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MICROPLASTICS POLLUTION MITIGATION IN WASTEWATER TREATMENT: CURRENT PRACTICES, CHALLENGES, AND FUTURE PERSPECTIVES

(Pengurangan Pencemaran Mikroplastik dalam Rawatan Air Sisa: Amalan Semasa, Cabaran dan Perspektif Masa Depan)

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Abstract

The growing attention to microplastics stems from their significant environmental and human impacts. Microplastic accumulation in the environment also contributes to the spread of micropollutants. Daily human activities involving the use of plastics, especially synthetic materials, lead to their eventual presence in wastewater treatment plants (WWTPs). Although WWTPs play a crucial role in removing microplastics during the treatment process, the technologies currently in use are not entirely effective in filtering out all microplastic particles. As a result, WWTPs are recognized as major contributors to microplastic release into the environment. This review delves into the sources and prevalence of microplastics, the methods used for their removal in WWTPs, and the potential risks they pose to human health. Several removal methods are discussed, including sedimentation and flotation, activated sludge and sedimentation, reverse osmosis, and rapid sand filtration. The efficiency of each method is critically assessed, highlighting their strengths and weaknesses in addressing microplastic contamination. Moreover, this review underscores the importance of ongoing comprehensive research and development to improve the removal efficiency of microplastics in WWTPs. Efforts to optimize existing removal techniques and investigate new technologies should be intensified to achieve more holistic microplastic removal. By tackling the microplastics issue at the WWTP level, we can reduce their release into the environment, thereby diminishing potential health risks. In conclusion, the environmental presence of microplastics and their associated micropollutants demands robust removal strategies within WWTPs.

While existing technologies offer some level of effectiveness, there is a need for further advancements to ensure more comprehensive microplastic removal. This review offers valuable insights into the current state of microplastic removal in WWTPs, emphasizing the need for continued research to protect both the environment and human health.

Keywords: microplastics, chemical contaminants, wastewater treatment plants, removal techniques

Abstrak

Mikroplastik telah menjadi tumpuan kerana kesannya yang ketara terhadap alam sekitar dan manusia. Pengumpulan mikroplastik di persekitaran membawa kepada penyebaran bahan pencemar mikro . Aktiviti harian manusia yang melibatkan penggunaan plastik, terutamanya bahan sintetik, mengakibatkan mereka masuk ke dalam loji rawatan air sisa (WWTP). WWTP memainkan peranan penting dalam membuang mikroplastik semasa proses rawatan, Walaubagaimanapun, teknologi sedia ada yang digunakan tidak berkesan sepenuhnya dalam menapis semua zarah mikroplastik. Kajian semula ini memfokuskan kepada sumber dan kewujudan mikroplastik, kaedah semasa yang digunakan untuk penyingkiran mikroplastik di WWTP, dan risiko terhadap kesihatan manusia. Pelbagai kaedah penyingkiran telah dipertimbangkan, termasuk pemendapan dan pengapungan, enap cemar dan pemendapan diaktifkan, osmosis terbalik, dan penapisan pasir pantas. Kecekapan dan keberkesanan setiap kaedah diperiksa secara kritikal, menjelaskan keupayaan dan batasannya dalam mengurangkan pencemaran mikroplastik. Kajian semula ini juga menekankan keperluan untuk penyelidikan dan pembangunan komprehensif yang berterusan untuk meningkatkan keberkesanan penyingkiran mikroplastik dalam WWTP. Strategi untuk mengoptimumkan kaedah penyingkiran sedia ada dan meneroka teknologi baru harus diteruskan untuk mencapai penyingkiran mikroplastik yang lebih komprehensif. Dengan menangani isu mikroplastik di peringkat WWTP, pembebasan zarah ini ke alam sekitar dapat diminimumkan, seterusnya mengurangkan potensi risiko kepada kesihatan manusia. Kesimpulannya, kehadiran mikroplastik dan bahan pencemar mikro yang berkaitan dalam alam sekitar memerlukan strategi penyingkiran yang mantap. Walaupun teknologi semasa menunjukkan beberapa keberkesanan, kemajuan selanjutnya diperlukan bagi memastikan penyingkiran mikroplastik yang lebih cekap dan menyeluruh. Oleh itu, semakan ini memberikan pandangan yang berharga tentang keadaan semasa penyingkiran mikroplastik di WWTP, menekankan kepentingan penyelidikan berterusan untuk menjaga integriti alam sekitar dan kesejahteraan manusia.

Kata kunci: mikroplastik, bahan cemar kimia, loji rawatan air sisa, teknik penyingkiran

Introduction

Plastic is a ubiquitous material that has revolutionized modern life since its inception in 1907 [1]. Its versatility, low cost, and moldability make it an ideal choice for a myriad of applications. One of the primary advantages of plastics is their lightweight nature, which is particularly beneficial in the transportation industry and consumer goods [2]. The chemical structure of plastics is based on long chains of molecules, known as polymers, which consist of repeating units. These units can be tailored to produce plastics with a diverse range of physical and chemical properties, such as transparency, flexibility, and resistance to heat, moisture, and chemicals. Packaging is one of the primary applications for plastics, owing to their exceptional barrier properties. They can be engineered to be impermeable to gases, moisture, and light, making them perfect for safeguarding food, pharmaceuticals, and other delicate materials [3]. According to a 2021 survey in Europe, polypropylene (PP), low-density polyethylene (LDPE), and high-density polyethylene (HDPE) are the three most widely used polymers, as cited by [4]. PP is in high demand, making up roughly 19% of total demand, because of its superior strength, chemical resistance, and recyclability. This makes it apt for a variety of applications, including packaging, automotive, and textiles. Conversely, LDPE and HDPE, which account for about 18% and 12% of the total plastic demand, respectively, also have a significant footprint in the European polymer industry [4]. Figure 1 presents the statistics of plastic demand in Europe in 2021.

