Chapter 5
Microplastics in Wastewater Treatment Plants: Occurrence, Fate and Mitigation Strategies

Angel Joseph, Azmat Naseem, and Arya Vijayanandan

Abstract Environmental contamination caused by microplastics (MPs) is an issue of grave concern which is pervasive in global water, air, and soil. Wastewater treatment plants (WWTPs) are recognized as the vital source of MPs into the environment. Hence understanding the fate and behavior of MPs in WWTPs is of utmost importance. Studies have also reported the presence of MPs in the treated effluent. Challenges in MPs removal in different treatment units need to be identified, and advancements of existing treatment technologies are to be explored for enhancing the removal of MPs in WWTPs. This chapter presents the occurrence and fate of MPs in different treatment processes such as biodegradation, adsorption, membrane processes, filtration, electrocoagulation, and advanced oxidation processes. The removal efficiency of MPs in different treatment units, the mechanism of removal, and the challenges involved in removing MPs in each treatment unit are discussed in detail. The efficiency of the existing treatment technologies in WWTPs are compared, and the modifications suggested by recent studies to improve the removal of MPs are presented in this chapter.

Keywords Microplastics · Occurrence · Mitigation · Advanced oxidation processes · Adsorption · Bioreactor · Electrocoagulation · Filtration · Wastewater treatment

5.1 Introduction

Plastics are considered the modern marvel due to their benefits across all the fields ranging from health to food sectors saving countless lives (Golwala et al. 2021; Wang et al. 2021). The property that makes the plastics suitable also renders their ubiquitous presence in the environment (Guo et al. 2020; Yang et al. 2021). Depending on the usage pattern of plastic, the shelf life of the plastic items varies from 1 to 50 years or beyond before they are dumped as trash from where it can be recycled (9%),

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abandoned in the landfill (8%), utilized for energy recovery (12%), or dissipated in the environment (71%) (Dris et al. 2015a; Gregory 2009; Foerster 2018). Microplastics (MPs) are of significant concern de to their persistence and capability to act as carriers for other toxic pollutants such as dioxins, aldrin, perfluorooctane sulfonic acid, triclosan, tonalite chlordane, hexachlorobenzene, etc. (Mammo et al. 2020). Once MPs enter the food chain, it would result in bioaccumulation and will impart adverse health effects on living organisms and human beings as well (Miller et al. 2020). It is imperative to highlight that MPs are not a single type of contaminant but a suite of contaminants and are considered among the emerging contaminants (Jain et al. 2021). Owing to this serious concern, the European Parliament recently framed a resolution proposal (TA/2019/0071) emphasizing the urgent need for addressing MPs contamination related to wastewater treatment (Edo et al. 2020). MPs are small fragments ($\leq$5 mm), synthetic polymer fragments which have either been deliberately manufactured in smaller sizes known as primary MPs or developed due to the disintegration of bigger plastic known as secondary MPs (Frias and Nash 2019; Hartmann et al. 2019).

MPs are reported to be extensively present in the soil (Guo et al. 2020), oceans (Wang et al. 2020c), atmosphere (Abbasi et al. 2019), freshwater systems (Han et al. 2020), and are also detected in the sediments (González-Pleiter et al. 2019). It is essential to consider that WWTPs majorly act as the source for the entry of MPs into the environment as single treatment plant effluent can release up to 10^{10} MPs per day (Mintenig et al. 2017). These fragments of plastics, whether in larger or smaller forms, would cause serious adverse repercussions for biota, ecosystems, and the environment (Hartline et al. 2016; He et al. 2020; Magnusson and Norén 2014; Michielssen et al. 2016; Ou and Zeng 2018; Rummel et al. 2017; Wang et al. 2020b; Wright et al. 2020). In the natural hydrological cycle, an appreciable proportion of MPs is detected in lakes, oceans, rivers, atmospheric precipitation, and wastewater and treated water (Alia et al. 2016; Andrady, 2011; Dris et al. 2015b). In the case of the anthropogenic hydrological cycle, micro-sized litter finds its way in sewers (Tagg et al. 2015), which are ultimately sent to the influent load of the WWTPs (Carr et al. 2016).

