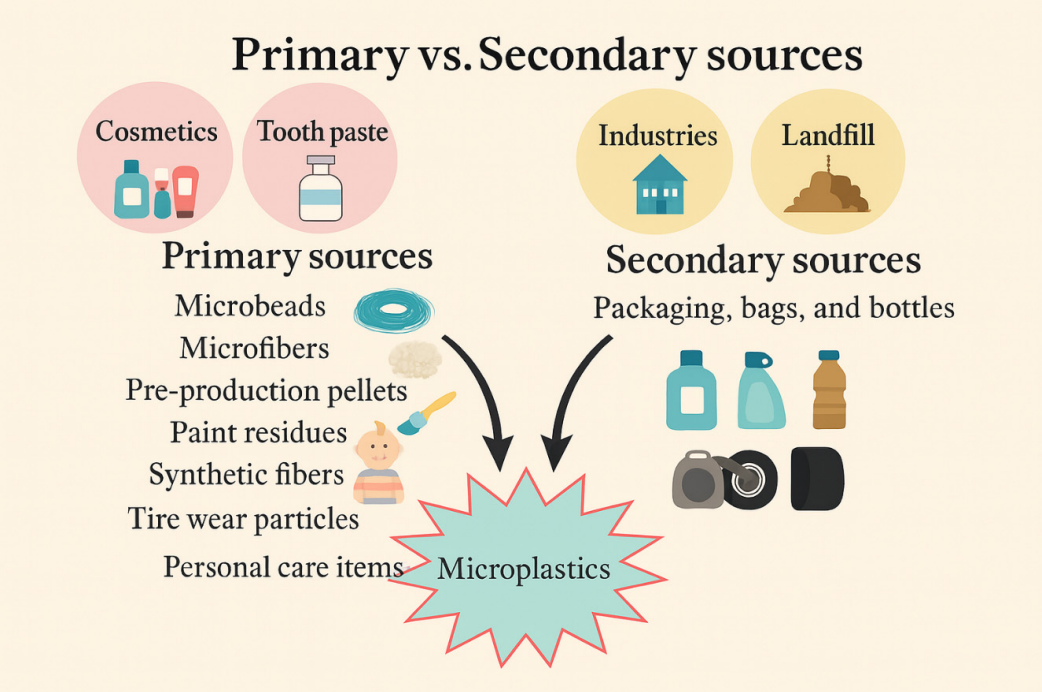


Figure 3. Types, sources, and the way of formation of primary and secondary MPs [11].

Primary MPs are manufactured as small particles or pieces, typically less than 5 mm in size, and are released directly into the environment. Polyethylene (PE), polypropylene (PP), and polystyrene (PS) are examples of primary MPs that come from a variety of sources [73]. Microbeads, microfibers, pre-production pellets, paint residues, synthetic fibers, tire wear particles, personal care items, cosmetics, and MPs from consumer goods are

common sources. Primary MPs are also caused by volatile particle pollutants from printing toners, including micro-polyester, nano-sized FeO_4, and SiO_2 [74–76]. Potential primary MP sources include pharmaceuticals, including drug transporters [61]. Furthermore, tiny pieces of plastic called microbeads (10–500 µm) are used as viscosity enhancers in toothpaste formulas and as exfoliants in personal care products like face and hand scrubs [77].

Secondary MPs originate from the degradation of larger plastic items, such as packaging, bags, and bottles. This fragmentation occurs due to weathering processes, including ultraviolet radiation, physical abrasion, hydrolysis, and microbiological activity [10,78]. Larger plastic items can take decades to break down, leading to the continuous generation of secondary MPs. During washing, synthetic textiles like polyester and nylon clothing emit large volumes of microfibers that build up in WWTPs and cause MPs pollution [79]. Research indicates that microfibers lost during laundry represent approximately 35% of the microplastics found in the ocean [80]. Table 1 summarizes the primary and secondary MPs, their sources, and characteristics.

Table 1. Summary of the primary and secondary MPs.

Type of MPs	Source	Characteristics	Refs.
Primary MPs	Microbeads, Pre-production Pellets	<5 mm in size, used in cosmetics and manufacturing.	[74]
	Synthetic Fibers	Released from textiles during washing.	[75]
	Volatile Pollutants	Includes micro-polyester and nano-sized particles.	[76]
Secondary MPs	Fragmentation of Larger Plastics	Result from weathering processes.	[78,79]
	Synthetic Textiles	Emit microfibers during washing.	[81]

Several factors influence the release of microfibers from synthetic textiles during washing. Textile properties, such as knit structure and polymer type, significantly affect fiber shedding. For instance, polyester fabrics tend to release more fibers than acrylic fabrics [81]. Fiber release is also affected by washing factors, such as temperature, mechanical agitation, water flow, and length; longer cycles and higher temperatures increase shedding [82,83]. Additionally, fabric softeners may decrease friction by coating fibers, hence decreasing shedding, whereas enzymatic or alkaline detergents can break down fibers, improving release [84].

ECs represent a wide range of substances, including pharmaceuticals, personal care products, pesticides, and industrial chemicals. Many ECs are hydrophilic, allowing them to dissolve easily in water and disperse throughout aquatic environments. This property enables certain pharmaceuticals to travel long distances in their dissolved form, posing risks to aquatic organisms [59,69,70].

Hydrophobic ECs can adhere to MPs, enhancing their bioavailability and potential for accumulation in aquatic species [85]. This interaction can lead to localized concentrations of toxicity, raising concerns about long-term impacts on ecosystems and food webs [85]. The bioaccumulation of ECs can disrupt endocrine systems, impair reproductive health, and result in developmental issues in marine organisms [85]. Table 2 summarizes the sources and characteristics of ECs.

Table 2. Summary of sources and characteristics of ECs.

Type of ECs	Source	Characteristics	Ref.
Pharmaceuticals	Wastewater discharges	Residual chemicals from medical applications.	[86]
Personal Care Products	Cosmetics and toiletries	Microbeads and synthetic materials.	[87]
Pesticides	Agricultural runoff	Chemicals utilized for pest management.	[88]
Industrial Chemicals	Manufacturing processes	Pollutants from various industrial activities.	[89]
Hydrophilic ECs	Soluble in water	Easily transported through aquatic environments.	[69]
Hydrophobic ECs	Adhere to particulate matter	Increased bioavailability and risk of bioaccumulation.	[90]

2.5. Physicochemical Properties of MPs and ECs

MPs and ECs exhibit various physicochemical properties that significantly influence their behavior and interactions in aquatic environments.

The most common MP polymer types identified in aquatic environments include polyethylene (PE) at 25%, polyethylene terephthalate (PET) at 16.5%, polyamide (PA) at 12%, polypropylene (PP) at 14%, polystyrene (PS) at 8.5%, polyvinyl alcohol (PVA) at 6%, and polyvinyl chloride (PVC) at 2% [91,92]. Figure 4 shows the global percentage distribution of these plastic polymers [91–93]. Among these, PVC, PS, and PET are classified as amorphous polymers, whereas PE and PP are semi-crystalline [94].

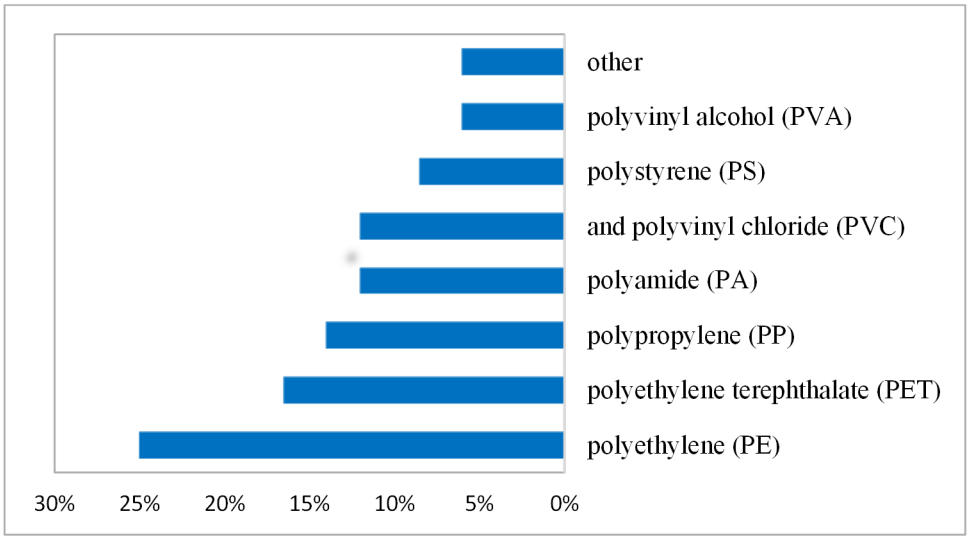


Figure 4. The global percentage distribution of plastic polymer.

The structural characteristics of these polymers influence not only their degradation rates but also their interactions with other pollutants, including ECs and heavy metals. Factors such as surface roughness, porosity, and the presence of functional groups determine their sorption potential and microbial colonization [95].

MPs exhibit a variety of physicochemical properties that influence their behavior in aquatic environments. These properties include polymer type, size, shape, and density [96,97]. The distribution of these polymer types varies across different aquatic compartments, as summarized in Table 3.

Table 3. Polymer type distributions in aquatic environments.

Study/Compartment	Major Polymers Identified	Approximate % (or Relative Abundance)	Ref.
Lentic ecosystems (lakes, freshwater)	PE, PP, PS	PE ~28% (95% CI 20–36) PP ~18% (95% CI 13–23) PS ~7% (95% CI 3–12)	[98]
Marine environment	PE, PP dominate surface; denser polymers at depth	Surface ocean: PE ~42%, PP ~25% Deep Sea: PE and PP ~2–3%	[99]
Rivers in Europe	PE, PP, PS	PE + PP + PS ~70–80% in surface waters	[96]
Yangtze Estuary	PE, PP, α-cellulose fibers	Surface: PE ~37.3% Sediment: PP ~28.6%	[97]
Freshwater microplastics	PE, PP, PS consistently among most reported	Precise % vary widely	[100]
Sources, transport and accumulation	PE, PP contribute most in all environments	Not quantified	[101]

Table 3 summarizes the findings from selected studies, analyses, and systematic studies regarding the distribution of plastic polymer types across various aquatic compartments. Values are approximate, as methodologies and compartments differ, but PE and PP consistently dominate. The prevalence of PE and PP is likely due to their widespread use in packaging and consumer products [101].

2.6. Physical and Biological Degradation

In the environment, MPs are subjected to fragmentation and degradation through various mechanisms. Photo-oxidation caused by UV exposure, thermal degradation, oxidation, and microbial attack all contribute to surface abrasion and breakdown of plastics [102,103].

Despite these processes, MPs are highly resistant to degradation due to their crystallinity and chemical additives, which enhance durability. NP particles below 1000 nm are the ultimate products of prolonged fragmentation, and their environmental behavior is distinct due to increased surface reactivity and potential toxicity [50].

2.7. Chemical Properties of MPs and ECs

Emerging pollutants display diverse chemical properties that influence their behavior in wastewater. A multitude of ECs are hydrophilic, low-volatility substances, including medicines, endocrine-disrupting chemicals, and synthetic surfactants. Substances such as polyfluoroalkyl substances (PFAS) and polychlorinated biphenyls (PCBs) have hydrophobic properties and demonstrate significant environmental persistence [24]. These contaminants do not dissolve easily in water and tend to accumulate in sediments and biological organisms [24]. Their hydrophobic nature contributes to their environmental persistence, making them challenging to remediate [24]. The low volatility of many ECs further exacerbates this issue, as they do not readily evaporate and instead accumulate in water bodies, leading to prolonged exposure for aquatic organisms [24]. Chemical stability is another critical factor influencing the behavior of ECs. Many emerging pollutants resist degradation processes that typically occur during wastewater treatment. This resistance can lead to bioaccumulation, where contaminants build up in the tissues of organisms over time, potentially causing toxic effects [24].

MPs are composed of various polymers, each with unique chemical properties that affect their environmental behavior. Common types of MPs include high-density polyethylene (HDPE), known for its durability; low-density polyethylene (LDPE), which is flexible; polypropylene (PP), recognized for its heat resistance; polystyrene (PS), often used in packaging; polyvinyl chloride (PVC), widely utilized in construction; acrylates; biopolymers; melamine; polyurethane (PUR), found in foams and coatings; polyvinyl alcohol (PVA); rubber; Teflon; and several unidentified polymers [104]. The degree of crystallinity in these

polymers has a direct impact on their mechanical properties and degradation rates [104]. Research has identified at least 17 distinct types of MP polymers in urban wastewater, including those mentioned above [104]. Polymers with higher crystallinity typically exhibit greater strength and lower permeability, making them more resistant to environmental breakdown. In contrast, those with lower crystallinity may be more susceptible to degradation but can also be more flexible [104].

Surface characteristics of MPs are also vital in determining their interactions with other pollutants. Factors such as surface roughness, porosity, and the presence of functional groups influence their ability to adsorb other substances, including ECs and heavy metals [105]. This sorption can enhance the bioavailability of these contaminants, leading to increased toxicity for aquatic organisms. Additionally, many MP polymers contain chemical additives—such as plasticizers and stabilizers—that can leach into the environment, further complicating their ecological impacts [104].

2.8. Physical Properties of MPs and ECs

In aquatic environments, the interactions between polymeric particles and biological systems are greatly influenced by particle form. The form and size of polymeric particles play a crucial role in determining their toxicity and interactions with biological systems. For example, the amphipod Hyalella Azteca has shown shape-dependent toxicity to PP fibers [106]. Surface ablation is mostly caused by fragmentation processes, and changes in the surface area of MPs are directly related to their particle size [107]. The sinking and sorption behaviors of MPs are also influenced by particle size and surface area [108]. Furthermore, polymer crystallinity is improved by oxidation processes, including photo-oxidation and thermo-oxidation [102]. This increased resilience can contribute to the persistence of MPs in ecosystems, prolonging their ecological footprint [102].

2.9. Biological Properties and Biodegradation

Because of their high crystallinity, plastic particles typically resist microbial decomposition, making biodegradation a difficult process [109]. Recent research, however, has demonstrated that a variety of microorganisms, such as fungi and bacteria, can promote the breakdown of plastic [110,111]. Because different degradative microorganisms have different ideal development habitats, soil conditions are important in this process [112]. Furthermore, the efficiency of biodegradation is greatly influenced by biotic and abiotic environmental conditions, microorganism type, pretreatment techniques, polymer properties (such as mobility, toxicity, crystallinity, molecular weight, functional groups, and presence of additives or plasticizers), and more [113].

3. Membrane Technologies for Removal and Recovery

Membrane separation employs a semi-permeable membrane that permits water to pass through while retaining pollutants through sieving and diffusion, facilitated by pressure. This technology has emerged as a viable, energy-efficient, and cost-effective solution for the removal of MPs from municipal and industrial wastewater, characterized by operational simplicity, stability, and potential for resource recovery [111].

Membrane-based techniques are becoming sophisticated and effective methods for treating saline wastewater. They have considerable promise for both pollution elimination and the recovery of important resources, establishing them as sustainable alternatives to traditional treatment approaches [96]. Moreover, membrane technology enables the processing of substantial quantities of water while facilitating operational control, making it exceptionally suitable for scalability in industrial applications. This scalability offers a unique advantage compared to most traditional treatment techniques. Membrane processes

can be classified into many types based on pore size and separation technique, including RO, NF, UF, MF, dialysis, MBRs, dynamic membranes, and electrodialysis [114].

3.1. Conventional Membrane Technologies

Membrane separation procedures are varied, each characterized by unique separation mechanisms [115]. Membranes employed in water and wastewater treatment systems are primarily categorized into two primary types based on their composition: organic (polymeric) membranes and inorganic membranes. Polymeric membranes are preferred in numerous applications due to their lower production costs and simpler manufacturing processes compared to inorganic membranes [116]. A wide range of polymeric materials is employed in membrane filtration applications because of their favorable physicochemical properties and processability. In contrast, inorganic membranes are typically fabricated from materials such as alumina (Al_2O_3), titania (TiO_2), silica (SiO_2), zirconia (ZrO_2), silicon carbide (SiC), silicon nitride, and zeolite. These materials provide excellent thermal and chemical resistance, making inorganic membranes ideal for harsh operational conditions [117]. However, MBRs, which combine biological treatment with UF or MF membranes, are considered part of conventional membrane-based processes, as the membranes perform size-selective separation similar to standalone UF/MF systems while enhancing microplastic retention during wastewater treatment [118].

3.1.1. Nanofiltration (NF)

NF membranes are pressure-driven devices with pore diameters between 1 and 10 nanometers, generally operating at pressures of 5 to 15 bar [119]. These membranes can efficiently remove divalent salts, larger monovalent ions, various chemical molecules, and certain viruses. NF is particularly adept for applications including water softening by eliminating calcium and magnesium, treating brackish water, and removing specific organic contaminants such as pesticides and dyes. Their practical applications encompass the treatment of industrial wastewater, textile dye effluents, and municipal water systems, where the selective removal of contaminants is crucial [45,120].