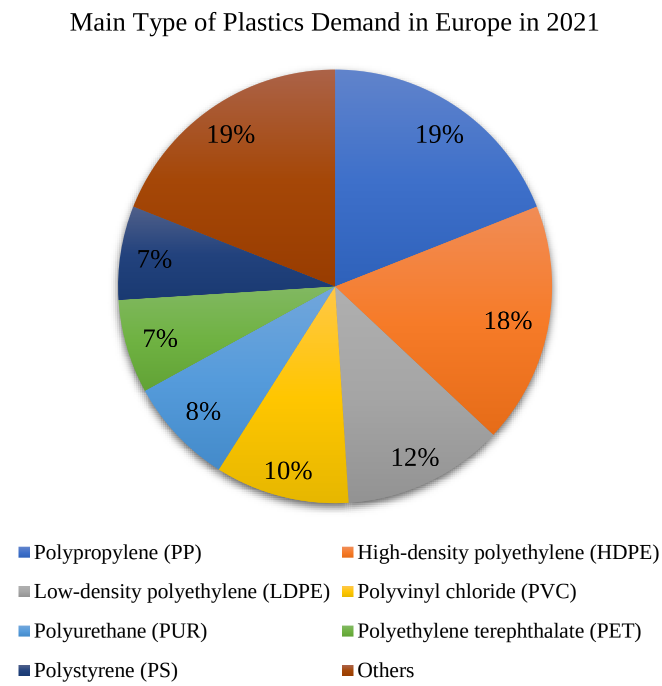

Figure 1. Plastics demand statistics in Europe in 2021

Despite their numerous advantages, the extensive use of plastics has led to significant environmental challenges, notably plastic pollution in oceans and waterways. Plastic waste varies in size from minuscule micrometre-sized particles to large meter-sized items and can originate from diverse sources, including both domestic and industrial [5]. Prior research indicates that domestic plastic production has consistently risen over the past decade, with only a minor fraction being recycled or incinerated [2]. In fact, about 79% of plastic waste either finds its way into landfills or is directly released into the environment, where it accumulates and can persist for centuries [6]. The build-up of plastic waste in aquatic environments is especially alarming due to its potentially detrimental effects on marine life. For instance, marine animals can become entangled in plastic debris, leading to suffocation, or they might ingest it, resulting in health complications or even death [7]. Moreover, plastic waste can release toxic chemicals into water, further jeopardizing the health of aquatic ecosystems [8].

The enduring presence of plastic waste in the environment results in the release of microplastics (MPs) – tiny plastic particles less than 5 mm in size. MPs are divided into two categories: primary and secondary MPs. Primary MPs are deliberately produced in small sizes, such as microbeads in personal care products, plastic pellets in feedstock or plastic manufacturing, and plastic powders for moulding. These particles are inherently small and can linger in the environment for prolonged periods, accumulating in various ecosystems, including oceans. According to Hwang et al. (2020), primary MPs constitute approximately 10% of global plastic waste, equating to 1.5 million metric tons annually [10]. Secondary MPs, conversely, form from the degradation of larger plastic items. They arise from various human activities like textile washing, tire wear, and paint chipping. These particles are minute enough to bypass wastewater treatment plants, eventually entering the environment. The scientific community has increasingly focused on these materials, believed to accumulate in the environment either due to direct discharge or from the fragmentation of larger particles [10].

The potential adverse health implications of microplastic exposure, whether through physical or chemical pathways in daily life, are becoming a pressing concern. In vivo studies have shown that certain microplastics, especially polystyrene ones, can infiltrate body cells like macrophages, erythrocytes, and rat alveolar epithelial cells, causing intracellular structure damage [11]. The mechanisms by which microplastics enter cells remain elusive, but they are thought to penetrate through various pathways, including phagocytosis, endocytosis, and passive diffusion [12]. Once inside, microplastics can disrupt standard cellular functions, leading to cellular stress and inflammation. This can negatively impact human health and might even play a role in the onset of various diseases. Furthermore, the diminutive size of microplastics allows them to migrate to different organs and tissues in the body, potentially causing more health issues [13]. The accumulation of microplastics in tissues and organs can result in chronic inflammation, tissue damage, and disruption of regular organ function [14].

Additionally, the propensity of MPs to adsorb persistent organic pollutants, metals, and pathogenic microorganisms is alarming, as it can lead to the build-up of these noxious substances in the environment, posing potential risks to humans and other organisms. MPs have a high surface area to volume ratio, making them particularly adept at absorbing and concentrating both organic and inorganic pollutants in the environment [15]. This can happen through various physical and chemical mechanisms, such as electrostatic attraction, van der Waals forces, and hydrophobic interactions [16]. The adsorption of pollutants onto MPs can lead to aggregate formation, which, when ingested by organisms, can induce toxicity. The leaching of chemical additives from microplastics can further amplify their toxic effects [8]. Furthermore, MPs can contain various chemical additives like plasticizers, flame retardants, and pigments, which might be released into the environment as the plastic degrades [17]. These chemical additives can adversely affect both human and environmental health, leading to endocrine disruption, neurotoxicity, and even carcinogenicity [18]. While the potentially harmful effects of microplastics on human health are still debated, several studies have reported alarming findings. For instance, Prata noted an elevated risk of respiratory symptoms in workers exposed to polypropylene flocks compared to their non-exposed counterparts [19]. Chronic inhalation exposure to fine particles has also been associated with gene mutations. Synthetic textile workers exposed to polypropylene for 10-20 years had a higher cancer incidence. Moreover, polyvinyl chloride workers exhibited an increased lung cancer risk, correlated with age, years of work, and exposure duration at the factories [20].