Previous studies focused on the source, composition, and concentration of MPs have reported that the MPs in the influent of WWTPs are majorly composed of small-sized fibers discharged from laundries (Baldwin et al. 2011), microbeads used in personal grooming products (Ezel et al. 2016). Pollutants such as heavy metals (Yazdani Foshtomi et al. 2019), polycyclic aromatic hydrocarbons (Sørensen et al. 2020), pharmaceutical compounds and cosmetic products (Liu et al. 2019a; Ma et al. 2019), and polybrominated biphenyl ethers (Singla et al. 2020) gets adsorbed from surrounding media to MPs due to their large surface area and low volume (Thompson et al. 2004). High concentrations of micro-sized plastic litter in water affect the efficiency of water purification processes like filtration units that get choked or malfunctioned due to clogging (Chesters et al. 2013; Guo et al. 2012). There is also a possibility that MPs experience shear forces generated by pumping or mixing, which further disintegrates MPs into much smaller fragments leading to the formation of nano plastics released in the water matrix (Lee et al. 2019).

The research focusing on the sources, occurrence, and fate of MPs in WWTPs has gained a lot of attention in recent years (Bakaraki Turan et al. 2021; Edo et al. 2020; Habib et al. 2020; Liu et al. 2021; Ngo et al. 2019; Raju et al. 2018; Sun et al. 2019;

Xu et al. 2021). Various technologies are being adopted for the removal of MPs at different treatment stages. A detailed review of the occurrence and the fate of MPs in WWTPs are presented in this chapter. In addition, this article aims to provide a comprehensive review of the mechanism of removal of MPs in specific treatment units for a better understanding of research gaps that need to be addressed in the future. Occurrence of MPs in wastewater treatment plants.

Contamination of MPs in municipal sewage is reported in several parts of the world (Iyare et al. 2020). WWTPs are considered the prime source of MPs in the water bodies (Tang et al. 2020a, 2020b) MPs are mainly introduced into wastewater through stormwater discharge and outlets from residential structures and multiple production units (Salmi et al. 2021). The release of MPs can occur throughout the life cycle of the plastic products from the production and formulation stage to transport, utilization, and final disposal (Wang et al. 2021). These MPs are being transported to different environmental matrices through runoff, sewage, landfills, industries, and weathering (Lambert et al. 2014).

The origin and composition of MPs found in WWTPs are challenging to analyze due to their smaller particle size and wide range of unknown sources (Kaliszewicz et al. 2020; Ziajahromi et al. 2016, 2017). Primary MPs detected in WWTPs include tiny beads that are used in several cosmetic products such as scrubs, face wash, toothpaste, etc. (Chang 2015; Fendall and Sewell 2009). The other sources can be plastic pellets, fishing gear, and building paints which yield small-sized MPs (0.5–6 mm) released into water systems (Kärrman et al. 2016). However, the most considerable contribution is from the automobile sector. The tires release 50,000–135,000 tons of MPs of range > 0.01 mm, and the smallest recorded micro fragments of size > 5 μm originate from fertilizers and detergents (Viveknand et al. 2021). A common source of MPs in the WWTPs is microbeads (Kärrman et al. 2016), and it is estimated that nearly 94,500 microbeads are discharged on single wash from cosmetic products (Napper et al. 2015).

Secondary MPs directly discharged into the sewers include tiny fiber litter (of size 12–16 μm) from clothing, and it is estimated that every wash of a single garment using a household machine would generate > 1900 fibers (Browne et al. 2011). The formation of secondary MPs is due to regular disintegration of larger plastics under nominal atmospheric conditions due to exposure to the sunlight or by mechanical disintegration during pumping and mixing in WWTPs (Eriksen et al. 2014). Larger plastic items are broken down by different mechanisms such as hydrolysis, photo-oxidation, mechanical breakage caused by turbulent water or sand abrasion, or microorganisms-assisted bio-assimilation (Gewert et al. 2015; Niaounakis 2017). Determining particle shape, size, amount, and surface chemistry of MPs is challenging, especially in the case of secondary MPs (Andrady 2017). In a recent study, the samples obtained from the WWTPs reported MPs' presence that can be categorized into six shapes: pellets, granules, fibers, films, fragments, and foams (Yang et al. 2021). Fibers and fragments are most abundantly found in WWTPs, and these fibers possessing a greater length to width ratio, are difficult to remove in the treatment units (Sol et al. 2020).