NF membranes offer significant advantages over UF membranes by achieving superior salt rejection under similar operating conditions. Additionally, NF membranes demonstrate better flux performance compared to RO membranes, making them an attractive choice for applications requiring effective separation with minimal energy consumption [121]. The particle rejection efficiency and elevated selectivity of NF membranes render them very proficient in eliminating water-soluble plastics from wastewater, chiefly owing to their unique charge-based separation mechanisms.

Zhang et al. [122] developed hybrid NF membranes with titanium/polyethyleneimine composites using electrostatic repulsion to enhance separation efficacy. NF membranes are often employed as a preliminary treatment before RO, mitigating fouling, scaling, and energy expenditure. Fabrication techniques include phase inversion and interfacial polymerization, as demonstrated by Figoli et al. [123], who illustrated the creation of both flat sheet and hollow fiber membranes. Despite their benefits, such as high permeability and energy efficiency, NF membranes still face challenges, including fouling and the flux-selectivity trade-off.

3.1.2. Ultrafiltration (UF)

UF membranes are porous structures with pore sizes ranging from 1 to 100 nm, typically operating under pressures of 1–10 bar [124]. These membranes are ideal for separating suspended solids, colloids, bacteria, and larger macromolecules. Unlike NF or RO, UF does not generally remove dissolved salts, allowing it to serve as an efficient pretreatment for RO systems. UF membranes are widely used in treating oily wastewater, pharmaceutical effluents,

and municipal sewage [125,126]. They primarily function through a sieving mechanism and can act as alternatives or supplements to traditional processes like flocculation, sedimentation, and coagulation in wastewater treatment [127]. However, membrane fouling remains a significant challenge in the treatment of oily wastewater, mainly due to the deposition of small oil droplets on the membrane surface and the blockage of pores [128,129].

Numerous studies have demonstrated the effectiveness of coagulation and UF methods in removing MPs from water. Fe- and Al-based coagulants, when used in conjunction with UF, achieved polyethylene removal efficiencies of up to 90.9%, with complete removal observed in some cases, due to changes in adsorption dynamics and membrane architecture [130]. Advanced UF membranes, including micellar-enhanced and polymer-modified variants, exhibit improved performance due to electrostatic interactions [131]. Modified polyacrylonitrile UF membranes show promising results in MP removal through pore size reduction [132].

UF membranes generally outperform MF membranes in MP removal due to their smaller pore sizes. Ma et al. [130] and Tadsuwan and Babel [133] reported nearly total MP elimination in wastewater systems utilizing commercial UF membranes, enhancing the overall MP removal efficiency of wastewater treatment facilities to approximately 97%. However, the effectiveness of MP removal is also influenced by the properties of the membrane material, including hydrophobicity, surface charge, zeta potential, and surface roughness.

3.1.3. Microfiltration (MF)

MF membranes are characterized by pore sizes ranging from 0.1 to 10 μm and typically operate under low pressures of approximately 0.1 to 2 bar [134]. These membranes are primarily effective for removing suspended solids, larger MPs, and microorganisms, making them suitable for various applications in water and wastewater treatment [135]. MF membranes function through a size-exclusion mechanism, effectively filtering out larger particles while allowing water and smaller solutes to pass through [135]. They are commonly used as a preliminary treatment step before more advanced processes such as UF and RO, helping to reduce the load on these downstream treatments [136].

Applications of MF include treating surface water [137] and wastewater [135]. However, while MF membranes excel in removing larger particulates, they are less efficient at removing smaller colloids and macromolecules compared to UF membranes [136]. Despite their advantages, MF membranes also face challenges, including membrane fouling due to the deposition of larger particles and biofilms on the membrane surface, necessitating regular cleaning to maintain performance [138]. Point-of-use filtration systems, such as bottles with integrated filters, show variable effectiveness against microplastics depending on filter design and pore size. Recent studies indicate that membrane-based microfiltration and ultrafiltration devices (≈0.1–0.2 μm) can retain a substantial fraction of larger microplastic particles, whereas adsorptive or coarse filters provide only partial removal. However, even advanced portable systems remain limited in their ability to capture smaller micro- and nanoplastic fractions under practical use conditions [139,140].

3.1.4. Reverse Osmosis (RO)

RO membranes constitute one of the most accurate membrane separation technologies, possessing pore diameters less than 0.001 μm [11]. These membranes function under elevated pressure, generally beyond 20 bar, to enable water passage through a compact polymeric layer [141]. RO membranes operate on the solution-diffusion principle and may reject solutes with molecular weights under 200 g/mol, rendering them highly efficient in eliminating dissolved salts, organic compounds, and pathogens. The majority of

commercial RO membranes are designed as spiral-wound modules, providing a compact configuration and extensive surface area [142]. These membranes are extensively utilized in saltwater desalination, the manufacture of ultrapure water for industrial purposes, and advanced wastewater reclamation [143]. Although RO systems exhibit remarkable separation efficiency, they are energy-intensive owing to the operational pressure required.

RO membranes are extensively utilized in the desalination of seawater and brackish water, in addition to drinking water production and wastewater treatment. In contrast to MF, UF, and NF membranes, RO membranes can eliminate nearly all pollutants, including monovalent ions, rendering them the most effective barrier in membrane-based water purification systems [143]. Recent technological improvements in drinking water treatment are essential for the elimination of nitrates, predominantly introduced from industrial pollution [144]. RO membranes provide superior technology for pollutant removal, surpassing MF, UF, and NF membranes, especially in contexts with rigorous effluent regulations. Likewise, Sun et al. [145] indicated that MPs less than 50 µm, predominantly fibers, were identified following RO treatment, implying that the elongated morphology of fibers aids their translocation through membrane pores.

Although RO membranes can attain removal efficiencies of 98–100% based on particle size 6, their efficiency is affected by variables such as membrane pore size, surface characteristics, and feedwater MP concentration. Mohana et al. [146] identified elevated removal efficiencies (up to 99%) with reduced pore diameters, whereas Krishnan et al. noted a decline in efficiency (88–97%) at increased MP concentrations. Table 4 summarizes the characteristics of the different types of membranes.

A special diagram is presented in Figure 5 to illustrate how MF, UF, NF, and RO separate different forms and size classes of microplastics. MF and UF primarily retain fibers and fragments larger than 1 µm, whereas NF and RO are required for efficient removal of sub-micron microplastics and nanoplastics [147]. This classification aligns membrane pore sizes with reported microplastic size distributions in water systems.

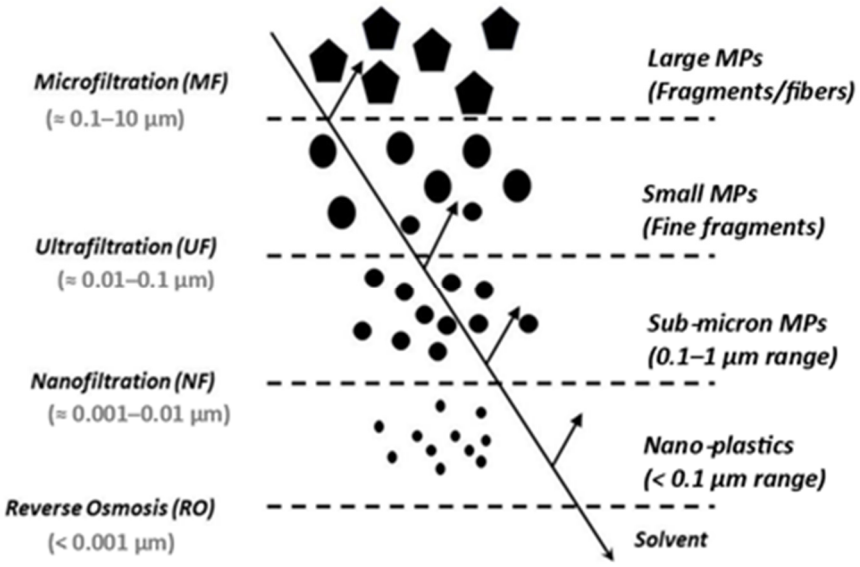


Figure 5. Schematic of MF, UF, NF, and RO showing typical pore sizes and the microplastic particle sizes retained (Modified from [135]).

Table 4. Summary of characteristics of membranes.

Membrane Type	Pore Size (μm)	Operating Pressure (bar)	Target Pollutants	Removal Mechanism	MP Removal Efficiency	Refs.
MF	0.1–10	~0.1–2	Suspended solids, large MPs	Size exclusion	Moderate (up to ~80%)	[134,135]
UF	0.01–0.1	1–10	Colloids, bacteria, larger MPs	Sieving, adsorption	High (~90–97%)	[130–133]
NF	0.001–0.01	4–30	Divalent salts, organics, small MPs/ECs	Size exclusion, electrostatic repulsion	Very high (>95%)	[119–122]
RO	<0.001	>30	All dissolved solutes, monovalent ions	Diffusion through dense membrane matrix	Extremely high (98–100%)	[145]

3.2. Advanced Membrane Materials and Functionalization Nanocomposite Membranes

Membranes used in water and wastewater treatment must meet critical characteristics, including low cost, excellent mechanical, chemical, and thermal resistance, and reduced fouling propensity. Researchers have investigated optimization parameters such as polymer dosage [148], solvent type and concentration [149], and pore-forming agent content [150] to enhance the performance of polymeric membranes. Recent advancements have concentrated on integrating ultralow concentrations (below 1 wt%) of inorganic nanomaterials such as TiO_2, SiO_2, and Fe_3O_4 into polymeric membrane matrices. This integration has yielded significant improvements in permeability, contaminant rejection efficiency, and fouling resistance [151]. These "nano-reinforced" membranes replicate the advantages of ceramics (e.g., dimensional stability, mechanical resilience) while maintaining the flexibility and cost-effectiveness of polymers.

Recent evaluations emphasize that adjusting the type, loading, surface functionality, and manufacturing parameters of nanomaterials enables the rational design of features such as hydrophilicity, charge, and porosity. This optimization aims to enhance the collection of MPs and emerging contaminants [152], imparting ceramic-like benefits to economical polymeric membranes. Composite membranes, including polymer–nanoparticle, polymer–ceramic, or biomaterial-based variants, integrate multiple functionalities. Thin-film nanocomposites (TFNs) can improve permeability by as much as 50%, while polymer–ceramic hybrids demonstrate thermal stability above 500 °C, thereby extending operational lifespan by two to three times [153,154]. These hybrids combine the mechanical strength and thermal resistance of ceramics with the flexibility and adaptability of polymeric substrates.

Ceramic MF membranes are conventionally composed of aluminum oxide, titanium dioxide, while ceramic MF membranes are traditionally composed of aluminum oxide, titanium dioxide, and zirconium oxide. Recent studies highlight the potential of alternative raw materials such as sepiolite, kaolin, and dolomite. Ceramic nanocomposite membranes containing oxide nanoparticles have demonstrated efficacy in removing MPs from wastewater [154].

3.3. MBRs for MPs and ECs: Integration of MBRs in WWTPs

MBRs represent an innovative hybrid method for wastewater treatment, integrating biological degradation with membrane filtration. MBRs combine the activated sludge process with advanced membrane separation, often utilizing MF or UF membranes, to enhance pollutant removal efficiency, including MPs and emerging contaminants [155,156].

MBRs are predominantly designed in two configurations: submerged (internal) and side-stream (external) systems. In submerged MBRs, the membrane modules are directly immersed in the bioreactor, facilitating biological treatment. This configuration allows for direct suction of treated water over the membranes, resulting in energy-efficient performance due to reduced TMP and minimal piping needs, making it suitable for municipal applications. Conversely, side-stream MBRs incorporate external membrane units, necessitating the recirculation of wastewater from the bioreactor to the membrane module and back. This configuration supports elevated operational pressures, enhances cleaning efficiency, and is better suited for industrial wastewater treatment with high solids concentrations [45,157,158]. Figure 6 illustrates the two configurations of MBRs: submerged MBRs are placed inside the biological treatment tank, while side-stream MBRs are located outside the tank.

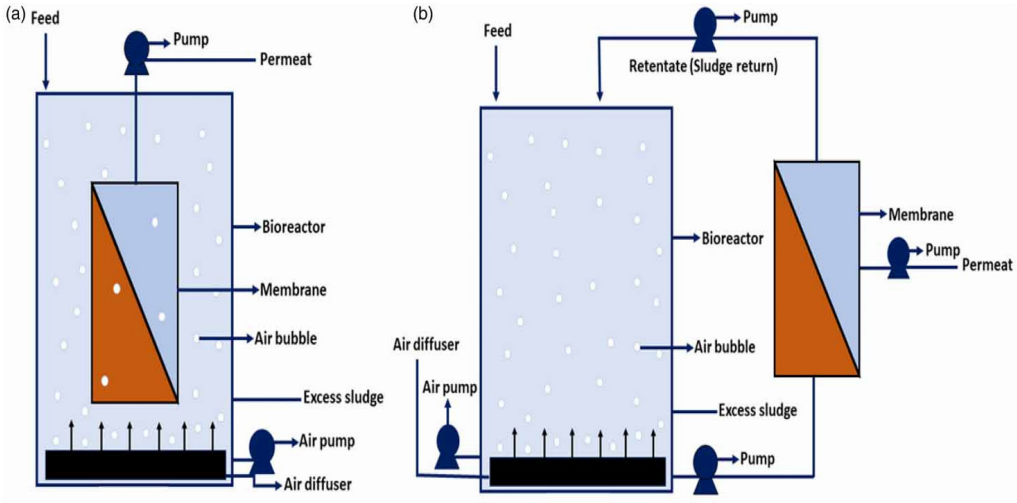


Figure 6. Typical Configurations of Membrane Bioreactors (MBRs): (**a**) Submerged System and (**b**) Side-Stream System [159].

The fundamental components of MBR systems consist of: (i) bioreactor tanks housing concentrated activated sludge, (ii) membrane modules for solid–liquid separation, and (iii) aeration units to provide oxygen and reduce membrane fouling. MBR systems are recognized for their ability to operate at elevated mixed liquid suspended solids (MLSS), facilitating increased organic loading and reduced system dimensions [160,161].

Regarding MP removal, MBRs have shown superior efficacy. Talvitie et al. [127] reported a 99.9% MPs removal efficiency in Finland utilizing a pilot-scale MBR with flat sheet membranes (0.4 µm pore size), significantly outperforming the conventional activated sludge (CAS) process, which achieved 98.3% efficiency. Lares et al. [162] reported analogous findings, indicating a 99.4% removal of MPs from primary wastewater utilizing MBRs, in contrast to 1.0 ± 0.4 MP/L in effluent treated by CAS. Bayo et al. [74] demonstrated that MBRs surpassed rapid sand filtration (RSF) throughout an 18-month operational period. Notwithstanding their efficacy, MBRs are linked to several problems. Despite their efficacy, MBRs are associated with several challenges, including substantial capital and operational expenditures, membrane fouling, and the need for periodic membrane replacement [163]. Recent advancements in membrane materials, including nanoparticles (TiO_2, AgNPs, GO), biomaterials (chitosan, alginate), and advanced composites, have improved fouling resistance, permeability, and selectivity [164–166]. For example, GO membranes achieved a 99% rejection rate for heavy metals while enhancing water flux by 30–50%, and TiO_2 coatings demonstrated a 50% reduction in fouling [167,168].

Future advancements in MBR development will focus on maximizing energy efficiency, improving membrane durability, incorporating real-time monitoring systems, and creating scalable, modular units suitable for both centralized and decentralized applications [159]. Research highlights the potential for integrating MBR with adsorption methods or enzymatic treatments for the targeted removal of complex emerging pollutants (Comprehensive evaluation of ECs: Detection technologies, environmental impact, and management options).

Table 5 shows a comparison of membrane technologies for wastewater treatment, which reveals important practical trade-offs. Ultrafiltration (UF) and membrane bioreactor (MBR) systems generally achieve high MP removal efficiencies (>94–99%), outperforming conventional processes but facing moderate to severe fouling that increases operational maintenance [169]. NF and integrated UF–NF approaches also show high removal but require elevated pressures and energy inputs [169,170]. RO delivers very high rejection of contaminants but is constrained by high energy costs and concentrate management issues, and fine fibers may still permeate under some conditions [170,171]. These findings highlight that while advanced membranes improve treatment performance, fouling control, energy demand, and cost remain central constraints for full-scale wastewater applications.

Table 5. Comparative performance of different membrane technologies in wastewater treatment.