Microplastic sources and occurrence

The widespread presence of microplastics in aquatic ecosystems is a growing concern due to their potential adverse effects on the environment and its inhabitants. Microplastics can be transported globally by various means, including ocean currents, wind, and other environmental factors. This has led to the detection of microplastics in all ocean basins and numerous freshwater systems.

The primary sources of microplastics are diverse, encompassing household sewage, polymeric particles from cosmetics and cleaning products, feedstocks for plastic product manufacturing, and plastic pellets or powders used for air blasting [21]. These sources discharge microplastics directly into the environment, contributing to their accumulation in aquatic ecosystems. Additionally, microplastics can form through the degradation of larger plastic items due to mechanical forces or UV light exposure [22]. This process results in the creation of microplastics that can accumulate in the environment. The fragmentation of larger plastic items into smaller microplastics can occur through various processes, such as photodegradation, thermal degradation, and mechanical abrasion [10]. Once released, microplastics can persist for extended periods due to their resistance to degradation.

The global ingestion of microplastics by a variety of aquatic organisms has unveiled new and concerning environmental threats, as reported by [23]. The consumption of microplastics has been extensively documented in fish, shellfish, and other aquatic creatures, raising concerns about potential adverse effects on their health and the broader food chain. Microplastics can enter wastewater treatment plants (WWTPs) through various sources, eventually finding their way into water bodies and, subsequently, the wastewater treatment system. Recent research underscores the role of WWTPs in mitigating microplastic presence in the environment. According to Bretas Alvim et al., conventional WWTPs can remove up to 90% of microplastics. However, these systems remain a primary source of microplastic introduction into the environment. This is partly due to the direct release of microplastic-containing skincare products and toothpaste into wastewater from daily human activities [24]. Additionally, during washing, synthetic garments made of polyester and nylon can shed vast quantities of fibers, which can accumulate in WWTPs and contribute to microplastic release [19, 25].

The release of synthetic textile fibers during washing is a significant source of microplastic pollution in oceans. According to Boucher and Friot, about 35% of oceanic microplastics originate from synthetic textile fibers shed during washing [27]. The number of fibers released per wash can vary dramatically, with some studies reporting up to a million fibers shed by a single garment. For instance, Acharya et al. estimated the annual release of polyester and cotton microfibers during washing in Finland to range from 154,000 to 411,000 kg [28].

Several factors influence the release of microplastic fibers from synthetic textiles during washing. Textile properties, such as polymer type and knit structure, can affect fiber shedding [29]. For example, polyester fabrics tend to release more fibers per wash than acrylic fabrics [30]. Washing conditions, including temperature, friction, velocity, and duration, also play a role [30, 31]. Higher washing temperatures and extended durations can increase fiber release [30, 32], as well as mechanical friction and water velocity [31]. Additionally, the use of certain detergents and softeners can influence fiber release. Enzymatic or high-pH detergents can degrade fibers, increasing their release, while fabric softeners can coat fibers, reducing friction and shedding [33].

Microplastics entering WWTPs are typically captured and removed by designed systems. However, some microplastics still find their way into aquatic ecosystems, leading to environmental pollution and potential human health risks. The release of microplastics from WWTPs has garnered increased attention from researchers [34]. Studies have shown that while larger plastic particles are efficiently removed, microplastics can bypass the system and accumulate in aquatic ecosystems [35]. Given that many WWTPs are located near coastal areas and water sources, the discharge of microplastics can pose significant challenges. For example, in mainland China, 1,873 of the 3,340 WWTPs, with a treatment capacity of 78×106 m^3/day, are situated in coastal regions. Their effluents can directly or indirectly enter aquatic ecosystems [36]. To address this issue, researchers are examining the sources, occurrence, and removal of microplastics in WWTPs [21, 37, 38]. Table one summarizes the sources and types of plastics entering WWTPs.

Table 1. Source and type of plastics entering WWTPs

Source	Type	References
Domestic	Polyethylene (PE) Polyethylene terephthalate (PET) Polyester (PES) Polyacrylate (PAC) Polyamide (nylon)(PA) High-density polyethylene (HDPE) Low-density polyethylene (LDPE)	[39, 40]

Source	Type	References
Landfill	Polyacrylate (PAC)	[41–43]
	Polyimide (PI)	
	Polyethylene terephthalate (PET)	
	Polyoxymethylene (POM)	
	Polystyrene (PS)	
	Polyester (PES)	
	Polypropylene (PP)	
Stormwater runoff	Styrene-butadiene-rubber (SBR)	[44]
	Synthetic rubber (SR)	
Industry	Polyethylene terephthalate (PET)	[45]
	Polyester (PES)	
	Polyacrylate (PAC)	
	Polyamide (nylon)(PA)	
	Polystyrene (PS)	
	Polyvinyl chloride (PVC)	