Physical, chemical, and biological treatment techniques could be responsible for changing the configuration of primary MPs to secondary MPs (González-Pleiter et al. 2019), rendering WWTPs the key contributor of secondary MPs in the terrestrial as well as in aquatic media (Liu et al. 2021). Depending upon the level of treatment, WWTPs have a high propensity of removing MPs; however, they are critical contributors to contamination as water remains the prime carrier for the diffusion of MPs in the environment (Bayo et al. 2020; Bretas Alvim et al. 2020; Edo et al. 2020; Sol et al. 2020; Ziajahromi et al. 2016). At various treatment levels involved in WWTPs, such as preliminary followed by primary, secondary, and terminating at the tertiary, approximately 87–99% of plastic litter is removed from the sewage (Viveknand et al. 2021). A schematic representation of the sources and pathway of MPs during in WWTPs is shown in Fig. 5.1.

Despite the high rates of removal of MPs in WWTP, still, a large proportion of this debris-loaded wastewater is regularly released to the water streams (Carr et al. 2016). A Scotland-based treatment plant was reported to release about 6.5×107 MPs daily into its neighborhood (Murphy et al. 2016), and another WWTP in Italy was found to discharge around 1.6×10^8 MPs per day (Magni et al. 2019). Murphy et al. 2016 reported that the influent loading of MPs in a WWTP in England was close to 15.70 ($\pm$ 5.20) particles/L and was lowered to 0.25 ($\pm$ 0.04) particles/L in the discharged effluent. A study conducted in a WWTP in China reported that the MPs with mass $<$ 10 kg were released into the water system per day, and the proportion of fragments is abundant (Lv et al. 2019). Gies et al. (2018) estimated the dominance of different types of MPs such as fibers (65.6%), fragments (28.1%), pellets (5.4%), granules (0.45%), foam (0.22%), and sheets (0.20%) in samples collected from a WWTP in Canada.

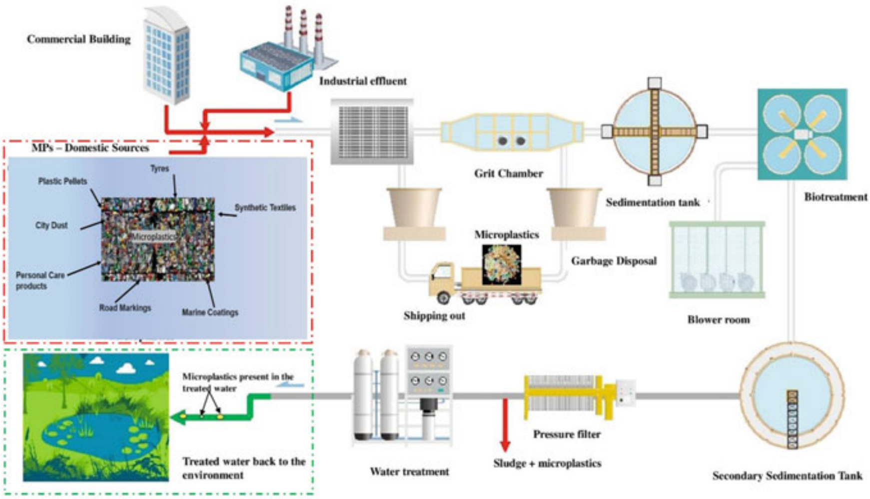

Fig. 5.1 Different sources, occurrence and pathways of MPs in WWTPs (figure modified from Zhang et al.(2020))

5.2 Treatment Methods and the Mechanism Involved in Removing MPs from WWTPs

Existing WWTPs are not carefully designed for removing MPs from wastewater. Literature suggests that a significant quantity of MPs was released to the environment in each treatment option adopted in the WWTPs (Joo et al. 2021). Depending upon the treatment methods and physicochemical characteristics of the polymer, such as particle density, size, charge, hydrophobicity, etc., variable removal efficiencies can be expected in different treatment technologies (Bond et al. 2018). The efficacy of any removal treatment method is highly dependent on the quality of influent and the characteristics of MPs in it.