Membrane Type	Removal Efficiency (%)	Fouling/Operational Issues	Cost and Practical Constraints	Refs.
MF	High TSS and turbidity removal (87–96%) in industrial wastewater but lower efficiency for dissolved contaminants and fine particles	Lower fouling relative to tighter membranes; effective pre-treatment stage	Lower capital/energy cost but limited for MPs and ECs alone; needs integration in treatment trains	[169,170]
UF	>85% MPs removal reported; strong particle rejection in MBR systems	Moderate fouling increases with organics; long-term flux decline and cleaning needs highlighted	Moderate cost; cleaning/maintenance and membrane replacement key cost drivers	[171,172]
NF	NF-based MBR showed high pollutant removal and low fouling under ultralow flux conditions	Fouling significant at higher flux; severe at high pressures if not managed	Higher capital cost than UF/MF; energy lower than RO, but cleaning still required	[170,173]
RO	Very high removal (up to 98–100% for dissolved contaminants) reported in wastewater/leachate contexts	Prone to scaling and biofouling; requires rigorous pre-treatment	High energy and maintenance costs; concentrated disposal issues; high initial cost	[174,175]
MBR	Up to ~99–99.9% MPs removal in pilot/full systems; superior to conventional activated sludge	Fouling is a major challenge; MPs can intensify biofilm/EPS formation and cake layer growth	Highest operational complexity; requires skilled management but combines biological removal with filtration	[170,176]

3.4. Hybrid Membrane Processes and Emerging Technologies

In the forthcoming years, membrane-based technologies are expected to garner increasing interest and investment in the water treatment sector due to their efficacy and versatility. Membrane technologies are rarely used as standalone treatment units and are typically integrated into multi-step schemes combining physical, chemical, and biological processes. For example, conventional drinking water treatment often couples coagulation, rapid sand filtration, and UF or RO membranes, while MBRs combine biological treatment with UF

membranes for enhanced microplastic and micropollutant removal. Such integration ensures optimal particle retention and overall treatment efficiency [177]. Table 6 summarizes significant findings regarding hybrid membrane processes. It presents hybrid membrane technologies that integrate conventional membrane filtration with complementary treatment processes to enhance contaminant removal. Table shows that combining RO with activated carbon improves treatment of high-strength emulsified effluents by enhancing permeate flux and overall efficiency, while ultrasound–adsorption–membrane systems achieve nearly complete elimination of organic matter by coupling physical, chemical, and membrane-based mechanisms. These hybrid approaches demonstrate that integrating multiple treatment modalities can significantly improve removal efficiencies, particularly for recalcitrant pollutants and complex wastewater matrices.

Table 6. Summary of hybrid membrane technologies.

Technology	Description	Removal Efficiency	Notes	Ref.
Hybrid RO with activated carbon	Combines RO membrane filtration with an activated carbon unit for treating high-strength emulsified edible oil effluent.	Up to 99%.	Activated carbon pretreatment enhances permeate flux and overall treatment efficiency.	[178]
Ultrasound–Adsorption–Membrane filtration (USAMe)	Integrates ultrasound, adsorption, and membrane filtration to eliminate organic matter from water.	Nearly total elimination	Effective after biological treatment, mitigating the effects of natural organic matter.	[179]

4. Mechanisms of Removal and Recovery

The physicochemical characteristics of the particles, the particular treatment technologies employed, and the process operating parameters all affect how effectively MPs are removed in WWTPs [180]. There are usually five main steps involved in wastewater treatment. Preliminary treatment, the first step, uses physical and mechanical methods to remove big particles. In the second stage, known as primary treatment, organic matter and suspended solids are eliminated using physicochemical techniques, frequently aided by precipitation or coagulation [181]. The third stage, secondary treatment, uses microorganisms to break down organic contaminants and nutrients while concentrating on biological and chemical processes. Activated sludge and trickling filters are common methods, and disinfection is occasionally used to eliminate germs [38]. Using techniques, including filtration, adsorption, and RO, the fourth step, known as tertiary or advanced treatment, further eliminates any remaining contaminants. For better purification, methods like ozonation and membrane filtration can also be used [182]. Using techniques, including controlled disposal, recycling, or incineration, the fifth entails managing the sludge generated during the treatment cycle [38].

Notably, WWTPs that use tertiary treatment procedures have greater MP removal efficiency than those that just use primary or secondary treatments. The use of cutting-edge technologies like MBRs, fast sand filtration, and RO, which are frequently used in tertiary stages and serve as efficient physical barriers against MP discharge into natural water bodies, is probably responsible for this improved performance. Therefore, reducing the amount of MPs released into the environment requires a thorough understanding of the removal efficiency and underlying mechanisms at each stage of the treatment process [183].

In addition to traditional methods, several recovery techniques have been used to remove pollutants, including solvent extraction, evaporation, oxidation, electrochemical treatment, membrane separation, MBR, ion exchange, and burning. New techniques for

treating difficult-to-remove pollutants have recently surfaced, including enhanced oxidation, biosorption, biomass utilization, NF, and adsorption onto atypical materials [184]. While NF, which has particle diameters between UF and RO, is efficient in removing organics, inorganics, medications, and endocrine disruptors, biosorption and biomass approaches use microorganisms or plants to absorb pollutants from wastewater [182]. Additionally, inexpensive adsorbents like biochar and agricultural waste have demonstrated encouraging outcomes in applications involving the removal of contaminants [185].

4.1. Pre-Treatment and Primary Treatment

By removing coarse particulates and debris, the first stages of wastewater treatment, often referred to as preliminary or pre-treatment, protect later procedures. Mechanical methods, including screening, grit removal, sedimentation, and flotation, are usually used to do this. Primary sedimentation and flotation tanks are particularly useful in removing MP because they avoid clogging and equipment damage [38,183]. Sedimentation or flotation are the main methods used in primary treatment to target suspended particles and biodegradable organics. Chemical aids like coagulants or precipitants are frequently used to enhance solids separation. Before biological treatment, these actions serve as the crucial basis for lowering the pollution load [181].

Physical sedimentation effectively removes MPs with densities greater than wastewater, including polybutylene terephthalate (PBT), polyethylene terephthalate (PET), and PVC. Because low-density particles stay suspended, this procedure lowers the total density of MPs in the effluent [183]. Conversely, low-density MPs like polyethylene (PE) and PP, as well as moderate-density kinds like PS and PA, have been successfully separated by air flotation [186]. Dispersed air flotation, dissolved air flotation, and electro-flotation are common flotation techniques in WWTPs. By binding with suspended particles utilizing microbubbles, these methods raise the particles and create a surface foam that makes removal easier [187].

During the first treatment, coagulation plays a major role in MP elimination. To counteract surface charges and encourage floc formation with MPs in wastewater, coagulants like aluminum and ferric salts are utilized. After that, these flocs are separated by skimming or settling. Coagulation can attain up to 90% elimination efficiency under ideal circumstances, taking into account pH, MP characteristics, coagulant type, and dosage [188]. One of the main mechanisms for removing MPs during primary treatment is sorption, which is the result of both hydrophobic absorption of MPs into the lipid-rich fraction of sludge and electrostatic adsorption onto the surfaces of sludge particles [189,190].

4.2. Secondary Treatment

For treating municipal wastewater, activated sludge technologies and their more sophisticated variations are the most often used biological techniques. Through microbial activity and adsorption, these systems efficiently remove suspended particles, dissolved, colloidal organic waste, and MPs. Microbial activities are the main tool used in secondary treatment to decompose organic contaminants and nutrients in wastewater. Activated sludge systems, trickling filters, and other biological reactors are examples of common methods [191]. Disinfection can be used to remove pathogens and other dangerous organisms to guarantee microbiological safety. As the last line of defense against contaminants, the tertiary stage uses sophisticated physical or chemical methods, including filtration, adsorption, or RO. The effluent is subjected to secondary treatment after primary treatment, which mainly aims to remove dissolved organic matter through biological processes [191].

A popular technique is activated sludge, which uses a secondary clarifier and an aeration tank. Diffusers at the bottom of the aeration tank provide compressed air to supply oxygen, promoting microbial activity that breaks down organics and reduces the water's biochemical oxygen demand (BOD). Activated sludge settles in the secondary clarifier after the primary effluent passes through it. To sustain microbial populations, about 30% of the settled biomass is recycled back into the aeration tank; the remaining biomass is sent for additional processing and disposal [192]. By replacing the secondary clarifier with MF or UF membranes, an MBR, a variation on the activated sludge process, improves the quality of the effluent [193]. The anaerobic-anoxic-aerobic (A^2O) process is another version that is intended for the removal of nutrients, specifically phosphate and nitrogen [194]. There are three successive tanks in it: aerobic, anoxic, and anaerobic. Phosphorus-accumulating organisms remove phosphorus in the anaerobic tank; denitrification, which turns nitrate into nitrogen gas, is facilitated in the anoxic tank; and both BOD removal and nitrification, which turns ammonia into nitrate, are supported in the aerobic tank [195].

4.3. Tertiary Treatment

Cutting-edge technology is utilized as efficient tertiary treatment choices to improve water quality, such as membrane filtration and ozonation [38]. To further remove suspended solids, tertiary treatment usually involves dissolved air flotation or filtration via a variety of media, including sand, disk filters, biologically active filters, UV irradiation, chlorination, GAC, and gravity filters [6,195,196]. Remaining organic molecules can also be eliminated by activated carbon filtering. Advanced membrane technologies, including RO and UF, are occasionally used for improved purification, despite being less common in traditional WWTPs [6,197]. Distillation is a thermal separation process applied in wastewater treatment primarily to recover high-purity water from industrial or highly contaminated streams. By evaporating water and condensing the vapor, distillation can effectively remove dissolved salts, residual organic pollutants, and microplastic particles that are not retained by conventional filtration, providing a complementary treatment step when ultrafiltration or reverse osmosis are insufficient [198].

Tertiary treatment is essential to reducing MP contamination since it is the last line of defense before treated wastewater is released into natural habitats. Although primary and secondary processes play a major role in the removal of MP, they are frequently less successful at trapping smaller particles, especially those that resemble synthetic fibers and microbeads, which are common in wastewater from homes and businesses. Therefore, improving tertiary treatment technologies to effectively target and eliminate these fine MPs should be the top priority of future research efforts. For this reason, further research and optimization should be performed on advanced filtration technologies, including RO, membrane filtration, and quicksand filtration. To increase retention rates, a better comprehension of the relationship between the filtration media and the physical and chemical properties of MPs is also necessary [195].

4.4. Rapid Sand Filtration (RSF)

RSF is a popular and reasonably priced technique for treating water and wastewater, especially in WWTPs as a tertiary stage. Through physical and biological processes like sedimentation, adsorption, and microbial activity, it efficiently removes organic debris, suspended materials, and pathogens by running water through a bed of sand. It is a viable option for improving water quality in a variety of applications because of its inexpensive operating and maintenance expenses [74].

RSF is widely used in conventional drinking water treatment due to its low cost, simplicity, and high removal efficiency for microplastics larger than ~10 μm through

interception, entanglement, and adsorption mechanisms, often achieving >80% removal under pilot conditions (RSF can reach ~84–98% for <10 μm MPs) and enhanced performance with backwashing [199]. However, RSF exhibits reduced retention for smaller microplastics and nanoplastics, with efficiency strongly influenced by particle size distribution, filter media characteristics, and hydrodynamic conditions, and may contribute to fragmentation of MPs into smaller particles, complicating downstream removal [200]. These limitations highlight the need for complementary treatment steps or optimized media and operational strategies to improve removal of fine microplastics in full-scale systems.

RSFs, which are made up of layered media like anthracite, silica sand, and gravel, have shown promise in WWTPs for the removal of MP, as well as suspended organic and inorganic particles, microorganisms, plankton, and emulsified oils [188]. Multiple factors can affect the efficiency of MP removal in RSF, with particle size being one of the most critical. The effectiveness of removal may vary depending on the size distribution of MPs present in the influent, as different particle sizes interact differently with the sand filtration medium. These interactions influence the extent to which MPs are retained or pass through the filter, ultimately impacting overall removal performance [26].

MPs' surface properties, polymer type, and additives can all have a big impact on how well they interact with sand media and how effective their removal is. While some MPs resist adhesion, others stick to sand particles more easily. Furthermore, the total efficacy of MP removal is greatly influenced by operational parameters such as filtration rate, contact time, and filter bed quality [201]. RSF efficiently eliminates several contaminants, but its ability to remove MP has drawn increasing attention. According to comparative research, quick sand filtering performed marginally better, achieving an efficiency of up to 99.9%, but MBRs only managed an MP removal efficiency of 97.1% [202]. These results demonstrate the potential of sand filtration while also emphasizing how crucial it is to comprehend its operating constraints.

MPs that are present in low concentrations can be effectively removed by sand filtration. Activated carbon is a well-researched adsorbent for a variety of contaminants because of its high porosity and surface area. It makes combined removal through adsorption and biodegradation easier when biomass growth is supported. MPs and NPs were removed with a 60.9% removal efficiency using GAC filters, with PE being removed more successfully than PAM and PP [203]. Overly high filtration rates may restrict the effectiveness of removal by shortening the period that MPs and the filter media are in contact [204]. Furthermore, the system's ability to retain MPs over time may be hampered by the slow accumulation of organic debris and biofilm on the filter bed, which can change pore size and decrease porosity [205].

In conventional drinking water treatment plants, coagulation enhances aggregation and removal of larger microplastics during subsequent sand filtration, while ozonation may alter polymer surfaces and promote fragmentation rather than complete mineralization. Activated carbon filtration can further reduce microplastic concentrations through adsorption and physical retention, particularly for irregular fragments. Consequently, tap water generally contains substantially reduced levels of large microplastics, although smaller microplastics and nanoplastics may still persist [200]. As a result, human exposure through tap water is expected to be dominated by small microplastics and potentially nanoplastics that bypass conventional treatment barriers, highlighting the limits of current systems in fully eliminating plastic-derived particles [206].

4.5. Coagulation

In the chemical treatment process known as coagulation, coagulants are added to wastewater to destabilize colloidal particles, causing flocculation and separation. Parti-

cle aggregation is facilitated by electrolyte-induced compression or charge neutralization. Additionally, MPs are agglomerated by polymer adsorption through sediment trapping and bridging mechanisms [183]. Coagulation and sedimentation together produced removal efficiencies for MP that ranged from 40.5% to 54.5%. Nevertheless, coagulation demonstrated a noteworthy performance when specifically targeting plastic microspheres, lowering their concentration in secondary effluent by more than 80%. In comparison to MBR, RSF, and disk filtering systems, this demonstrates its potential as a supplemental procedure to improve total MP removal efficiency [207].

Future studies should concentrate on coagulant optimization and combining coagulation with other treatments, as aluminum-based coagulants have demonstrated encouraging MP removal efficiency [130]. Most MPs are eliminated during pre-treatment; however, differences in starting MP concentrations or detection techniques may have an impact on the lower removal rates. Particle properties like size, shape, and density all affect MP removal performance, underscoring the need for more precise and uniform assessment methods.

4.6. Disk-Filtration

An inventive filtration method that is being used more in tertiary wastewater treatment is the disk-filter (DF) system. It is a compact and effective construction made up of several layers of overlapping filter screens and flange rings that are intended to absorb tiny particles floating in wastewater. The DF system effectively removes small particles, including MPs, thanks to its multi-layered design, which increases surface area and filtration capacity [183].

According to studies, WWTPs using DF technology in the last stage of treatment were able to obtain MP concentrations in the effluent that were less than 0.3 MP/L [197], demonstrating great filtration efficiency. Furthermore, DF systems showed a MPs removal effectiveness of up to 89.7% when applied directly to raw wastewater, highlighting their potential for MP interception at an early stage. However, a sizable number of MP particles have been found in the treated effluent despite these encouraging results. Interestingly, a few of these particles were larger than the disk filters' stated pore sizes, indicating that MPs might slip past or pass through the filtration media in specific operating circumstances. The consistency and dependability of DF systems in fully retaining MPs are called into question by this phenomenon, particularly when flow rates or particle loads fluctuate [208].

4.7. Membrane Bioreactor Systems

The effectiveness of advanced biological treatment technologies in wastewater treatment applications, such as MBR systems, fluidized bed reactors, and rotating biological contactors, has been recognized more and more [209]. MBR technology is unique among these because it combines membrane-based solid–liquid separation with biological degradation to provide a portable and effective treatment solution [210]. MBRs are unique because they employ membranes with much lower pore sizes, usually between 0.01 and 5 μm, which effectively retains MPs that could otherwise evade traditional filtration systems [211]. For the enhanced removal of MPs and other fine pollutants from wastewater streams, MBRs are therefore especially well-suited.

Applying MBRs directly to primary effluent produced an amazing 99.9% MP removal efficiency, surpassing the majority of traditional secondary treatment techniques, according to a study by Talvitie et al. [127]. These results imply that MBR technology is one of the best methods for removing MPs from wastewater that is currently available, regardless of whether it is used as a secondary or tertiary treatment stage.