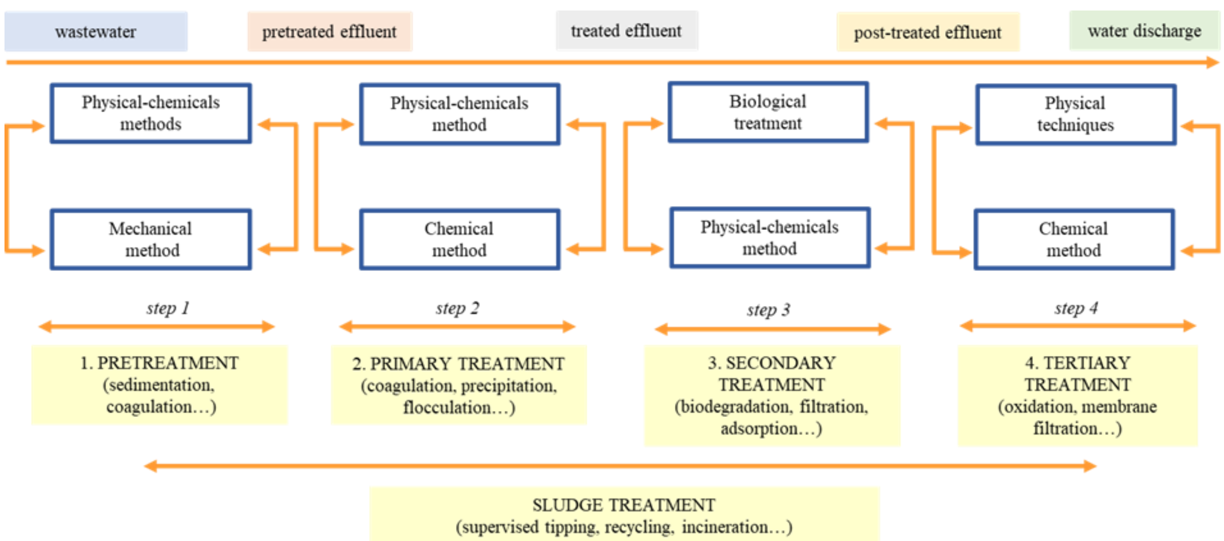

Figure 2. The schematic diagram of general process of WWTPs

Introduction to wastewater treatment plant

Efficient wastewater treatment is essential to maintain a clean and healthy environment and to comply with legal regulations that define decontamination objectives. Typically, conventional wastewater treatment combines physical, chemical, and biological processes to remove solids, including colloids, organic matter, nutrients, and soluble contaminants (e.g., metals, organics) from effluents. Figure 2 provides a comprehensive overview of available technologies for removing various contaminants from wastewater. Conventional methods encompass physical, chemical, and biological processes such as coagulation/flocculation, precipitation, biodegradation, filtration, and adsorption using activated carbon. These methods, established for contaminant removal in wastewater treatment, are widely employed in conventional treatment plants [46].

Besides conventional methods, established recovery processes, including solvent extraction, evaporation, oxidation, electrochemical treatment, membrane separation, membrane bioreactors, ion exchange, and incineration, have also been utilized for contaminant removal [47]. Emerging removal methods under development and investigation include advanced oxidation, adsorption onto non-conventional solids, biosorption, biomass, and nanofiltration [47]. These methods are gaining popularity due to their high efficiency and ability to treat contaminants challenging to address using conventional methods. Advanced oxidation processes are explained in Tufail et al. [48]. Adsorption onto non-conventional solids, like agricultural waste or biochar, shows promise for contaminant removal, as discussed in Wang et al. [49]. Biosorption and biomass methods utilize microorganisms or plants to remove contaminants from wastewater through absorption or uptake. Nanofiltration, which uses membranes with pore sizes between ultrafiltration and reverse osmosis, effectively removes organic and inorganic compounds and has proven efficient in removing pharmaceuticals and endocrine disruptors, as mentioned in Tufail et al. [48].

The wastewater treatment process generally consists of five steps, as illustrated in Figure 2. The first step, preliminary treatment, uses physical and mechanical methods to remove large solids and debris. The second step, primary treatment, employs physicochemical and chemical processes to remove suspended solids and organic matter. Chemical coagulation or precipitation may enhance particle settling, as discussed in Turan et al. [37]. The third step, secondary treatment or purification, uses chemical and biological methods to degrade organic matter and nutrients with microorganisms. Efrin et al. [50] details the use of activated sludge systems, trickling filters, and other biological reactors for this purpose. Chemical treatments, like disinfection, may also be used to eliminate pathogens and other harmful microorganisms. The fourth step, tertiary or final treatment, uses physical and chemical methods such as filtration, adsorption, or reverse osmosis to remove any remaining contaminants. Advanced treatment methods like membrane filtration and ozonation may also be employed, as discussed in Tufail et al. [48]. The fifth step addresses the treatment of sludge generated during the process, which may involve supervised disposal, recycling, or incineration, as mentioned in Ngo et al. [51].

The first two steps of the wastewater treatment process are often referred to as pre-treatment or preliminary steps, depending on the context. Pre-treatment involves removing large solids and debris that might damage downstream equipment or block pipes, typically using screens or grit chambers, as described in Efrin et al. [50]. Primary treatment focuses on removing suspended solids and organic matter, often through sedimentation or flotation. It may also involve chemical coagulation or precipitation to enhance particle settling, as discussed in Turan et al. [37].

Secondary treatment, the subsequent step, relies on microorganisms to degrade organic matter and nutrients in the wastewater. This can be achieved using activated sludge systems, trickling filters, or other biological reactors, as explained in Enfrin et al. [50]. Chemical treatments, like disinfection, may also be used to eliminate pathogens and other harmful microorganisms. The tertiary or final treatment step typically employs physical or chemical methods, such as filtration, adsorption, or reverse osmosis, to further purify the wastewater. This step might also involve adding chemicals to adjust pH or remove specific contaminants. Enfrin et al. [50] discusses using advanced treatment methods like membrane filtration and ozonation for tertiary treatment. Lastly, treating the sludge generated during the process is crucial. This might involve landfill disposal or specialized techniques like composting, anaerobic digestion, or incineration to convert the sludge into a stable and safe material, as mentioned in [37].