Primary treatments involving coarse screening remove most of the MPs, while grit sedimentation, screening, degreasing, and primary sedimentation contribute to further removal. The biological processes followed by sedimentation in secondary treatment accounts for approximately 20% removal efficiency (Xu et al. 2021). About 69–79% of MPs introduced into WWTPs are eliminated at the primary screening stage with grit removal methods (Ziajahromi et al. 2021). Low-weight floating MPs could bypass the grease skimming method (Sun et al. 2019). Primary sedimentation could remove particles with a spherical shape having a diameter > 27–149 µm (Iyare et al. 2020). In combination with the grit and grease removal units, the primary settling unit potentially improves the efficacy of removing MPs. A recent study reported that treatment units such as sedimentation and skimming units have the potential to remove almost 72% of MPs present in sewage influent (Xu et al. 2021).

Another study reported higher removal efficiency for MPs having size (106–300 µm) than MPs with range (>300 µm) (Lee and Kim, 2018). Smaller MPs can be trapped easily in the grit and grease removal stage and adhere to the biofilm or flocs. A study conducted by Liu et al. (2019) suggested that MPs removal is closely associated with turbidity removal from primary sedimentation as well as secondary treatment. In WWTPs, the major fraction of microbeads ends up in the sludge, with the remaining microbeads released into receiving streams (Mason et al. 2016; Murphy et al. 2016). Many of the available treatment techniques eliminate MPs by entrapping this litter in sludge; however, dedicated techniques for removing MPs are lacking. There is still the persistence of MPs in the final effluent discharged via WWTPs, signifying the inability of existing treatment methods in completely eliminating MPs in wastewater (Ziajahromi et al. 2017). Secondary and tertiary treatments in WWTPs remove 88–94% of MPs loaded in the sewage influent, and about 72% removal efficacy was reported during preliminary and primary treatment (Iyare et al. 2020). The following section discusses the detailed removal mechanisms of MPs in specific treatment units in WWTPs.

5.2.1 Biological Processes

Bioreactors are adopted as a secondary treatment option for the removal of MPs in WWTPs. The MPs are hardly degraded within a short period. The extracellular polymer substances secreted by the microorganisms facilitate the initial trapping of MPs (Zhang et al. 2020). The degradation of MPs by the microbes followed by the formation of sludge aggregates causes the effective removal of MPs in bioreactors. The accumulated MPs in the sludge were then removed in a secondary clarifier (Jeong et al. 2016). Recent studies have reported the biological degradation of MPs by various organisms (Yuan et al. 2020; Miri et al. 2021). Polymer digestion by the microbes present in the sludge is the plausible mechanism of MPs removal (Miri et al. 2022).

Biodegradation of MPs takes place in four successive steps: colonization, bio-fragmentation, assimilation, and mineralization (Dussud and Ghiglione 2014). The biodegradation of MPs initiates with the formation of microbial colonies over the surface of the polymer (Oberbeckmann et al. 2015). This colonization causes macro-molecular modifications on the MPs by physical (biofilms forcing cracks and pits on the polymer surface) and chemical (the secretion of acids by the microbial colonies weakens the polymer structure) pathways (Yoshida et al. 2016). Moreover, the enzymes secreted on the MPs aids in disintegrating the polymer to a low molecular weight oligomer during bio-fragmentation (Skariyachan et al. 2018). The bio-fragmentation stage is continued with subsequent assimilation of fragmented oligomers by the microbial colony. This stage is called assimilation, and in the final stage of mineralization, bacteria consume all useful energy out of oligomers and release oxidized waste into the surrounding environment through multiple biochemical pathways (Hou et al. 2021; Miri et al. 2022). However, in most of the biological treatment processes, degradation of MPs is minimum; rather removal occurs due to adsorption and entrapment (Zhang et al. 2020).