5. Challenges and Limitations of Membrane Technologies

In wastewater treatment, membrane technologies have become useful instruments for the simultaneous removal of ECs and MPs. However, despite their effectiveness, several operational and technical challenges persist, primarily due to membrane fouling. This issue occurs when impurities in the feed water clog the membrane pores or accumulate on the surface, creating a thick layer of cake. Larger particles tend to contribute to surface accumulation, while smaller particles may penetrate the pores, leading to narrowing and blockage [212]. This fouling process significantly reduces membrane flux and increases energy expenditure, which poses a notable barrier to their broader application. Membrane fouling can be categorized into four distinct types: standard blocking, total blocking, intermediate blocking, and cake formation. Standard blocking occurs when larger particles accumulate on the membrane surface, preventing water from passing through. Total blocking happens when incoming foulants completely obstruct the pores, ceasing the filtration process altogether. Intermediate blocking involves the random deposition of particles across the membrane surface, leading to a layered buildup that further complicates filtration. Lastly, cake formation entails the continuous accumulation of particles on the membrane surface, resulting in a thick, impermeable layer that severely restricts water flow [176,212]. In addition to fouling, membrane structures may be damaged by the chemical cleaning processes employed to mitigate these issues, ultimately reducing their operational longevity. High operating costs, maintenance requirements, and scalability constraints also hinder the widespread adoption of membrane-based systems in both industrial and municipal wastewater treatment applications [176,212].

Mechanical abrasion caused by suspended particles in crossflow filtration systems can lead to surface degradation of membranes, resulting in diminished filtration efficiency. This physical wear compromises the integrity of the membranes and poses long-term performance challenges [213]. An increase in TMP and a corresponding decline in permeate flux are key indicators of membrane fouling. As pollutants accumulate on the membrane surface and within its pores, TMP rises while flux diminishes. The presence of MPs in wastewater further exacerbates this issue, intensifying fouling and leading to a more significant reduction in membrane performance by elevating TMP and decreasing water permeability. Fine particles enter the membrane pores and stick to their interior surfaces in the case of typical pore blockage, gradually narrowing the flow channels and reducing the permeate flux. Total blocking occurs when incoming foulants completely plug the pores, which stops the filtration process. The random and layered deposition of particles across the membrane surface, both on exposed areas and on top of preexisting deposits, is a characteristic of the intermediate blocking mechanism. On the other hand, the mechanism by which the cake layer forms entails the constant buildup of particles on the membrane surface, culminating in the creation of a thick, impermeable layer that severely limits the flow of water [152,214].

The use of functionalized membranes with antimicrobial qualities, such as those embedded with silver nanoparticles, the application of anti-fouling coatings, and the addition of hydrophilic surface layers, are some of the methods that have been developed to reduce membrane fouling [45]. A major problem in addition to biofouling is scaling brought on by the deposition of inorganic salts, especially calcium carbonate and magnesium sulfate, which decreases water flux and shortens the lifespan of membranes [126,215].

The development of sophisticated anti-scaling surface coatings, water softening methods, and the application of anti-scalants are prevention tactics for membrane degradation [216]. Membrane lifespans are often between three and five years; however, fouling, scaling, and exposure to harsh chemicals can shorten this time. The use of more resilient materials, such as ceramic and graphene-based membranes, has demonstrated significant

promise in overcoming these constraints. Additionally, by making component replacement easier, modular membrane system designs provide financial benefits. However, the economic viability of membrane technology is still threatened by the high energy requirements of procedures like RO. Therefore, to improve sustainability, operational effectiveness, and wider applicability of these technologies, advancements in low-energy membrane development and energy recovery systems are essential [217,218].

Membrane bioremediation systems are a potential method for treating advanced wastewater, but their general implementation is still hampered by several issues with scalability, economic viability, and technical complexity. MBR systems are roughly 15–25% more expensive than traditional treatment technologies due to their high capital expenditures, which are estimated to be between $500 and $2000 per cubic meter of daily treatment capacity [158]. This limits the practical deployment of MBR systems.

Energy consumption, which ranges from 0.5 to 1.5 kWh per cubic meter of treated water, and the requirement for regular membrane cleaning are the main factors affecting operational costs in membrane-based wastewater treatment systems. Interestingly, around half of the energy required is for aeration alone. Recent developments, such as the creation of membranes augmented with nanomaterials and self-cleaning technologies, have shown promise in reducing energy consumption by 20–30% while also cutting maintenance needs and related expenses [218,219]. The detrimental effects of MPs and NPs on membrane function have been amply illustrated by a number of experimental investigations. According to Enfrin et al. [220], the permeate flux decreased by less than 15% when distilled water and a UF polysulfone (PSF) membrane were used under controlled circumstances for 48 h at 1 bar. Nevertheless, the flow reduction increased dramatically to 38% when MPs/NPs were added to the feed water under the same circumstances, suggesting a notable amplification of fouling. Li et al. [221] also investigated how membrane fouling was affected by the size and concentration of MPs. Their findings demonstrated that more severe fouling was caused by larger concentrations and smaller MPs (1 μm). By the tenth day of operation, the TMP increased from 35.5 kPa (without MPs) to 74.0 kPa (with 1 mg/L of 1 μm polystyrene MPs) when raw water was filtered over a PVDF hollow fiber UF membrane, indicating the increased membrane resistance brought on by MP accumulation. These and Ma et al. [130] results consistently show that smaller MPs worsen membrane fouling, resulting in larger flux decreases and more pronounced TMP rises.

Recent studies have demonstrated that the integration of hydrophilic nanomaterials into polymeric membrane matrices significantly enhances surface hydrophilicity and strengthens the membrane's resistance to fouling [222,223]. The flow recovery ratio (FRR) is commonly used to assess the antifouling performance of membranes; higher FRR values signify stronger fouling resistance. Hydrophilic nanoparticles have been found to improve FRR against a variety of pollutants, including oil, BSA, humic acid, sodium alginate, and dyes [224–227]. Increased surface hydrophilicity, which lessens foulant adherence and makes cleaning simpler, is responsible for this improvement. Nevertheless, no research has been conducted on the FRR performance following filtration of water containing MP and subsequent cleaning. To create membranes with better resistance to MP fouling, future research should examine the interaction between membrane surface features (such as hydrophilicity, roughness, and charge) and MP characteristics (such as polymer type, size, shape, and surface charge). These developments can lower operating expenses, chemical usage, and cleaning frequency. Furthermore, recent research has investigated membranes' self-cleaning capabilities for improved antifouling performance [228,229].

Although synthetic polymeric membranes are effective at retaining microplastics, recent studies show that these membranes themselves can release microplastic particles, particularly under chemical cleaning, mechanical stress, and long-term operation, with

released particles often in the size range of ~1–5 µm originating from the membrane material and equipment components. Evidence of microplastic release and alterations in microplastic composition in permeate has been observed under varying operational conditions, indicating that membrane degradation and surface wear can contribute to secondary microplastic contamination. These findings highlight the need to consider membrane-derived microplastics and their mitigation when evaluating the net benefit of membrane processes for water treatment [147,230].

Photocatalytic self-cleaning membranes offer a sustainable solution for wastewater treatment by decreasing the requirement for chemical cleaning, increasing operating time, and lowering maintenance frequency and environmental impact [227]. These membranes contain photocatalysts like ZnO and TiO_2, which produce electron-hole pairs when exposed to light that is greater than their band gap energy. Organic and bioorganic foulants are broken down by the ensuing reactive species, superoxide and hydroxyl radicals, into innocuous byproducts such H_2O and CO_2 [231]. According to studies, catalytic membranes perform noticeably better at self-cleaning when exposed to UV light than non-catalytic ones, especially when it comes to decomposing organic surface pollutants [228,232].

To summarize the challenges and limitations associated with membrane technologies, Table 7 provides a comprehensive overview of the key issues impacting their performance and operational viability.

Table 7. Major Challenges and limitations of membrane technologies.

Challenge/Limitations	Description	Impact	Refs.
Membrane Fouling	Clogging of membrane pores or accumulation on the surface, leading to reduced flux and increased energy costs.	Lowers membrane performance and operational efficiency.	[176,212]
Types of Fouling	Includes standard blocking, total blocking, intermediate blocking, and cake formation, each affecting filtration differently.	Affects filtration efficiency and membrane lifespan.	[176]
Chemical Cleaning Damage	Cleaning methods can harm membrane structures, reducing their longevity.	Results in increased replacement costs and downtime.	[213]
Mechanical Abrasion	Suspended particles can cause surface degradation, compromising membrane integrity and performance.	Decreases long-term operational effectiveness.	[152,213,214]
Scaling	Inorganic salt deposition reduces flux and shortens membrane lifespan	Increases cleaning frequency and operational costs.	[45,126,215]
High Operational Costs	Initial capital expenditures for systems like MBRs are higher than traditional technologies, limiting deployment.	Challenges economic viability, especially in municipal settings.	[158]
Energy Consumption	High energy requirements, particularly for processes like RO, impact sustainability.	Increases operational costs and environmental impact.	[218,219]
Nanomaterial Integration	Advances with hydrophilic nanomaterials improve fouling resistance but require further research on interactions with MPs.	Potential to enhance membrane performance but requires validation	[219]
Self-Cleaning Technologies	Photocatalytic membranes can reduce chemical cleaning needs, but effectiveness varies based on conditions.	Promises reduced maintenance and improved sustainability.	[224–227]

6. Future Perspectives and Research Directions

Future research on membrane-based microplastic separation should focus on quantifying how emerging membrane materials and surface-engineered structures alter size-selective retention, particle–surface interactions, and shear-induced fragmentation of microplastics under realistic hydraulic and cleaning conditions, rather than on generalized performance enhancements. Nanomaterials like graphene oxide, MOFs, and zwitterionic polymers will be used in next-generation membranes to enhance their permeability, selectivity, and antifouling capabilities.

Future membrane systems will be developed to recover valuable resources, such as clean water, biogas, nutrients (N, P), and maybe MPs, improving their environmental impact and economic worth. Closed-loop wastewater valorization will be made possible by MBRs, which will establish treatment facilities as centers for material and energy recovery. Predictive maintenance, real-time optimization, and less chemical cleaning will be made possible by artificial intelligence and Internet of Things-enabled monitoring devices. By simulating system behavior under changing circumstances, digital twins can increase long-term efficiency and lower operational uncertainty.

Water treatment in isolated, resource-constrained, or disaster-prone places will be supported by modular and decentralized membrane systems.

7. Conclusions

This review discusses the growing importance of advanced membrane technologies in addressing the challenge of removing and recovering microplastics and emerging contaminants from wastewater. This study reveals that while conventional systems like ultrafiltration, nanofiltration, reverse osmosis, and membrane bioreactors offer high removal efficiencies, their widespread application is still hindered by membrane fouling, energy demands, and economic constraints. Innovative approaches such as nanocomposite membranes, antifouling surface treatments, and integrated hybrid systems show promise in overcoming these limitations. Furthermore, combining membrane processes with adsorption, enzymatic treatments, or advanced oxidation processes can significantly improve treatment outcomes.

Future research should focus on enhancing membrane durability, developing low-energy systems, and optimizing modular configurations for both centralized and decentralized applications. The adoption of smart technologies, such as AI-based monitoring and responsive membranes, will be critical in managing complex and variable wastewater streams. Additionally, integrating resource recovery like extracting nutrients or biogas into membrane systems aligns with circular economic principles, enhancing both environmental sustainability and economic viability. Overall, advanced membranes represent a transformative path toward sustainable, resilient, and efficient wastewater management capable of meeting future global water quality challenges.

Author Contributions: Conceptualization, M.Y.D.A.; Methodology, Y.T.; Writing—original draft, Y.T.; Writing—review and editing, T.M.A.-Z.; Visualization and Tables/Figures, S.A.; Supervision and Scientific Design, M.J.K.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: All data generated or analyzed during this study are included in this published article.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

A^2O	Anaerobic-Anoxic-Aerobic	PC	Polycarbonate
Al_2O_3	Alumina	PCBs	Polychlorinated Biphenyls
BOD	Biochemical Oxygen Demand	PE	Polyethylene
CA	Cellulose Acetate	PEI	Polyetherimide
CAS	Conventional Activated Sludge	PES	Polymeric Polyester
COD	Chemical Oxygen Demand	PET	Polyethylene Terephthalate
DF	Dis-Filter	PFAS	Polyfluoroalkyl Substances
ECs	Emerging Contaminants	PP	Polypropylene
EVOH	Ethylene Vinyl Alcohol	PS	Polystyrene
FRR	Flow Recovery Ratio	PSF	Polysulfone
FTIR	Fourier-Transform Infrared Spectroscopy	PTFE	Polytetrafluoroethylene
GAC	Granular Activated Carbon	PUR	Polyurethane
HDPE	High-Density Polyethylene	PVA	Polyvinyl alcohol
LDPE	Low-Density Polyethylene	PVC	polyvinyl chloride
MBR	Membrane Bioreactor	PVDF	Polyvinylidene Fluoride
MF	Microfiltration	RO	Reverse Osmosis
MLSS	Mixed Liquid Suspended Solids	RSF	Rapid Sand Filtration
MPs	Microplastics	SiC	Silicon Carbide
MT	Metric Tons	SiO_2	Silica
NF	Nanofiltration	TFNs	Thin-Film Nanocomposites
NP	Nanoplastic	TiO_2	Titania
PA	Polyamide	TMP	Transmembrane Pressure
Pac	Polyacetylene	UF	Ultrafiltration
PAMs	Polyacrylamide	USAMe	Ultrasound–Adsorption–Membrane Filtration
PAN	Polyacrylonitrile	UV	Ultraviolet
PBDEs	Polybrominated Diphenyl Ethers	WWTPs	Wastewater Treatment Plants
PBT	Polybutylene Terephthalate	ZrO_2	Zirconia

References

1. Bachi, O.E.; Halilat, M.T.; Bissati, S.; Al-Ansari, N.; Saggai, S.; Kouadri, S.; Najm, H.M. Wastewater Treatment Performance of Aerated Lagoons, Activated Sludge and Constructed Wetlands under an Arid Algerian Climate. *Sustainability* **2022**, *14*, 16503. [CrossRef]
2. Tayeh, Y.A.; Alazaiza, M.Y.D.; Alzghoul, T.M.; Bashir, M.J. A Comprehensive Review of RO Membrane Fouling: Mechanisms, Categories, Cleaning Methods and Pretreatment Technologies. *J. Hazard. Mater. Adv.* **2025**, *18*, 100684. [CrossRef]
3. Cherian, T.; Ragavendran, C.; Vijayan, S.; Kurien, S.; Peijnenburg, W.J.G.M. A Review on the Fate, Human Health and Environmental Impacts, as Well as Regulation of Antibiotics Used in Aquaculture. *Environ. Adv.* **2023**, *13*, 100411. [CrossRef]
4. Edo, C.; González-Pleiter, M.; Leganés, F.; Fernández-Piñas, F.; Rosal, R. Fate of Microplastics in Wastewater Treatment Plants and Their Environmental Dispersion with Effluent and Sludge. *Environ. Pollut.* **2020**, *259*, 113837. [CrossRef]
5. Simon, M.; van Alst, N.; Vollertsen, J. Quantification of Microplastic Mass and Removal Rates at Wastewater Treatment Plants Applying Focal Plane Array (FPA)-Based Fourier Transform Infrared (FT-IR) Imaging. *Water Res.* **2018**, *142*, 1–9. [CrossRef]
6. Ziajahromi, S.; Neale, P.A.; Rintoul, L.; Leusch, F.D.L. Wastewater Treatment Plants as a Pathway for Microplastics: Development of a New Approach to Sample Wastewater-Based Microplastics. *Water Res.* **2017**, *112*, 93–99. [CrossRef]
7. Rodrigues dos Santos, C.; Pinheiro Drumond, G.; Rezende Moreira, V.; Valéria de Souza Santos, L.; Cristina Santos Amaral, M. Microplastics in Surface Water: Occurrence, Ecological Implications, Quantification Methods and Remediation Technologies. *Chem. Eng. J.* **2023**, *474*, 144936. [CrossRef]
8. Sarker, A.; Deepo, D.M.; Nandi, R.; Rana, J.; Islam, S.; Rahman, S.; Hossain, M.N.; Islam, M.S.; Baroi, A.; Kim, J.-E. A Review of Microplastics Pollution in the Soil and Terrestrial Ecosystems: A Global and Bangladesh Perspective. *Sci. Total Environ.* **2020**, *733*, 139296. [CrossRef]
9. Derraik, J.G. The Pollution of the Marine Environment by Plastic Debris: A Review. *Mar. Pollut. Bull.* **2002**, *44*, 842–852. [CrossRef] [PubMed]
10. Napper, I.E.; Wright, L.S.; Barrett, A.C.; Parker-Jurd, F.N.F.; Thompson, R.C. Potential Microplastic Release from the Maritime Industry: Abrasion of Rope. *Sci. Total Environ.* **2022**, *804*, 150155. [CrossRef]