Microplastic removal efficiency in WWTP

Sedimentation and flotation

Two technologies commonly used for MP removal are sedimentation and air flotation. The sedimentation process involves the settling of heavier MPs, such as those with high densities, to the bottom of the tank due to gravity. Concurrently, some MPs might get trapped in the solid flocs that form during the process. The effectiveness of the sedimentation process depends on several factors, including the size, shape, and density of the MPs. The shape of the MPs can significantly influence their settling velocity, with spherical particles generally settling more slowly than irregularly shaped ones, as discussed in Li et al. [52]. The density of the MPs also affects their settling velocity, with higher-density MPs settling faster than those with lower density. Figure 3 below illustrates the process of flocculation and sedimentation in WWTPs.

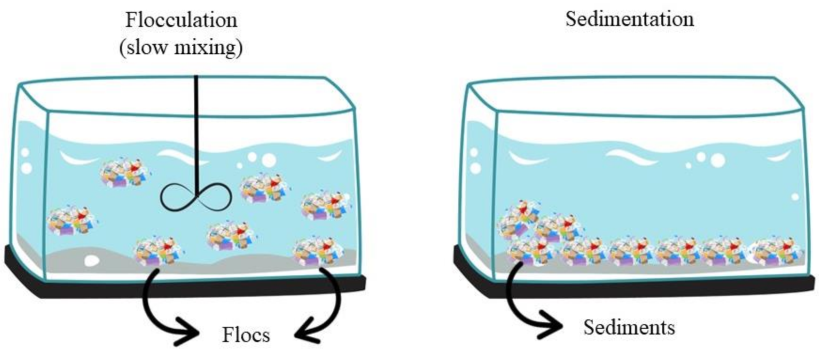

Figure 3. Flocculation and sedimentation process in WWTPs

The efficiency of sedimentation in removing MPs varies, with some studies reporting removal rates as low as 40.7% and others as high as 91.7%. This variation in removal efficiency can be attributed to differences in polymer types, and the size and shape of MPs in the wastewater flow [51, 53]. Polymer types such as PES, PET, and POM, which are denser than wastewater, are more readily removed by physical sedimentation, leading to higher removal efficiency [51]. The natural buoyancy of pollutants in the wastewater environment can also influence the effectiveness of sedimentation technology. Chemical compounds adsorbed onto the surface of MP particles can change their buoyancy, making them harder to remove [54]. The shape and size of the MPs also play a role in their removal efficiency, with fragments and granules being more easily removed than fibers [34].

A study by Liu et al. found that a combination of a coarse and fine grid, aerated grit chamber, and primary settlement tank reduced MPs from 79.9 to 47.4 nL^{-1}, achieving a removal rate of 40.7% [55]. However, another study by Turan et al. discovered that approximately 45% of influent MPs were trapped in the grit and grease fractions of the WWTP, while around 34% were retained within the primary sedimentation tank [37]. This indicates that a total of 80% of MPs accumulated in the primary sludge fraction, also referred to as biosolids. Using biosolids as fertilizer can introduce MPs into the environment, posing a potential risk to human health [56, 57].

Air flotation technology, in contrast, capitalizes on the density difference between the microplastics and the surrounding water. During this process, air bubbles are introduced, allowing MPs with a lower density to attach to them and rise to the water's surface, where they can be skimmed off. The shape and size of the MPs can also affect their removal efficiency in air flotation. Generally, MPs with larger sizes and irregular shapes exhibit higher removal efficiencies, as cited in literatures [51, 58]. Moreover, the presence of surfactants, which can stabilize the MPs and reduce their density, can diminish the effectiveness of air flotation, as noted by Swat et al. [59].

Activated sludge and sedimentation

Activated sludge is a prevalent technology in municipal WWTPs, typically employed after primary treatment processes such as sedimentation tanks, aerated grit chambers, or dissolved air flotation. Figure 4 illustrates the activated sludge and sedimentation process in WWTPs. During the growth phase, sludge flocs or bacterial extracellular polymers assist in accumulating

MPs contaminants in sewage, which are then removed during the sedimentation process. However, the intricate interaction between MPs and microorganisms, as well as the degree to which the process can capture MPs, remains ambiguous and requires further research [60].