11. Acarer, S. Microplastics in Wastewater Treatment Plants: Sources, Properties, Removal Efficiency, Removal Mechanisms, and Interactions with Pollutants. *Water Sci. Technol.* **2023**, *87*, 685–710. [CrossRef]
12. MacLeod, M.; Arp, H.P.H.; Tekman, M.B.; Jahnke, A. The Global Threat from Plastic Pollution. *Science* **2021**, *373*, 61–65. [CrossRef] [PubMed]
13. Kabir, M.S.; Wang, H.; Luster-Teasley, S.; Zhang, L.; Zhao, R. Microplastics in Landfill Leachate: Sources, Detection, Occurrence, and Removal. *Environ. Sci. Ecotechnol.* **2023**, *16*, 100256. [CrossRef] [PubMed]
14. Shen, M.; Xiong, W.; Song, B.; Zhou, C.; Almatrafi, E.; Zeng, G.; Zhang, Y. Microplastics in Landfill and Leachate: Occurrence, Environmental Behavior and Removal Strategies. *Chemosphere* **2022**, *305*, 135325. [CrossRef]
15. Rossatto, A.; Arlindo, M.Z.F.; de Morais, M.S.; de Souza, T.D.; Ogrodowski, C.S. Microplastics in Aquatic Systems: A Review of Occurrence, Monitoring and Potential Environmental Risks. *Environ. Adv.* **2023**, *13*, 100396. [CrossRef]
16. Nunes, B.Z.; Huang, Y.; Ribeiro, V.V.; Wu, S.; Holbech, H.; Moreira, L.B.; Xu, E.G.; Castro, I.B. Microplastic Contamination in Seawater across Global Marine Protected Areas Boundaries. *Environ. Pollut.* **2023**, *316*, 120692. [CrossRef]
17. Mintenig, S.M.; Löder, M.G.J.; Primpke, S.; Gerdts, G. Low Numbers of Microplastics Detected in Drinking Water from Ground Water Sources. *Sci. Total Environ.* **2019**, *648*, 631–635. [CrossRef] [PubMed]
18. Muhib, M.I.; Uddin, M.K.; Rahman, M.M.; Malafaia, G. Occurrence of Microplastics in Tap and Bottled Water, and Food Packaging: A Narrative Review on Current Knowledge. *Sci. Total Environ.* **2023**, *865*, 161274. [CrossRef]
19. Samandra, S.; Johnston, J.M.; Jaeger, J.E.; Symons, B.; Xie, S.; Currell, M.; Ellis, A.V.; Clarke, B.O. Microplastic Contamination of an Unconfined Groundwater Aquifer in Victoria, Australia. *Sci. Total Environ.* **2022**, *802*, 149727. [CrossRef]
20. Tong, H.; Jiang, Q.; Hu, X.; Zhong, X. Occurrence and Identification of Microplastics in Tap Water from China. *Chemosphere* **2020**, *252*, 126493. [CrossRef]
21. Mason, S.A.; Welch, V.G.; Neratko, J. Synthetic Polymer Contamination in Bottled Water. *Front. Chem.* **2018**, *6*, 407. [CrossRef] [PubMed]
22. Dris, R.; Gasperi, J.; Saad, M.; Mirande, C.; Tassin, B. Synthetic Fibers in Atmospheric Fallout: A Source of Microplastics in the Environment? *Mar. Pollut. Bull.* **2016**, *104*, 290–293. [CrossRef]
23. Renzi, M.; Guerranti, C.; Blašković, A. Microplastic Contents from Maricultured and Natural Mussels. *Mar. Pollut. Bull.* **2018**, *131*, 248–251. [CrossRef]
24. Hossain, N.; Bhuiyan, M.A.; Pramanik, B.K.; Nizamuddin, S.; Griffin, G. Waste Materials for Wastewater Treatment and Waste Adsorbents for Biofuel and Cement Supplement Applications: A Critical Review. *J. Clean. Prod.* **2020**, *255*, 120261. [CrossRef]
25. Frias, J.; Pagter, E.; Nash, R.; O'Connor, I.; Carretero, O.; Filgueiras, A.; Viñas, L.; Gago, J.; Antunes, J.; Bessa, F.; et al. *Standardised Protocol for Monitoring Microplastics in Sediments; WP4 Deliverable D4.2*; JPI-Oceans: Bruxelles, Belgium, 2018. [CrossRef]
26. Koelmans, A.A.; Mohamed Nor, N.H.; Hermsen, E.; Kooi, M.; Mintenig, S.M.; De France, J. Microplastics in Freshwaters and Drinking Water: Critical Review and Assessment of Data Quality. *Water Res.* **2019**, *155*, 410–422. [CrossRef]
27. Niccolai, E.; Colzi, I.; Amedei, A. Adverse Effects of Micro- and Nanoplastics on Humans and the Environment. *Int. J. Mol. Sci.* **2023**, *24*, 15822. [CrossRef]
28. Yee, M.S.-L.; Hii, L.-W.; Looi, C.K.; Lim, W.-M.; Wong, S.-F.; Kok, Y.-Y.; Tan, B.-K.; Wong, C.-Y.; Leong, C.-O. Impact of Microplastics and Nanoplastics on Human Health. *Nanomaterials* **2021**, *11*, 496. [CrossRef]
29. Nugnes, R.; Lavorgna, M.; Orlo, E.; Russo, C.; Isidori, M. Toxic Impact of Polystyrene Microplastic Particles in Freshwater Organisms. *Chemosphere* **2022**, *299*, 134373. [CrossRef] [PubMed]
30. Lee, J.-H.; Kang, J.-C.; Kim, J.-H. Toxic Effects of Microplastic (Polyethylene) on Fish: Accumulation, Hematological Parameters and Antioxidant Responses in Korean Bullhead, Pseudobagrus Fulvidraco. *Sci. Total Environ.* **2023**, *877*, 162874. [CrossRef]
31. Woods, M.N.; Stack, M.E.; Fields, D.M.; Shaw, S.D.; Matrai, P.A. Microplastic Fiber Uptake, Ingestion, and Egestion Rates in the Blue Mussel (*Mytilus edulis*). *Mar. Pollut. Bull.* **2018**, *137*, 638–645. [CrossRef]
32. Choi, J.S.; Jung, Y.-J.; Hong, N.-H.; Hong, S.H.; Park, J.-W. Toxicological Effects of Irregularly Shaped and Spherical Microplastics in a Marine Teleost, the Sheepshead Minnow (*Cyprinodon variegatus*). *Mar. Pollut. Bull.* **2018**, *129*, 231–240. [CrossRef] [PubMed]
33. Leung, J.; Chan, K.Y.K. Microplastics Reduced Posterior Segment Regeneration Rate of the Polychaete Perinereis Aibuhitensis. *Mar. Pollut. Bull.* **2018**, *129*, 782–786. [CrossRef] [PubMed]
34. Rist, S.; Baun, A.; Almeda, R.; Hartmann, N.B. Ingestion and Effects of Micro- and Nanoplastics in Blue Mussel (*Mytilus edulis*) Larvae. *Mar. Pollut. Bull.* **2019**, *140*, 423–430. [CrossRef]
35. Yang, X.; Xu, X.; Zhou, Y.; Yao, Y.; Shen, C.; Liu, J. Longitudinal and Vertical Distribution of Microplastics in Various Pipe Scales in an Operating Drinking Water Distribution System. *J. Hazard. Mater.* **2023**, *459*, 132108. [CrossRef]
36. Chen, Q.; Gao, J.; Yu, H.; Su, H.; Yang, Y.; Cao, Y.; Zhang, Q.; Ren, Y.; Hollert, H.; Shi, H.; et al. An Emerging Role of Microplastics in the Etiology of Lung Ground Glass Nodules. *Environ. Sci. Eur.* **2022**, *34*, 25. [CrossRef]
37. Blackburn, K.; Green, D. The Potential Effects of Microplastics on Human Health: What Is Known and What Is Unknown. *Ambio* **2022**, *51*, 518–530. [CrossRef]

38. Enfrin, M.; Dumée, L.F.; Lee, J. Nano/Microplastics in Water and Wastewater Treatment Processes—Origin, Impact and Potential Solutions. *Water Res.* **2019**, *161*, 621–638. [CrossRef]
39. Xiong, X.; Bond, T.; Saboor Siddique, M.; Yu, W. The Stimulation of Microbial Activity by Microplastic Contributes to Membrane Fouling in Ultrafiltration. *J. Memb. Sci.* **2021**, *635*, 119477. [CrossRef]
40. Luo, Y.; Le-Clech, P.; Henderson, R.K. Assessing the Performance of Membrane Photobioreactors (MPBR) for Polishing Effluents Containing Different Types of Nitrogen. *Algal Res.* **2020**, *50*, 102013. [CrossRef]
41. Peng, Y.-Y.; Gao, F.; Yang, H.-L.; Wu, H.-W.-J.; Li, C.; Lu, M.-M.; Yang, Z.-Y. Simultaneous Removal of Nutrient and Sulfonamides from Marine Aquaculture Wastewater by Concentrated and Attached Cultivation of Chlorella Vulgaris in an Algal Biofilm Membrane Photobioreactor (BF-MPBR). *Sci. Total Environ.* **2020**, *725*, 138524. [CrossRef]
42. Feng, T.; Wang, B.; Li, J.; Wang, T.; Huang, P.; Xu, X. Metal–Organic Framework Based Photocatalytic Membrane for Organic Wastewater Treatment: Preparation, Optimization, and Applications. *Sep. Purif. Technol.* **2025**, *355*, 129540. [CrossRef]
43. Aditya, L.; Vu, H.P.; Nguyen, L.N.; Mahlia, T.M.I.; Hoang, N.B.; Nghiem, L.D. Microalgae Enrichment for Biomass Harvesting and Water Reuse by Ceramic Microfiltration Membranes. *J. Memb. Sci.* **2023**, *669*, 121287. [CrossRef]
44. Castro-Muñoz, R.; García-Depraect, O. Membrane-Based Harvesting Processes for Microalgae and Their Valuable-Related Molecules: A Review. *Membranes* **2021**, *11*, 585. [CrossRef]
45. Hashmi, Z.; Idriss, I.M.; Zaini, J.; Abu Bakar, M.S.; Wibisono, Y.; Abdullah, R.; Bilad, M.R. Advancements in Membrane Modifications for Enhanced Microalgae Harvesting: A Comprehensive Review. *Sep. Purif. Technol.* **2025**, *360*, 131012. [CrossRef]
46. Cosenza, A.; Gulhan, H.; Maida, C.M.; Mannina, G. Nutrient Recovery from Wastewater Treatment by Ultrafiltration Membrane for Water Reuse in View of a Circular Economy Perspective. *Bioresour. Technol.* **2022**, *363*, 127929. [CrossRef] [PubMed]
47. Lai, H.; Liu, X.; Qu, M. Nanoplastics and Human Health: Hazard Identification and Biointerface. *Nanomaterials* **2022**, *12*, 1298. [CrossRef] [PubMed]
48. Wang, J.; Peng, J.; Tan, Z.; Gao, Y.; Zhan, Z.; Chen, Q.; Cai, L. Microplastics in the Surface Sediments from the Beijiang River Littoral Zone: Composition, Abundance, Surface Textures and Interaction with Heavy Metals. *Chemosphere* **2017**, *171*, 248–258. [CrossRef]
49. Alibade, A.; Lakka, A.; Bozinou, E.; Lalas, S.I.; Chatzilazarou, A.; Makris, D.P. Development of a Green Methodology for Simultaneous Extraction of Polyphenols and Pigments from Red Winemaking Solid Wastes (Pomace) Using a Novel Glycerol-Sodium Benzoate Deep Eutectic Solvent and Ultrasonication Pretreatment. *Environments* **2021**, *8*, 90. [CrossRef]
50. Lamichhane, G.; Acharya, A.; Marahatha, R.; Modi, B.; Paudel, R.; Adhikari, A.; Raut, B.K.; Aryal, S.; Parajuli, N. Microplastics in Environment: Global Concern, Challenges, and Controlling Measures. *Int. J. Environ. Sci. Technol.* **2023**, *20*, 4673–4694. [CrossRef]
51. Lambert, S.; Sinclair, C.; Boxall, A. Occurrence, Degradation, and Effect of Polymer-Based Materials in the Environment. In *Reviews of Environmental Contamination and Toxicology*; Springer: Berlin/Heidelberg, Germany, 2014; Volume 227, pp. 1–53.
52. Anderson, A. Sources, Fate and Effects of Microplastics in the Marine Environment: A Global Assessment: GESAMP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection. GESAMP Reports Stusies Serie. 2015, p. 220. Available online: https://www.gesamp.org/site/assets/files/1275/sources-fate-and-effects-of-microplastics-in-the-marine-environment-part-2-of-a-global-assessment-en.pdf (accessed on 20 January 2026).
53. Kershaw, P.; Turra, A.; Galgani, F. Guidelines for the Monitoring and Assessment of Plastic Litter and Microplastics in the Ocean. 2019. Available online: https://www.gesamp.org/site/assets/files/2002/rs99e.pdf (accessed on 1 February 2026).
54. Jiang, J.-Q. Occurrence of Microplastics and Its Pollution in the Environment: A Review. *Sustain. Prod. Consum.* **2018**, *13*, 16–23. [CrossRef]
55. Kunz, A. Microplastic Research in Taiwan. 2020. Available online: https://microplasticresearch.wordpress.com/ (accessed on 22 January 2026).
56. Zaidi, N.; Mir, M.A.; Chang, S.K.; Abdelli, N.; Hasnain, S.M.; Ali Khan, M.A.; Andrews, K. Pharmaceuticals and Personal Care Products as Emerging Contaminants: Environmental Fate, Detection, and Mitigation Strategies. *Int. J. Environ. Anal. Chem.* **2025**, *105*, 8837–8865. [CrossRef]
57. Morin-Crini, N.; Lichtfouse, E.; Fourmentin, M.; Ribeiro, A.R.L.; Noutsopoulos, C.; Mapelli, F.; Fenyvesi, É.; Vieira, M.G.A.; Picos-Corrales, L.A.; Moreno-Piraján, J.C.; et al. Removal of Emerging Contaminants from Wastewater Using Advanced Treatments. A Review. *Environ. Chem. Lett.* **2022**, *20*, 1333–1375. [CrossRef]
58. Alazaiza, M.Y.D.; Alzghoul, T.M.; Ramu, M.B.; Abu Amr, S.S.; Abushammala, M.F.M. PFAS Contamination and Mitigation: A Comprehensive Analysis of Research Trends and Global Contributions. *Case Stud. Chem. Environ. Eng.* **2025**, *11*, 101127. [CrossRef]
59. Zhang, H.; Shen, N.; Li, Y.; Hu, C.; Yuan, P. Source, Transport, and Toxicity of Emerging Contaminants in Aquatic Environments: A Review on Recent Studies. *Environ. Sci. Pollut. Res.* **2023**, *30*, 121420–121437. [CrossRef]
60. Tisler, S.; Christensen, J.H. Non-Target Screening for the Identification of Migrating Compounds from Reusable Plastic Bottles into Drinking Water. *J. Hazard. Mater.* **2022**, *429*, 128331. [CrossRef]
61. Andrady, A.L. Microplastics in the Marine Environment. *Mar. Pollut. Bull.* **2011**, *62*, 1596–1605. [CrossRef]