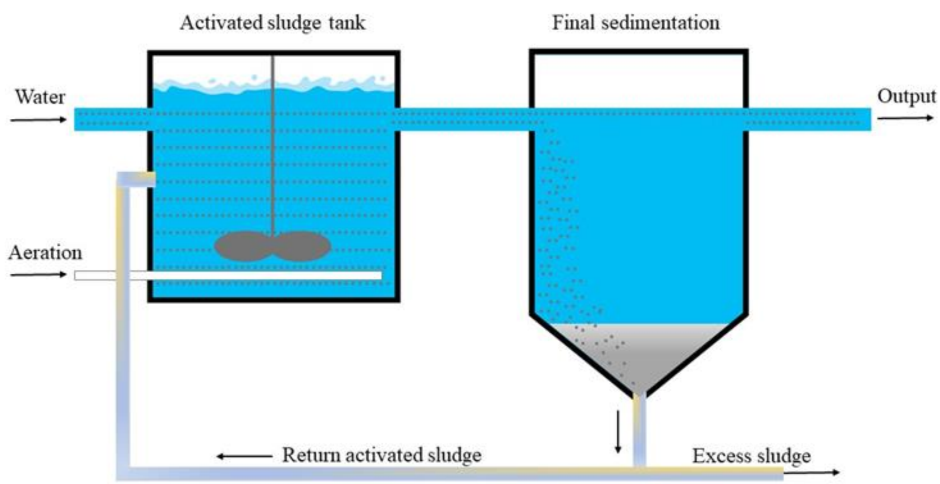

Figure 4. Example of activated sludge and sedimentation process

Ziajahromi et al. [61], Liu et al. [62], and Yang et al. [45] have reported MPs removal rates in activated sludge ranging from 28.1% to 66.7%. This variation is attributed to factors such as retention time and nutrient levels [61]. Extended contact times enhance the likelihood of surface biofilm formation on MPs, altering the surface, size, and relative densities of contaminants. Magni et al. reported that the number of MPs in WWTP sludge was 113 ± 57 MPs/g sludge dry weight (dw), with MPPs/g and MPFs/g accounting for 59.5 ± 21.6 and 53.3 ± 48.9, respectively [63]. The estimated daily accumulation of 3.4 billion MPs in sewage sludge underscores the importance of effective MP removal methods in WWTPs. While WWTPs can mitigate the direct introduction of MPs into aquatic environments by transferring some MPs to sludge during treatment, applying this sludge can introduce MPs into the soil. Li et al. (2018) estimated the total amount of MPs in dry sludge produced by W- and X-WWTP to be 1.64 × 108 and 1.88 × 108 particles per year, respectively [64].

Despite the potential of activated sludge technology to remove MPs, its inconsistent removal rate emphasizes the need for supplementary methods for effective MP removal. Combining sedimentation and air flotation with activated sludge might achieve optimal MP removal efficiency. Additionally, the role of microorganisms in accumulating MPs in sludge flocs, as highlighted by Scherer et al., stresses the significance of studying MPs removal mechanisms in wastewater treatment processes [60]. By understanding these mechanisms, we can pinpoint potential strategies to enhance MP removal in WWTPs, thereby reducing MP pollution in the environment.

Reverse osmosis (RO)

The application of RO (Reverse Osmosis) technology for MP (microplastics) removal has garnered attention as a potential solution to mitigate microplastic pollution in water sources. RO, a method widely employed for desalination and water purification, works by using a semipermeable membrane to separate contaminants based on their size and charge, as depicted in Figure 5. While RO is highly effective in removing dissolved substances, its efficiency in eliminating microplastics is contingent on various factors. This discussion offers an overview of the application of RO technology for microplastics removal, bolstered by pertinent statistical data.

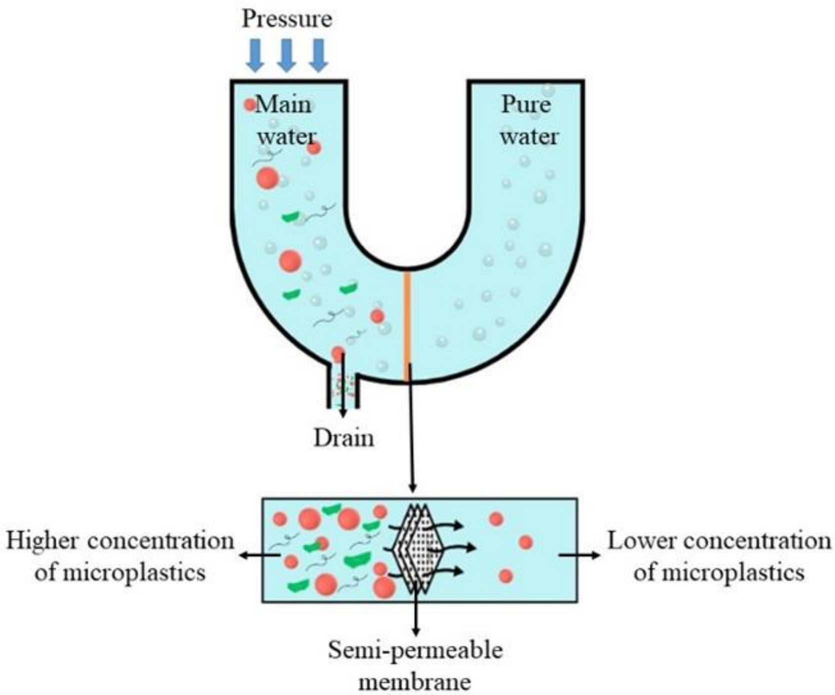

Figure 5. Semipermeable membrane used to separate contaminants

Several studies have evaluated the efficacy of RO in removing microplastics from water sources, yielding invaluable statistical insights. For instance, a study by Liu et al. explored the removal efficiency of RO membranes for microplastic particles ranging from 10-200 μm in size [64]. The research showed that RO achieved a microplastic removal efficiency spanning from 99% to 100% for microplastics of varying sizes. Another study by Ziajahromi et al. centered on the removal efficiency of RO for microplastic particles sized between 25 μm and 100 μm, revealing that RO could effectively eliminate microplastics with removal efficiencies reaching 98% [61].

Other studies have highlighted the impact of specific factors on the efficiency of microplastics removal via RO. Membrane characteristics, such as pore size and surface properties, are pivotal. Mohana et al. delved into the effect of different RO membrane pore sizes on microplastics removal, finding that membranes with tinier pore sizes displayed higher removal efficiencies, achieving 99% for microplastic particles larger than 0.4 μm [65]. The concentration of microplastics in the feedwater also significantly influences RO efficiency. Krishnan et al. assessed the effect of initial microplastic concentration on removal efficiency using RO, determining that higher initial microplastic concentrations resulted in diminished removal efficiencies, with rates ranging from 88% to 97% for initial concentrations from high to low [66].