62. Isobe, A.; Kubo, K.; Tamura, Y.; Kako, S.; Nakashima, E.; Fujii, N. Selective Transport of Microplastics and Mesoplastics by Drifting in Coastal Waters. *Mar. Pollut. Bull.* **2014**, *89*, 324–330. [CrossRef]
63. SpecialChem Density of Plastics: Technical Properties. *Omnexus*. Available online: https://omnexus.specialchem.com/polymer-property/density (accessed on 22 January 2026).
64. Zhang, Y.; Jiang, H.; Bian, K.; Wang, H.; Wang, C. Is Froth Flotation a Potential Scheme for Microplastics Removal? Analysis on Flotation Kinetics and Surface Characteristics. *Sci. Total Environ.* **2021**, *792*, 148345. [CrossRef] [PubMed]
65. Zhang, W.; Zhang, S.; Wang, J.; Wang, Y.; Mu, J.; Wang, P.; Lin, X.; Ma, D. Microplastic Pollution in the Surface Waters of the Bohai Sea, China. *Environ. Pollut.* **2017**, *231*, 541–548. [CrossRef] [PubMed]
66. Johansen, M.P.; Prentice, E.; Cresswell, T.; Howell, N. Initial Data on Adsorption of Cs and Sr to the Surfaces of Microplastics with Biofilm. *J. Environ. Radioact.* **2018**, *190–191*, 130–133. [CrossRef] [PubMed]
67. Sagawa, N.; Kawaai, K.; Hinata, H. Abundance and Size of Microplastics in a Coastal Sea: Comparison among Bottom Sediment, Beach Sediment, and Surface Water. *Mar. Pollut. Bull.* **2018**, *133*, 532–542. [CrossRef]
68. Wilkinson, J.L.; Hooda, P.S.; Barker, J.; Barton, S.; Swinden, J. Ecotoxic Pharmaceuticals, Personal Care Products, and Other Emerging Contaminants: A Review of Environmental, Receptor-Mediated, Developmental, and Epigenetic Toxicity with Discussion of Proposed Toxicity to Humans. *Crit. Rev. Environ. Sci. Technol.* **2016**, *46*, 336–381. [CrossRef]
69. Wang, H.; Gao, X.; Zuo, Y. Research and Application of Water Treatment Technologies for Emerging Contaminants (ECs): A Pathway to Solving Water Environment Challenges. *Water* **2024**, *16*, 1837. [CrossRef]
70. Sanusi, I.O.; Olutona, G.O.; Wawata, I.G.; Onohuean, H. Occurrence, Environmental Impact and Fate of Pharmaceuticals in Groundwater and Surface Water: A Critical Review. *Environ. Sci. Pollut. Res.* **2023**, *30*, 90595–90614. [CrossRef]
71. Nel, H.A.; Dalu, T.; Wasserman, R.J. Sinks and Sources: Assessing Microplastic Abundance in River Sediment and Deposit Feeders in an Austral Temperate Urban River System. *Sci. Total Environ.* **2018**, *612*, 950–956. [CrossRef]
72. Auta, H.S.; Emenike, C..; Fauziah, S. Distribution and Importance of Microplastics in the Marine Environment: A Review of the Sources, Fate, Effects, and Potential Solutions. *Environ. Int.* **2017**, *102*, 165–176. [CrossRef] [PubMed]
73. Horton, A.A.; Walton, A.; Spurgeon, D.J.; Lahive, E.; Svendsen, C. Microplastics in Freshwater and Terrestrial Environments: Evaluating the Current Understanding to Identify the Knowledge Gaps and Future Research Priorities. *Sci. Total Environ.* **2017**, *586*, 127–141. [CrossRef]
74. Bayo, J.; Olmos, S.; López-Castellanos, J. Microplastics in an Urban Wastewater Treatment Plant: The Influence of Physicochemical Parameters and Environmental Factors. *Chemosphere* **2020**, *238*, 124593. [CrossRef]
75. Cheung, P.K.; Fok, L. Characterisation of Plastic Microbeads in Facial Scrubs and Their Estimated Emissions in Mainland China. *Water Res.* **2017**, *122*, 53–61. [CrossRef]
76. Jujun, R.; Jia, L.; Zhenming, X. Improvements of the Recovery Line of Waste Toner Cartridges on Environmental and Safety Performances. *Environ. Sci. Technol.* **2013**, *47*, 6457–6462. [CrossRef] [PubMed]
77. Anagnosti, L.; Varvaresou, A.; Pavlou, P.; Protopapa, E.; Carayanni, V. Worldwide Actions against Plastic Pollution from Microbeads and Microplastics in Cosmetics Focusing on European Policies. Has the Issue Been Handled Effectively? *Mar. Pollut. Bull.* **2021**, *162*, 111883. [CrossRef]
78. Fok, L.; Cheung, P.K. Hong Kong at the Pearl River Estuary: A Hotspot of Microplastic Pollution. *Mar. Pollut. Bull.* **2015**, *99*, 112–118. [CrossRef]
79. Schöpel, B.; Stamminger, R. A Comprehensive Literature Study on Microfibres from Washing Machines. *Tenside Surfactants Deterg.* **2019**, *56*, 94–104. [CrossRef]
80. Vassilenko, E.; Watkins, M.; Chastain, S.; Mertens, J.; Posacka, A.M.; Patankar, S.; Ross, P.S. Domestic Laundry and Microfiber Pollution: Exploring Fiber Shedding from Consumer Apparel Textiles. *PLoS ONE* **2021**, *16*, e0250346. [CrossRef]
81. Özkan, İ.; Gündoğdu, S. Investigation on the Microfiber Release under Controlled Washings from the Knitted Fabrics Produced by Recycled and Virgin Polyester Yarns. *J. Text. Inst.* **2021**, *112*, 264–272. [CrossRef]
82. De Falco, F.; Di Pace, E.; Cocca, M.; Avella, M. The Contribution of Washing Processes of Synthetic Clothes to Microplastic Pollution. *Sci. Rep.* **2019**, *9*, 6633. [CrossRef] [PubMed]
83. Šaravanja, A.; Pušić, T.; Dekanić, T. Microplastics in Wastewater by Washing Polyester Fabrics. *Materials* **2022**, *15*, 2683. [CrossRef]
84. Periyasamy, A.P.; Tehrani-Bagha, A. A Review on Microplastic Emission from Textile Materials and Its Reduction Techniques. *Polym. Degrad. Stab.* **2022**, *199*, 109901. [CrossRef]
85. Clurman, A.M.; Rodríguez-Narvaez, O.M.; Jayarathne, A.; De Silva, G.; Ranasinghe, M.I.; Goonetilleke, A.; Bandala, E.R. Influence of Surface Hydrophobicity/Hydrophilicity of Biochar on the Removal of Emerging Contaminants. *Chem. Eng. J.* **2020**, *402*, 126277. [CrossRef]
86. Ahmad, N.; Ahmed, S.; Vambol, V.; Vambol, S. Treatment of Drug Residues (Emerging Contaminants) in Hospital Effluent by the Combination of Biological and Physiochemical Treatment Process: A Review. *Front. Eng. Built Environ.* **2021**, *1*, 1–13. [CrossRef]
87. Nawalage, N.S.K.; Bellanthudawa, B.K.A. Synthetic Polymers in Personal Care and Cosmetics Products (PCCPs) as a Source of Microplastic (MP) Pollution. *Mar. Pollut. Bull.* **2022**, *182*, 113927. [CrossRef]

88. Santos, V.S.; Anjos, J.S.X.; de Medeiros, J.F.; Montagner, C.C. Impact of Agricultural Runoff and Domestic Sewage Discharge on the Spatial–Temporal Occurrence of Emerging Contaminants in an Urban Stream in São Paulo, Brazil. *Environ. Monit. Assess.* **2022**, *194*, 637. [CrossRef]
89. Dsikowitzky, L.; Schwarzbauer, J. Industrial Organic Contaminants: Identification, Toxicity and Fate in the Environment. *Environ. Chem. Lett.* **2014**, *12*, 371–386. [CrossRef]
90. Wu, Y.; Jin, R.; Chen, Q.; Du, X.; Yang, J.; Liu, M. Organic Contaminants of Emerging Concern in Global Estuaries: Environmental Occurrence, Fate, and Bioavailability. *Crit. Rev. Environ. Sci. Technol.* **2023**, *53*, 550–575. [CrossRef]
91. Kole, P.J.; Löhr, A.J.; Van Belleghem, F.; Ragas, A. Wear and Tear of Tyres: A Stealthy Source of Microplastics in the Environment. *Int. J. Environ. Res. Public Health* **2017**, *14*, 1265. [CrossRef]
92. Burns, E.E.; Boxall, A.B.A. Microplastics in the Aquatic Environment: Evidence for or against Adverse Impacts and Major Knowledge Gaps. *Environ. Toxicol. Chem.* **2018**, *37*, 2776–2796. [CrossRef] [PubMed]
93. Bond, T.; Ferrandiz-Mas, V.; Felipe-Sotelo, M.; van Sebille, E. The Occurrence and Degradation of Aquatic Plastic Litter Based on Polymer Physicochemical Properties: A Review. *Crit. Rev. Environ. Sci. Technol.* **2018**, *48*, 685–722. [CrossRef]
94. Solayman, H.M.; Robby, M.D.A.; Satriaji, F.V.; Hossain, M.K.; Kang, K.; Abd Aziz, A.; Shiu, R.F.; Jiang, J.J. Mapping global microplastic pollution: Integrating advanced detection and monitoring in aquatic ecosystems. *Mar. Pollut. Bull.* **2026**, *222*, 118685. [CrossRef] [PubMed]
95. Verran, J.; Boyd, R.D. The Relationship between Substratum Surface Roughness and Microbiological and Organic Soiling: A Review. *Biofouling* **2001**, *17*, 59–71. [CrossRef]
96. Gao, S.; Orlowski, N.; Bopf, F.K.; Breuer, L. A Review on Microplastics in Major European Rivers. *WIREs Water* **2024**, *11*, e1713. [CrossRef]
97. Zhang, J.; Yu, Z. Transgenerational Effects of Different Sequential Exposure to 2,2′,4,4′-Tetra-Brominated Diphenyl Ether (BDE47) and Lead (Pb) on Caenorhabditis Elegans. *Environ. Sci. Eur.* **2020**, *32*, 44. [CrossRef]
98. Miranda-Peña, L.; Buitrago-Duque, L.; Rangel-Buitrago, N.; Gracia, C.A.; Arana, V.A.; Trilleras, J. Geographical Heterogeneity and Dominant Polymer Types in Microplastic Contamination of Lentic Ecosystems: Implications for Methodological Standardization and Future Research. *RSC Adv.* **2023**, *13*, 27190–27202. [CrossRef] [PubMed]
99. Erni-Cassola, G.; Zadjelovic, V.; Gibson, M.I.; Christie-Oleza, J.A. Distribution of Plastic Polymer Types in the Marine Environment; A Meta-Analysis. *J. Hazard. Mater.* **2019**, *369*, 691–698. [CrossRef] [PubMed]
100. Koelmans, A.A.; Redondo-Hasselerharm, P.E.; Nor, N.H.M.; de Ruijter, V.N.; Mintenig, S.M.; Kooi, M. Risk Assessment of Microplastic Particles. *Nat. Rev. Mater.* **2022**, *7*, 138–152. [CrossRef]
101. Schwarz, A.E.; Ligthart, T.N.; Boukris, E.; van Harmelen, T. Sources, Transport, and Accumulation of Different Types of Plastic Litter in Aquatic Environments: A Review Study. *Mar. Pollut. Bull.* **2019**, *143*, 92–100. [CrossRef]
102. ter Halle, A.; Ladirat, L.; Martignac, M.; Mingotaud, A.F.; Boyron, O.; Perez, E. To What Extent Are Microplastics from the Open Ocean Weathered? *Environ. Pollut.* **2017**, *227*, 167–174. [CrossRef] [PubMed]
103. Lee, H.; Shim, W.J.; Kwon, J.-H. Sorption Capacity of Plastic Debris for Hydrophobic Organic Chemicals. *Sci. Total Environ.* **2014**, *470–471*, 1545–1552. [CrossRef]
104. Bayo, J.; López-Castellanos, J.; Olmos, S. Membrane Bioreactor and Rapid Sand Filtration for the Removal of Microplastics in an Urban Wastewater Treatment Plant. *Mar. Pollut. Bull.* **2020**, *156*, 111211. [CrossRef]
105. Almeida-Naranjo, C.E.; Guerrero, V.H.; Villamar-Ayala, C.A. Emerging Contaminants and Their Removal from Aqueous Media Using Conventional/Non-Conventional Adsorbents: A Glance at the Relationship between Materials, Processes, and Technologies. *Water* **2023**, *15*, 1626. [CrossRef]
106. Au, S.Y.; Bruce, T.F.; Bridges, W.C.; Klaine, S.J. Responses of Hyalella Azteca to Acute and Chronic Microplastic Exposures. *Environ. Toxicol. Chem.* **2015**, *34*, 2564–2572. [CrossRef]
107. Crawford, C.B.; Quinn, B. *Microplastic Pollutants*; Elsevier Limited: Amsterdam, The Netherlands, 2016.
108. Hüffer, T.; Weniger, A.-K.; Hofmann, T. Sorption of Organic Compounds by Aged Polystyrene Microplastic Particles. *Environ. Pollut.* **2018**, *236*, 218–225. [CrossRef]
109. Mueller, R.-J. Biological Degradation of Synthetic Polyesters—Enzymes as Potential Catalysts for Polyester Recycling. *Process Biochem.* **2006**, *41*, 2124–2128. [CrossRef]
110. Jumaah, O.S. Screening of Plastic Degrading Bacteria from Dumped Soil Area. *IOSR J. Environ. Sci. Toxicol. Food Technol.* **2017**, *11*, 93–98. [CrossRef]
111. Ren, L.; Men, L.; Zhang, Z.; Guan, F.; Tian, J.; Wang, B.; Wang, J.; Zhang, Y.; Zhang, W. Biodegradation of Polyethylene by Enterobacter Sp. D1 from the Guts of Wax Moth Galleria Mellonella. *Int. J. Environ. Res. Public Health* **2019**, *16*, 1941. [CrossRef]
112. Zhang, X.; Li, Y.; Ouyang, D.; Lei, J.; Tan, Q.; Xie, L.; Li, Z.; Liu, T.; Xiao, Y.; Farooq, T.H.; et al. Systematical Review of Interactions between Microplastics and Microorganisms in the Soil Environment. *J. Hazard. Mater.* **2021**, *418*, 126288. [CrossRef]
113. Artham, T.; Doble, M. Biodegradation of Aliphatic and Aromatic Polycarbonates. *Macromol. Biosci.* **2008**, *8*, 14–24. [CrossRef] [PubMed]