While RO technology demonstrates the potential for microplastics removal, it is not without challenges and limitations. Fouling of the RO membrane by organic matter and particulate substances can compromise its efficiency. For example, a study referenced as [67] noted that microplastic removal efficiency was higher in tap water samples compared to raw water samples, both spiked with MPs (1 mg/L, 1 μm PS). The raw water sample exhibited a higher TMP value of 74.0 kPa, in contrast to 13.5 kPa for the tap water sample. An increase in the TMP value indicates more severe membrane fouling. Moreover, the energy demands of RO systems warrant consideration, as elevated energy consumption can lead to increased operational costs and environmental repercussions [68].

Rapid sand filtration

Rapid sand filtration is a widely used and economically viable technology for water treatment in various applications, including water supply and sewage treatment. This technique effectively removes impurities from water, making it a preferred choice globally [69, 70]. Within wastewater treatment plants (WWTPs), rapid sand filtration is often employed as a tertiary treatment stage to enhance water quality. Figure 6 illustrates the use of rapid sand filtration in WWTPs. The process works by passing water through a bed of sand, which serves as a filtration medium, removing suspended particles, pathogens, and organic matter. Both physical and biological mechanisms, such as adsorption, sedimentation, and microbial activity, contribute to contaminant removal and water quality improvement. One of the primary benefits of rapid sand filtration is its cost-effectiveness. The technology incurs relatively low operation and maintenance costs, making it an economically attractive choice for water treatment facilities [70]. Additionally, the system's simplicity promotes its broad adoption across various settings.

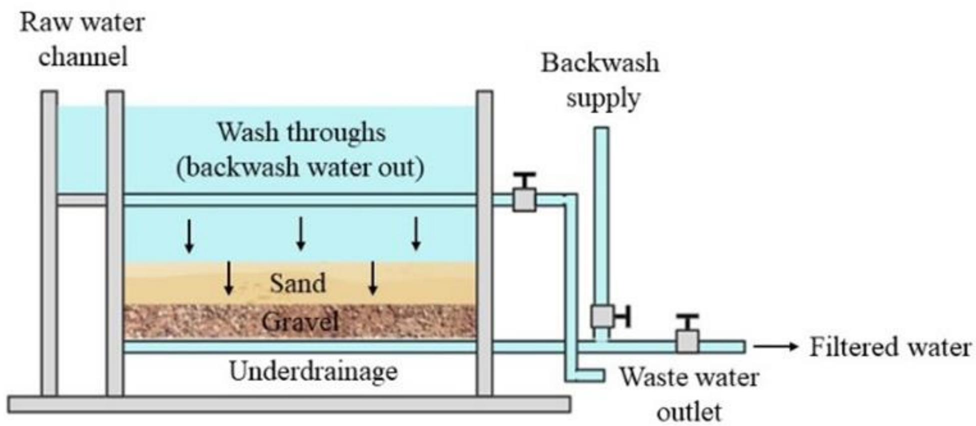

Figure 6. Rapid sand filtration in WWTPs

While rapid sand filtration effectively removes many impurities, its efficacy in MP removal has garnered significant attention. Several studies have explored the capability of rapid sand filtration in this regard, providing insights into its performance and limitations. When comparing the removal efficiency of MPs in different water treatment processes, rapid sand filtration seems to have a slightly lower efficiency than membrane bioreactors (MBRs). Egea-Corbacho et al. reported a removal efficiency of 97.1% for MPs in MBRs, while rapid sand filtration achieved 99.9% [38]. However, some inconsistencies in MP removal rates using rapid sand filtration have been observed. For instance, a study referenced as [71] found that a sand and anthracite coal filtration system in a WWTP in Western New York, USA, achieved only a 15% removal rate for MPs. The reduced efficiency in sand filters might be due to the potential mixing of anthracite coal and sand during filtration, possibly increasing the filter material's porosity over time. This diminished porosity might lead to bypassing or incomplete MP removal, affecting the system's overall efficiency. In contrast, filtration units using alternative methods have shown higher MP removal efficiencies, with several studies reporting rates exceeding 95% [51, 61, 72]. These findings underscore the effectiveness of such filtration units in removing MPs from water sources. Further research by Sembiring et al. identified a trend in MPs removal, indicating a decrease in removal percentages with increasing filtration rates. Their study revealed that the highest MP removal, at 95.5%, occurred at a filtration rate of 6 m/h after one hour of reactor operation. In contrast, the lowest removal, at 77.8%, was observed at a rate of 8 m/h after five hours of operation [73]. This pattern suggests that as the filtration rate rises, the efficiency of microplastic removal decreases.

Several factors can influence the efficiency of MP removal during rapid sand filtration. One such factor is the MPs' particle size, as removal efficiency may differ based on the size distribution of these particles in the influent water. Different MP sizes might interact uniquely with the sand filtration medium, influencing their capture and removal [74]. A study by Umar et al. reported that smaller microplastics exhibited the highest removal rates by sand filtration compared to larger sizes. Furthermore, the composition of MPs can also affect their removal efficiency. MPs can consist of various polymers, additives, and contaminants, each potentially interacting differently with the sand filtration media [75]. Some MPs might have surface properties that enhance their adhesion to sand particles, leading to better removal, while others might exhibit properties that reduce such interactions, resulting in lower efficiencies.

Operational conditions of the filtration system can also impact MP removal efficiency. Factors like filtration rate, contact time between microplastics and the filtration media, and the filter bed's condition can all influence the process's overall effectiveness [75]. For example, an excessively high filtration rate might reduce the contact time between MPs and the filtration media, limiting removal efficiency [73]. Over time, the accumulation of organic matter and biofilm on the filter bed's surface can alter the sand's pore size and porosity, potentially diminishing the system's ability to capture and retain MPs [76].