114. Werber, J.R.; Osuji, C.O.; Elimelech, M. Materials for Next-Generation Desalination and Water Purification Membranes. *Nat. Rev. Mater.* **2016**, *1*, 16018. [CrossRef]
115. Yan, H.; Lai, C.; Wang, D.; Liu, S.; Li, X.; Zhou, X.; Yi, H.; Li, B.; Zhang, M.; Li, L.; et al. In Situ Chemical Oxidation: Peroxide or Persulfate Coupled with Membrane Technology for Wastewater Treatment. *J. Mater. Chem. A* **2021**, *9*, 11944–11960. [CrossRef]
116. Algieri, C.; Chakraborty, S.; Pal, U. Efficacy of Phase Inversion Technique for Polymeric Membrane Fabrication. *J. Phase Chang. Mater.* **2021**, *17*, 445–456.
117. Kayvani Fard, A.; McKay, G.; Buekenhoudt, A.; Al Sulaiti, H.; Motmans, F.; Khraisheh, M.; Atieh, M. Inorganic Membranes: Preparation and Application for Water Treatment and Desalination. *Materials* **2018**, *11*, 74. [CrossRef]
118. Carnesi, M.; Mineo, A.; Amata, S.; Piccionello, A.P.; Rizzo, C.; Mannina, G. Emerging Contaminants in Wastewater Treatment: The Effect of Microplastics in an Integrated Fixed-Film Activated Sludge (IFAS) Membrane BioReactor (MBR). *Bioresour. Technol. Rep.* **2025**, *32*, 102374. [CrossRef]
119. Kang, Y.; Jang, J.; Kim, S.; Lim, J.; Lee, Y.; Kim, I.S. PIP/TMC Interfacial Polymerization with Electrospray: Novel Loose Nanofiltration Membrane for Dye Wastewater Treatment. *ACS Appl. Mater. Interfaces* **2020**, *12*, 36148–36158. [CrossRef] [PubMed]
120. Theodorakopoulos, G.V.; Arfanis, M.K.; Sánchez Pérez, J.A.; Agüera, A.; Cadena Aponte, F.X.; Markellou, E.; Romanos, G.E.; Falaras, P. Novel Pilot-Scale Photocatalytic Nanofiltration Reactor for Agricultural Wastewater Treatment. *Membranes* **2023**, *13*, 202. [CrossRef]
121. Abid, M.F.; Zablouk, M.A.; Abid-Alameer, A.M. Experimental Study of Dye Removal from Industrial Wastewater by Membrane Technologies of Reverse Osmosis and Nanofiltration. *Iran. J. Environ. Health Sci. Eng.* **2012**, *9*, 17. [CrossRef]
122. Zhang, H.; Mao, H.; Wang, J.; Ding, R.; Du, Z.; Liu, J.; Cao, S. Mineralization-Inspired Preparation of Composite Membranes with Polyethyleneimine–Nanoparticle Hybrid Active Layer for Solvent Resistant Nanofiltration. *J. Memb. Sci.* **2014**, *470*, 70–79. [CrossRef]
123. Figoli, A.; Marino, T.; Simone, S.; Di Nicolò, E.; Li, X.-M.; He, T.; Tornaghi, S.; Drioli, E. Towards Non-Toxic Solvents for Membrane Preparation: A Review. *Green Chem.* **2014**, *16*, 4034. [CrossRef]
124. Karimi, A.; Khataee, A.; Vatanpour, V.; Safarpour, M. High-Flux PVDF Mixed Matrix Membranes Embedded with Size-Controlled ZIF-8 Nanoparticles. *Sep. Purif. Technol.* **2019**, *229*, 115838. [CrossRef]
125. Hashmi, Z.; Fahrurrozi; Zaini, J.; Lim, J.W.; Abu Bakar, M.S.; Dani Nandiyanto, A.B.; Bilad, M.R. Current Progress on Filtration Techniques for Recovery of Microalgae-Based Products. In *Algal Bioreactors*; Elsevier: Amsterdam, The Netherlands, 2025; pp. 71–98.
126. Bilad, M.R.; Azizo, A.S.; Wirzal, M.D.H.; Jia Jia, L.; Putra, Z.A.; Nordin, N.A.H.M.; Mavukkandy, M.O.; Jasni, M.J.F.; Yusoff, A.R.M. Tackling Membrane Fouling in Microalgae Filtration Using Nylon 6,6 Nanofiber Membrane. *J. Environ. Manag.* **2018**, *223*, 23–28. [CrossRef]
127. Talvitie, J.; Mikola, A.; Koistinen, A.; Setälä, O. Solutions to Microplastic Pollution—Removal of Microplastics from Wastewater Effluent with Advanced Wastewater Treatment Technologies. *Water Res.* **2017**, *123*, 401–407. [CrossRef]
128. Ahmad, N.; Anae, J.; Khan, M.Z.; Sabir, S.; Yang, X.J.; Thakur, V.K.; Campo, P.; Coulon, F. Visible Light-Conducting Polymer Nanocomposites as Efficient Photocatalysts for the Treatment of Organic Pollutants in Wastewater. *J. Environ. Manag.* **2021**, *295*, 113362. [CrossRef]
129. Awad, E.S.; Sabirova, T.M.; Tretyakova, N.A.; Alsalhy, Q.F.; Figoli, A.; Salih, I.K. A Mini-Review of Enhancing Ultrafiltration Membranes (UF) for Wastewater Treatment: Performance and Stability. *ChemEngineering* **2021**, *5*, 34. [CrossRef]
130. Ma, B.; Xue, W.; Hu, C.; Liu, H.; Qu, J.; Li, L. Characteristics of Microplastic Removal via Coagulation and Ultrafiltration during Drinking Water Treatment. *Chem. Eng. J.* **2019**, *359*, 159–167. [CrossRef]
131. Korus, I.; Loska, K. Removal of Cr(III) and Cr(VI) Ions from Aqueous Solutions by Means of Polyelectrolyte-Enhanced Ultrafiltration. *Desalination* **2009**, *247*, 390–395. [CrossRef]
132. Muthumareeswaran, M.R.; Alhoshan, M.; Agarwal, G.P. Ultrafiltration Membrane for Effective Removal of Chromium Ions from Potable Water. *Sci. Rep.* **2017**, *7*, 41423. [CrossRef]
133. Tadsuwan, K.; Babel, S. Microplastic Abundance and Removal via an Ultrafiltration System Coupled to a Conventional Municipal Wastewater Treatment Plant in Thailand. *J. Environ. Chem. Eng.* **2022**, *10*, 107142. [CrossRef]
134. Fabris, R.; Lee, E.K.; Chow, C.W.K.; Chen, V.; Drikas, M. Pre-Treatments to Reduce Fouling of Low Pressure Micro-Filtration (MF) Membranes. *J. Memb. Sci.* **2007**, *289*, 231–240. [CrossRef]
135. Hakami, M.W.; Alkhudhiri, A.; Al-Batty, S.; Zacharof, M.-P.; Maddy, J.; Hilal, N. Ceramic Microfiltration Membranes in Wastewater Treatment: Filtration Behavior, Fouling and Prevention. *Membranes* **2020**, *10*, 248. [CrossRef]
136. Charcosset, C. Ultrafiltration, Microfiltration, Nanofiltration and Reverse Osmosis in Integrated Membrane Processes. In *Integrated Membrane Systems and Processes*; Wiley: Hoboken, NJ, USA, 2016; pp. 1–22.
137. Li, L.; Visvanathan, C. Membrane Technology for Surface Water Treatment: Advancement from Microfiltration to Membrane Bioreactor. *Rev. Environ. Sci. Bio/Technol.* **2017**, *16*, 737–760. [CrossRef]

138. Gul, A.; Hruza, J.; Yalcinkaya, F. Fouling and Chemical Cleaning of Microfiltration Membranes: A Mini-Review. *Polymers* **2021**, *13*, 846. [CrossRef] [PubMed]
139. da Costa, I.D.; Nunes, N.N.D.S.; Costa, L.L.; Zalmon, I.R. Are Water Filters Effective Against Microplastics? *Water* **2024**, *16*, 3189. [CrossRef]
140. Tang, K.H.D. Counteracting the Harms of Microplastics on Humans: An Overview from the Perspective of Exposure. *Microplastics* **2025**, *4*, 47. [CrossRef]
141. Licona, K.P.M.; Geaquinto, L.R.D.O.; Nicolini, J.V.; Figueiredo, N.G.; Chiapetta, S.C.; Habert, A.C.; Yokoyama, L. Assessing Potential of Nanofiltration and Reverse Osmosis for Removal of Toxic Pharmaceuticals from Water. *J. Water Process Eng.* **2018**, *25*, 195–204. [CrossRef]
142. Judd, S.; Jefferson, B. *Membranes for Industrial Wastewater Recovery and Re-Use*; Elsevier: Amsterdam, The Netherlands, 2003.
143. Tayeh, Y.A. A Comprehensive Review of Reverse Osmosis Desalination: Technology, Water Sources, Membrane Processes, Fouling, and Cleaning. *Desalin. Water Treat.* **2024**, *320*, 100882. [CrossRef]
144. Mohanavelu, A.; Shrivastava, S.; Naganna, S.R. Streambed Pollution: A Comprehensive Review of Its Sources, Eco-Hydro-Geo-Chemical Impacts, Assessment, and Mitigation Strategies. *Chemosphere* **2022**, *300*, 134589. [CrossRef] [PubMed]
145. Sun, J.; Zhu, Z.-R.; Li, W.-H.; Yan, X.; Wang, L.-K.; Zhang, L.; Jin, J.; Dai, X.; Ni, B.-J. Revisiting Microplastics in Landfill Leachate: Unnoticed Tiny Microplastics and Their Fate in Treatment Works. *Water Res.* **2021**, *190*, 116784. [CrossRef]
146. Mohana, A.A.; Rahman, M.; Sarker, S.K.; Haque, N.; Gao, L.; Pramanik, B.K. Nano/Microplastics: Fragmentation, Interaction with Co-Existing Pollutants and Their Removal from Wastewater Using Membrane Processes. *Chemosphere* **2022**, *309*, 136682. [CrossRef]
147. Maliwan, T.; Hu, J. Release of Microplastics from Polymeric Ultrafiltration Membrane System for Drinking Water Treatment under Different Operating Conditions. *Water Res.* **2025**, *274*, 123047. [CrossRef]
148. Alvi, M.A.U.R.; Khalid, M.W.; Ahmad, N.M.; Niazi, M.B.K.; Anwar, M.N.; Batool, M.; Cheema, W.; Rafiq, S. Polymer Concentration and Solvent Variation Correlation with the Morphology and Water Filtration Analysis of Polyether Sulfone Microfiltration Membrane. *Adv. Polym. Technol.* **2019**, *2019*, 1–11. [CrossRef]
149. Yin, J.-Y.; Boaretti, C.; Lorenzetti, A.; Martucci, A.; Roso, M.; Modesti, M. Effects of Solvent and Electrospinning Parameters on the Morphology and Piezoelectric Properties of PVDF Nanofibrous Membrane. *Nanomaterials* **2022**, *12*, 962. [CrossRef]
150. Gebru, K.A.; Das, C. Effects of Solubility Parameter Differences among PEG, PVP and CA on the Preparation of Ultrafiltration Membranes: Impacts of Solvents and Additives on Morphology, Permeability and Fouling Performances. *Chin. J. Chem. Eng.* **2017**, *25*, 911–923. [CrossRef]
151. Srivastava, A.; Raval, H.D. Investigating the Role of Copper and Zinc Oxide Nanomaterials in Abatement of Biofouling of Ultrafiltration Membrane in Dynamic Conditions. *J. Appl. Polym. Sci.* **2022**, *139*, 51879. [CrossRef]
152. Poon, Y.K.; Enche Ab Rahim, S.K.; Ng, Q.H.; Hoo, P.Y.; Abdullah, N.Y.; Nasib, A.; Abdullah, N.S. Synthesis and Characterisation of Self-Cleaning TiO2/PES Mixed Matrix Membranes in the Removal of Humic Acid. *Membranes* **2023**, *13*, 373. [CrossRef] [PubMed]
153. Hashmi, Z.; Bilad, M.R.; Fahrurrozi; Zaini, J.; Lim, J.W.; Wibisono, Y. Recent Progress in Microalgae-Based Technologies for Industrial Wastewater Treatment. *Fermentation* **2023**, *9*, 311. [CrossRef]
154. Kotobuki, M.; Gu, Q.; Zhang, L.; Wang, J. Ceramic-Polymer Composite Membranes for Water and Wastewater Treatment: Bridging the Big Gap between Ceramics and Polymers. *Molecules* **2021**, *26*, 3331. [CrossRef] [PubMed]
155. Shahid, M.; Yusuf, M. Sustainability in Textile Finishing: An Introduction to Current Challenges and Innovations. In *Sustainable Finishing Techniques in Textiles*; Springer Nature: Singapore, 2025; pp. 283–293.
156. Gurung, K.; Ncibi, M.C.; Fontmorin, J.M. Incorporating Submerged MBR in Conventional Activated Sludge Process for Municipal Wastewater Treatment: A Feasibility and Performance Assessment. *J. Membr. Sci. Technol.* **2016**, *6*, 1000158. [CrossRef]
157. Bai, Y.; Wu, Y.-H.; Wang, Y.-H.; Tong, X.; Zhao, X.-H.; Ikuno, N.; Hu, H.-Y. Membrane Fouling Potential of the Denitrification Filter Effluent and the Control Mechanism by Ozonation in the Process of Wastewater Reclamation. *Water Res.* **2020**, *173*, 115591. [CrossRef]
158. Echevarría, C.; Valderrama, C.; Cortina, J.L.; Martín, I.; Arnaldos, M.; Bernat, X.; De la Cal, A.; Boleda, M.R.; Vega, A.; Teuler, A.; et al. Techno-Economic Evaluation and Comparison of PAC-MBR and Ozonation-UV Revamping for Organic Micro-Pollutants Removal from Urban Reclaimed Wastewater. *Sci. Total Environ.* **2019**, *671*, 288–298. [CrossRef]
159. Nadeem, K.; Alliet, M.; Plana, Q.; Bernier, J.; Azimi, S.; Rocher, V.; Albasi, C. Modeling, Simulation and Control of Biological and Chemical P-Removal Processes for Membrane Bioreactors (MBRs) from Lab to Full-Scale Applications: State of the Art. *Sci. Total Environ.* **2022**, *809*, 151109. [CrossRef]
160. Prasertkulsak, S.; Chiemchaisri, C.; Chiemchaisri, W.; Yamamoto, K. Removals of Pharmaceutical Compounds at Different Sludge Particle Size Fractions in Membrane Bioreactors Operated under Different Solid Retention Times. *J. Hazard. Mater.* **2019**, *368*, 124–132. [CrossRef]

161. Barreto, C.M.; Garcia, H.A.; Hooijmans, C.M.; Herrera, A.; Brdjanovic, D. Assessing the Performance of an MBR Operated at High Biomass Concentrations. *Int. Biodeterior. Biodegrad.* **2017**, *119*, 528–537. [CrossRef]
162. Lares, M.; Ncibi, M.C.; Sillanpää, M.; Sillanpää, M. Occurrence, Identification and Removal of Microplastic Particles and Fibers in Conventional Activated Sludge Process and Advanced MBR Technology. *Water Res.* **2018**, *133*, 236–246. [CrossRef]
163. Rahman, T.U.; Roy, H.; Islam, M.R.; Tahmid, M.; Fariha, A.; Mazumder, A.; Tasnim, N.; Pervez, M.N.; Cai, Y.; Naddeo, V.; et al. The Advancement in Membrane Bioreactor (MBR) Technology toward Sustainable Industrial Wastewater Management. *Membranes* **2023**, *13*, 181. [CrossRef]
164. Thambiliyagodage, C.; Jayanetti, M.; Mendis, A.; Ekanayake, G.; Liyanaarachchi, H.; Vigneswaran, S. Recent Advances in Chitosan-Based Applications—A Review. *Materials* **2023**, *16*, 2073. [CrossRef] [PubMed]
165. Al-Maliki, R.M.; Alsalhy, Q.F.; Al-Jubouri, S.; Salih, I.K.; AbdulRazak, A.A.; Shehab, M.A.; Németh, Z.; Hernadi, K. Classification of Nanomaterials and the Effect of Graphene Oxide (GO) and Recently Developed Nanoparticles on the Ultrafiltration Membrane and Their Applications: A Review. *Membranes* **2022**, *12*, 1043. [CrossRef]
166. Damiri, F.; Andra, S.; Kommineni, N.; Balu, S.K.; Bulusu, R.; Boseila, A.A.; Akamo, D.O.; Ahmad, Z.; Khan, F.S.; Rahman, M.H.; et al. Recent Advances in Adsorptive Nanocomposite Membranes for Heavy Metals Ion Removal from Contaminated Water: A Comprehensive Review. *Materials* **2022**, *15*, 5392. [CrossRef]
167. Subramaniam, M.N.; Goh, P.S.; Lau, W.J.; Ismail, A.F. Exploring the Potential of Photocatalytic Dual Layered Hollow Fiber Membranes Incorporated with Hybrid Titania Nanotube-Boron for Agricultural Wastewater Reclamation. *Sep. Purif. Technol.* **2021**, *275*, 119136. [CrossRef]
168. Goswami, R.K.; Mehariya, S.; Verma, P.; Lavecchia, R.; Zuorro, A. Microalgae-Based Biorefineries for Sustainable Resource Recovery from Wastewater. *J. Water Process Eng.* **2021**, *40*, 101747. [CrossRef]
169. Pizzichetti, A.R.P.; Pablos, C.; Álvarez-Fernández, C.; Reynolds, K.; Stanley, S.; Marugán, J. Evaluation of Membranes Performance for Microplastic Removal in a Simple and Low-Cost Filtration System. *Case Stud. Chem. Environ. Eng.* **2021**, *3*, 100075. [CrossRef]
170. Abuabdou, S.M.A.; Ahmad, W.; Aun, N.C.; Bashir, M.J.K. A Review of Anaerobic Membrane Bioreactors (AnMBR) for the Treatment of Highly Contaminated Landfill Leachate and Biogas Production: Effectiveness, Limitations and Future Perspectives. *J. Clean. Prod.* **2020**, *255*, 120215. [CrossRef]
171. Cai, Y.; Wu, J.; Lu, J.; Wang, J.; Zhang, C. Fate of Microplastics in a Coastal Wastewater Treatment Plant: Microfibers Could Partially Break through the Integrated Membrane System. *Front. Environ. Sci. Eng.* **2022**, *16*, 96. [CrossRef]
172. Abuabdou, S.M.A.; Bashir, M.J.K.; Aun, N.C.; Sethupathi, S.; Yong, W.L. Development of a Novel Polyvinylidene Fluoride Membrane Integrated with Palm Oil Fuel Ash for Stabilized Landfill Leachate Treatment. *J. Clean. Prod.* **2021**, *311*, 127677. [CrossRef]
173. Zhou, C.; Shao, S.; Xiong, K.; Tang, C.Y. Nanofiltration-Based Membrane Bioreactor Operated under an Ultralow Flux: Fouling Behavior and Feasibility toward a Low-Carbon System for Municipal Wastewater Reuse. *ACS ES&T Eng.* **2023**, *3*, 1267–1275. [CrossRef]
174. Zhang, J.; Li, G.; Yuan, X.; Li, P.; Yu, Y.; Yang, W.; Zhao, S. Reduction of Ultrafiltration Membrane Fouling by the Pretreatment Removal of Emerging Pollutants: A Review. *Membranes* **2023**, *13*, 77. [CrossRef] [PubMed]
175. Abuabdou, S.M.A.; Jaffari, Z.H.; Ng, C.-A.; Ho, Y.-C.; Bashir, M.J.K. A New Polyvinylidene Fluoride Membrane Synthesized by Integrating of Powdered Activated Carbon for Treatment of Stabilized Leachate. *Water* **2021**, *13*, 2282. [CrossRef]
176. Acarer, S. A Review of Microplastic Removal from Water and Wastewater by Membrane Technologies. *Water Sci. Technol.* **2023**, *88*, 199–219. [CrossRef] [PubMed]
177. Bodzek, M.; Bodzek, P. Remediation of Micro- and Nanoplastics by Membrane Technologies. *Membranes* **2025**, *15*, 82. [CrossRef] [PubMed]
178. Elhady, S.; Bassyouni, M.; Mansour, R.A.; Elzahar, M.H.; Abdel-Hamid, S.; Elhenawy, Y.; Saleh, M.Y. Oily Wastewater Treatment Using Polyamide Thin Film Composite Membrane Technology. *Membranes* **2020**, *10*, 84. [CrossRef]
179. Naddeo, V.; Secondes, M.F.N.; Borea, L.; Hasan, S.W.; Ballesteros, F.; Belgiorno, V. Removal of Contaminants of Emerging Concern from Real Wastewater by an Innovative Hybrid Membrane Process—UltraSound, Adsorption, and Membrane Ultrafiltration (USAMe®). *Ultrason. Sonochem.* **2020**, *68*, 105237. [CrossRef]
180. Rout, P.R.; Shahid, M.K.; Dash, R.R.; Bhunia, P.; Liu, D.; Varjani, S.; Zhang, T.C.; Surampalli, R.Y. Nutrient Removal from Domestic Wastewater: A Comprehensive Review on Conventional and Advanced Technologies. *J. Environ. Manag.* **2021**, *296*, 113246. [CrossRef]
181. Bakaraki Turan, N.; Sari Erkan, H.; Onkal Engin, G. Microplastics in Wastewater Treatment Plants: Occurrence, Fate and Identification. *Process Saf. Environ. Prot.* **2021**, *146*, 77–84. [CrossRef]
182. Tufail, A.; Price, W.E.; Mohseni, M.; Pramanik, B.K.; Hai, F.I. A Critical Review of Advanced Oxidation Processes for Emerging Trace Organic Contaminant Degradation: Mechanisms, Factors, Degradation Products, and Effluent Toxicity. *J. Water Process Eng.* **2021**, *40*, 101778. [CrossRef]

183. Xu, Z.; Bai, X.; Ye, Z. Removal and Generation of Microplastics in Wastewater Treatment Plants: A Review. *J. Clean. Prod.* **2021**, *291*, 125982. [CrossRef]
184. Kehrein, P.; van Loosdrecht, M.; Osseweijer, P.; Garfí, M.; Dewulf, J.; Posada, J. A Critical Review of Resource Recovery from Municipal Wastewater Treatment Plants—Market Supply Potentials, Technologies and Bottlenecks. *Environ. Sci. Water Res. Technol.* **2020**, *6*, 877–910. [CrossRef]
185. Wang, Z.; Sedighi, M.; Lea-Langton, A. Filtration of Microplastic Spheres by Biochar: Removal Efficiency and Immobilisation Mechanisms. *Water Res.* **2020**, *184*, 116165. [CrossRef]
186. Ngo, P.L.; Pramanik, B.K.; Shah, K.; Roychand, R. Pathway, Classification and Removal Efficiency of Microplastics in Wastewater Treatment Plants. *Environ. Pollut.* **2019**, *255*, 113326. [CrossRef]
187. Rubio, J.; Souza, M.; Smith, R. Overview of Flotation as a Wastewater Treatment Technique. *Miner. Eng.* **2002**, *15*, 139–155. [CrossRef]
188. Bui, X.-T.; Vo, T.-D.-H.; Nguyen, P.-T.; Nguyen, V.-T.; Dao, T.-S.; Nguyen, P.-D. Microplastics Pollution in Wastewater: Characteristics, Occurrence and Removal Technologies. *Environ. Technol. Innov.* **2020**, *19*, 101013. [CrossRef]
189. Tuan Tran, H.; Lin, C.; Bui, X.-T.; Ky Nguyen, M.; Dan Thanh Cao, N.; Mukhtar, H.; Giang Hoang, H.; Varjani, S.; Hao Ngo, H.; Nghiem, L.D. Phthalates in the Environment: Characteristics, Fate and Transport, and Advanced Wastewater Treatment Technologies. *Bioresour. Technol.* **2022**, *344*, 126249. [CrossRef]
190. Gaur, V.K.; Gupta, S.; Sharma, P.; Gupta, P.; Varjani, S.; Srivastava, J.K.; Chang, J.-S.; Bui, X.-T. Metabolic Cascade for Remediation of Plastic Waste: A Case Study on Microplastic Degradation. *Curr. Pollut. Rep.* **2022**, *8*, 30–50. [CrossRef]
191. Ranade, V.V.; Bhandari, V.M. *Industrial Wastewater Treatment, Recycling and Reuse*; Butterworth-Heinemann: Waltham, MA, USA, 2014.
192. Rao, D.G.; Senthilkumar, R.; Byrne, J.A.; Feroz, S. *Wastewater Treatment: Advanced Processes and Technologies*; CRC Press: Boca Raton, FL, USA, 2012.
193. Iorhemen, O.; Hamza, R.; Tay, J. Membrane Bioreactor (MBR) Technology for Wastewater Treatment and Reclamation: Membrane Fouling. *Membranes* **2016**, *6*, 33. [CrossRef]
194. Zhang, S.; Li, Y.; Jiao, W.; Qiu, L.; Zhong, J.; Sun, W. Research on Lateral Flow Treatment Technology to Enhance Phosphorus Removal of AAO Process. *E3S Web Conf.* **2018**, *53*, 04029. [CrossRef]
195. Zhou, Z.; Wu, Z.; Wang, Z.; Tang, S.; Gu, G.; Wang, L.; Wang, Y.; Xin, Z. Simulation and Performance Evaluation of the Anoxic/Anaerobic/Aerobic Process for Biological Nutrient Removal. *Korean J. Chem. Eng.* **2011**, *28*, 1233–1240. [CrossRef]
196. Pal, P. *Industrial Water Treatment Process Technology*; Butterworth-Heinemann: Waltham, MA, USA, 2017.
197. Hidayaturrahman, H.; Lee, T.-G. A Study on Characteristics of Microplastic in Wastewater of South Korea: Identification, Quantification, and Fate of Microplastics during Treatment Process. *Mar. Pollut. Bull.* **2019**, *146*, 696–702. [CrossRef]
198. Gude, V.G. Sustainable Desalination Using Renewable Energy Sources. In *Renewable Energy Technologies and Water Infrastructure*; American Society of Civil Engineers: Reston, VA, USA, 2022; pp. 135–149.
199. Chabi, K.; Li, J.; Ye, C.; Kiki, C.; Xiao, X.; Li, X.; Guo, L.; Gad, M.; Feng, M.; Yu, X. Rapid Sand Filtration for <10 Mm-Sized Microplastic Removal in Tap Water Treatment: Efficiency and Adsorption Mechanisms. *Sci. Total Environ.* **2024**, *912*, 169074. [CrossRef]
200. Li, Y.; Chen, P.; Tang, Y.; Yang, Y.; Zhou, C.; Bu, J.; Zhong, S. Microplastics in Water: A Review of Characterization and Removal Methods. *Sustainability* **2024**, *16*, 4033. [CrossRef]
201. Umar, M.; Singdahl-Larsen, C.; Ranneklev, S.B. Microplastics Removal from a Plastic Recycling Industrial Wastewater Using Sand Filtration. *Water* **2023**, *15*, 896. [CrossRef]
202. Egea-Corbacho, A.; Martín-García, A.P.; Franco, A.A.; Quiroga, J.M.; Andreasen, R.R.; Jørgensen, M.K.; Christensen, M.L. Occurrence, Identification and Removal of Microplastics in a Wastewater Treatment Plant Compared to an Advanced MBR Technology: Full-Scale Pilot Plant. *J. Environ. Chem. Eng.* **2023**, *11*, 109644. [CrossRef]
203. Wang, R.; Zhang, L.; Chen, B.; Zhu, X. Low-Pressure Driven Electrospun Membrane with Tuned Surface Charge for Efficient Removal of Polystyrene Nanoplastics from Water. *J. Memb. Sci.* **2020**, *614*, 118470. [CrossRef]
204. Sembiring, E.; Fajar, M.; Handajani, M. Performance of Rapid Sand Filter—Single Media to Remove Microplastics. *Water Supply* **2021**, *21*, 2273–2284. [CrossRef]
205. Pronk, W.; Ding, A.; Morgenroth, E.; Derlon, N.; Desmond, P.; Burkhardt, M.; Wu, B.; Fane, A.G. Gravity-Driven Membrane Filtration for Water and Wastewater Treatment: A Review. *Water Res.* **2019**, *149*, 553–565. [CrossRef] [PubMed]
206. Jani, V.; Wu, S.; Venkiteshwaran, K. Advancements and Regulatory Situation in Microplastics Removal from Wastewater and Drinking Water: A Comprehensive Review. *Microplastics* **2024**, *3*, 98–123. [CrossRef]
207. Wang, Z.; Lin, T.; Chen, W. Occurrence and Removal of Microplastics in an Advanced Drinking Water Treatment Plant (ADWTP). *Sci. Total Environ.* **2020**, *700*, 134520. [CrossRef]
208. Simon, M.; Vianello, A.; Vollertsen, J. Removal of >10 Mm Microplastic Particles from Treated Wastewater by a Disc Filter. *Water* **2019**, *11*, 1935. [CrossRef]

209. Yi, H.; Li, M.; Huo, X.; Zeng, G.; Lai, C.; Huang, D.; An, Z.; Qin, L.; Liu, X.; Li, B.; et al. Recent Development of Advanced Biotechnology for Wastewater Treatment. *Crit. Rev. Biotechnol.* **2020**, *40*, 99–118. [CrossRef] [PubMed]
210. Luo, Y.; Guo, W.; Ngo, H.H.; Nghiem, L.D.; Hai, F.I.; Zhang, J.; Liang, S.; Wang, X.C. A Review on the Occurrence of Micropollutants in the Aquatic Environment and Their Fate and Removal during Wastewater Treatment. *Sci. Total Environ.* **2014**, *473–474*, 619–641. [CrossRef]
211. Meng, F.; Zhang, S.; Oh, Y.; Zhou, Z.; Shin, H.-S.; Chae, S.-R. Fouling in Membrane Bioreactors: An Updated Review. *Water Res.* **2017**, *114*, 151–180. [CrossRef]
212. Jatoi, A.S.; Hashmi, Z.; Mubarak, N.M.; Ali Mazari, S.; Karri, R.R.; Koduru, J.R.; Dehghani, M.H. Industrial Wastewater Treatment Using Carbon Nanotube Membranes—A Brief Review. In *Water Treatment Using Engineered Carbon Nanotubes*; Elsevier: Amsterdam, The Netherlands, 2024; pp. 179–207.
213. Pramanik, B.K.; Pramanik, S.K.; Monira, S. Understanding the Fragmentation of Microplastics into Nano-Plastics and Removal of Nano/Microplastics from Wastewater Using Membrane, Air Flotation and Nano-Ferrofluid Processes. *Chemosphere* **2021**, *282*, 131053. [CrossRef]
214. Hou, B.; Chen, J.; Li, Y.; Liu, P.; Liu, Y.; Lu, J. Development of a Novel Model by Combining the Intermediate Blocking and Cake Filtration Models for Assessment of the Prevailing Fouling Mechanism in a Microbial Fuel Cell-Facilitated Membrane Bioreactor. *AIP Adv.* **2021**, *11*, 065224. [CrossRef]
215. Baena-Moreno, F.M.; Rodríguez-Galán, M.; Arroyo-Torralvo, F.; Vilches, L.F. Low-Energy Method for Water-Mineral Recovery from Acid Mine Drainage Based on Membrane Technology: Evaluation of Inorganic Salts as Draw Solutions. *Environ. Sci. Technol.* **2020**, *54*, 10936–10943. [CrossRef] [PubMed]
216. Zhang, J.; Xu, Z.; Mai, W.; Min, C.; Zhou, B.; Shan, M.; Li, Y.; Yang, C.; Wang, Z.; Qian, X. Improved Hydrophilicity, Permeability, Antifouling and Mechanical Performance of PVDF Composite Ultrafiltration Membranes Tailored by Oxidized Low-Dimensional Carbon Nanomaterials. *J. Mater. Chem. A* **2013**, *1*, 3101. [CrossRef]
217. Anjali, C.; Kizhakayil, R.N. Graphene—The Material of the Era. In *Graphene-Based Photocatalysts for Hydrogen Production and Environmental Remediation*; Springer: Cham, Switzerland, 2024; pp. 3–47.
218. Ray, A.; Majumdar, S.; Ghosh, S. Performance Evaluation of Ceramic Membrane Based Process for Microalgal Biomass Harvesting: Analyzing the Effect of Membrane Pore Sizes, Process Optimization and Fouling Behavior. *Trans. Indian Ceram. Soc.* **2023**, *82*, 229–238. [CrossRef]
219. Kuwayama, Y.; Olmstead, S.M. Hydroeconomic Modeling of Resource Recovery from Wastewater: Implications for Water Quality and Quantity Management. *J. Environ. Qual.* **2020**, *49*, 593–602. [CrossRef]
220. Enfrin, M.; Lee, J.; Le-Clech, P.; Dumée, L.F. Kinetic and Mechanistic Aspects of Ultrafiltration Membrane Fouling by Nano- and Microplastics. *J. Memb. Sci.* **2020**, *601*, 117890. [CrossRef]
221. Li, J.; Wang, B.; Chen, Z.; Ma, B.; Chen, J.P. Ultrafiltration Membrane Fouling by Microplastics with Raw Water: Behaviors and Alleviation Methods. *Chem. Eng. J.* **2021**, *410*, 128174. [CrossRef]
222. Behdarvand, F.; Valamohammadi, E.; Tofighy, M.A.; Mohammadi, T. Polyvinyl Alcohol/Polyethersulfone Thin-Film Nanocomposite Membranes with Carbon Nanomaterials Incorporated in Substrate for Water Treatment. *J. Environ. Chem. Eng.* **2021**, *9*, 104650. [CrossRef]
223. Chu, Z.; Chen, K.; Xiao, C.; Ling, H.; Hu, Z. Performance Improvement of Polyethersulfone Ultrafiltration Membrane Containing Variform Inorganic Nano-Additives. *Polymer* **2020**, *188*, 122160. [CrossRef]
224. Ajibade, T.F.; Xu, J.; Tian, H.; Guan, L.; Zhang, K. O-MWCNT/PAN/PVDF Ultrafiltration Membranes with Boosted Properties for Oil and Water Separation. *Desalin. Water Treat.* **2021**, *224*, 122–135. [CrossRef]
225. Sri Abirami Saraswathi, M.S.; Rana, D.; Divya, K.; Gowrishankar, S.; Nagendran, A. Versatility of Hydrophilic and Antifouling PVDF Ultrafiltration Membranes Tailored with Polyhexanide Coated Copper Oxide Nanoparticles. *Polym. Test.* **2020**, *84*, 106367. [CrossRef]
226. Ghezelgheshlaghi, S.; Mehrnia, M.R.; Homayoonfal, M.; Montazer-Rahmati, M.M. Al2O3/Poly Acrylonitrile Nanocomposite Membrane: From Engineering Design of Pores to Efficient Biological Macromolecules Separation. *J. Porous Mater.* **2018**, *25*, 1161–1181. [CrossRef]
227. Koutahzadeh, N.; Esfahani, M.R.; Arce, P.E. Sequential Use of UV/H_2O_2—(PSF/TiO_2/MWCNT) Mixed Matrix Membranes for Dye Removal in Water Purification: Membrane Permeation, Fouling, Rejection, and Decolorization. *Environ. Eng. Sci.* **2016**, *33*, 430–440. [CrossRef]
228. Boopathy, G.; Gangasalam, A.; Mahalingam, A. Photocatalytic Removal of Organic Pollutants and Self-cleaning Performance of PES Membrane Incorporated Sulfonated Graphene Oxide/ZnO Nanocomposite. *J. Chem. Technol. Biotechnol.* **2020**, *95*, 3012–3023. [CrossRef]
229. Geng, Z.; Wang, X.; Jiang, H.; Zhang, L.; Chen, Z.; Feng, Y.; Geng, W.; Yang, X.; Huo, M.; Sun, J. High-Performance TiO_2 Nanotubes/Poly(Aryl Ether Sulfone) Hybrid Self-Cleaning Anti-Fouling Ultrafiltration Membranes. *Polymers* **2019**, *11*, 555. [CrossRef]

230. Yu, S.; Xie, S.; Zhu, Y.; Wang, W.; Liu, Z.; Bao, X.; Ma, J. Purifying or Polluting? Tracing Membrane-Based Microplastics Release for Long-Term Drinking Water Safety. *Water Res.* **2026**, *289*, 124991. [CrossRef] [PubMed]
231. Al Mayyahi, A.; Deng, B. Efficient Water Desalination Using Photo-Responsive ZnO Polyamide Thin Film Nanocomposite Membrane. *Environ. Chem. Lett.* **2018**, *16*, 1469–1475. [CrossRef]
232. Zhou, S.; Feng, X.; Zhu, J.; Song, Q.; Yang, G.; Zhang, Y.; Van der Bruggen, B. Self-Cleaning Loose Nanofiltration Membranes Enabled by Photocatalytic Cu-Triazolate MOFs for Dye/Salt Separation. *J. Memb. Sci.* **2021**, *623*, 119058. [CrossRef]

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