Limitations of current technology in WWTPs in removing MPs

All current technological approaches have their limitations in removing MPs. Sedimentation, flocculation, activated sludge, reverse osmosis, and sand filtration are effective existing technologies in WWTPs, but their efficiency in removing microplastics is limited. The small size and buoyancy of microplastics make their removal through sedimentation and flotation challenging due to difficulties in efficient capture. Activated sludge, which can inadvertently break plastic particles into MPs, may contribute to the release of secondary microplastics into the environment. While reverse osmosis has been touted as efficient in removing MPs, its effectiveness depends on several factors. Moreover, it is expensive and energy-intensive. Sand filtration, on the other hand, has limitations in removing MPs, especially those of sub-micron size. Over time, particles can pass through the filter material. These challenges underscore the need for more advanced and specific technologies, such as advanced oxidation processes, membrane filtration techniques, and emerging separation methods. Based on findings from relevant studies, these approaches aim to address the size, density, and efficiency issues inherent in conventional treatment techniques.

Conclusion and future perspectives

In conclusion, the efficiency of MP removal in WWTPs is influenced by variations in design and operational characteristics. While existing technologies predominantly achieve retention of microplastics in sludge and solid waste, they do not offer a comprehensive solution for complete removal. The presence of micropollutants, including pharmaceuticals and additives from cosmetics, poses a significant challenge, as biological treatment processes alone are insufficient for their complete removal. Consequently, WWTPs are increasingly opting to upgrade their facilities by incorporating downstream treatment stages, specifically aimed at the elimination of micropollutants.

Future studies should perform comprehensive investigations into various treatment stages aimed at enhancing the efficiency of MP elimination in WWTPs. These studies should encompass the exploration of various technologies and approaches, considering the intricate characteristics, interactions, and removal mechanisms associated with MPs. Additionally, it is crucial to address the simultaneous presence of micropollutants alongside MPs during treatment processes, as both contaminants necessitate comprehensive and integrated treatment strategies. The findings derived from such studies should be thoughtfully considered when implementing downstream treatment stages in WWTPs. The objective should be to develop and implement integrated treatment systems that not only target effective MP removal but also demonstrate efficacy in addressing micropollutants. This multidimensional approach may contribute to the realization of more efficient and sustainable wastewater treatment practices, consequently mitigating the release of MPs and micropollutants into the environment.

To achieve these goals, research efforts should focus on the following areas:

Advanced treatment technologies: Further exploration and evaluation of innovative treatment technologies, such as advanced oxidation processes, membrane filtration techniques, and emerging separation methods, should be pursued. In the advanced oxidation process, powerful oxidants are used to break down and remove various contaminants, including MPs present in the WWTPs. Meanwhile, membrane filtering techniques effectively capture and retain small particles of MPs, preventing their discharge into the environment. Emerging separation methods should be studied more since these approaches are continually evolving to offer more effective and focused removal. Therefore, these technologies hold promise for enhanced MP removal and micropollutant control in WWTPs.

Process optimization: Process optimization is a crucial strategy to overcome challenges and increase the effectiveness of MP removal and micropollutant control. Optimal operating conditions for MP removal should be identified through systematic optimization of process parameters such as contact time, filtration rates, and dosing of coagulants or adsorbents. The potential for MPs and micropollutants to interact with treatment agents may be increased by longer contact time, which would increase the effectiveness of removal. The removal efficiency may also increase when the filtration rates are adjusted to achieve a balance between the removal process and system capacity. Chemicals and their dosages used in a process also need to be optimized. Insufficient dosing may result in incomplete removal, while excessive dosing may increase costs and raise potential environmental issues. Therefore, process optimization in WWTPs is essential to help maximize the removal efficiency of MPs and micropollutants, save costs, and protect the environment.

Material development: Research should be dedicated to the development of novel materials with enhanced adsorption or filtration properties specifically designed for MP and micropollutant removal. This includes exploring the use of bio-based materials, nanomaterials, and hybrid composites. Bio-based materials from renewable sources such as agricultural waste, algae, and bacterial byproducts can exhibit good adsorption properties. The development of nanomaterials with a high surface area and reactivity will have a high potential for trapping MPs and micropollutants. Hybrid composites consist of various materials that benefit from their complementary properties. They may be designed to excel at trapping MPs and micropollutants while maintaining structural stability. By developing novel materials, the efficiency of MPs and micropollutant removal will be improved.

Fate and transport studies: Comprehensive investigations into the fate and transport of MPs within WWTPs, including their behaviour during different treatment stages and potential release pathways, should be conducted. Sample collection can be obtained at different stages of WWTPs, enabling the tracking of the movement and fate of MPs within the WWTPs. To ensure the accuracy of the data collected, a consistent methodology for the sampling step for each stage must be established. This will provide valuable insights for designing targeted removal strategies.

Monitoring and analysis: Advancements in analytical techniques and monitoring methodologies should be pursued to accurately quantify and characterize MPs in wastewater, treated effluent, and receiving water bodies. Monitoring will allow the assessment of the effectiveness of each stage of WWTPs. This will aid in assessing the efficiency of treatment processes and the environmental impact of released contaminants.

By focusing on these research directions, the researchers can further contribute to the development of more efficient and sustainable treatment solutions for MPs in WWTPs. This will in turn facilitate the implementation of comprehensive treatment strategies to safeguard water resources and protect environmental and human health.

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