The activated sludge process (ASP) has been effective in mitigating wastewater MPs after preliminary treatments (Bretas Alvim et al. 2021). The mineralization of MPs in ASP involves two processes (a) sorption and (b) degradation (Fig. 5.2). Most

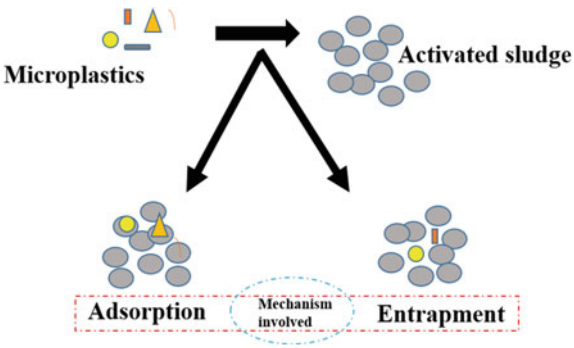

Fig. 5.2 Interactions of MPs with biomass in ASP (Figure modified from Zhang et al. 2020)

of the secondary treatment facilities in WWTPs combine biological processes with a clarification unit for the effective removal of biomass which also aids in the removal of MPs (Tang et al. 2020a, 2020b). The biological flocs promote growth on MPs' surface, which causes accumulation of MPs debris in the system, and subsequently, MPs may get settled in the clarifier (Hurley et al. 2018). Experimental results from a lab-scale SBR detected the presence of smaller fragments in the sludge and larger MPs in the effluent with a removal efficiency of 52% (Kalčíková et al. 2017).

The introduction of biofilters to remove MPs is considered a very simple and innovative concept. Liu et al. (2020) tested the biofilter consisting of different layers of stone wool as an advanced refining step for treated wastewater. The secondary effluent entered the filter through the top portion, and treated effluent was discharged from the bottom of the filter (Liu et al. 2020). The study reported that the filter could reduce MPs by 79–89% in effluents of the wastewater treatment plant. However, it is also observed that the biofilters are more recommended for the removal of larger plastic fragments, and hence a complete MPs removal could not be achieved by this method (Kuoppamäki et al. 2021). Maximum removal occurred at the top of the biofilter with the lower layers allowing limited surplus treatment efficacy (Thuptimdang et al. 2021). Large-sized MPs were retained by biofilter with no particles greater than 100 μm from the filter in the final effluent (Kuoppamäki et al. 2021).

Lee and Kim (2018) compared the removal efficiencies of 3 different configurations of the activated sludge process for MPs removal: sequencing batch reactor (SBR), anaerobic–anoxic–oxic (A^2O), and media process (A^2O basin with filled carrier). It was observed that all processes attained removal efficiencies > 98%, and SBR reported the highest rate of 99.2%. Jiang et al.2020 reported that the anoxic–oxic process (A/O) removed approximately 17% of MPs in wastewater. MPs show higher retention potential in most of the biological processes, and the treatment of MPs fraction with the sludge is of great concern (Liu et al. 2019c).

A significant portion of the MPs is reported to be accumulated in the waste activated sludge (WAS). WAS produced in the specific treatment units is further treated with an anaerobic digester (AD) (Wei et al. 2019). The treatment of WAS enriched with MPs has been challenging in recent times. The size and composition of the MPs are the predominant factors that determine the efficacy of anaerobic digestion (Chen et al. 2021). The composition of WAS enriched with larger-sized fractions of MPs has shown a reduction in methane production than in smaller fragments (Wei et al. 2019; Zhang et al. 2020). It has been reported that the presence of MPs in the WAS reduces the efficiency of the anaerobic digestion as the MPs also act as a carrier for the other antibiotics and other toxic pollutants (Wei et al. 2019). A recent study has investigated the co-effect of MPs and antibiotics in the anaerobic digestion and observed adsorption of antibiotics to MPs due to its hydrophobicity and larger specific area (Wang et al. 2020a). This causes a reduction in the anaerobic efficiency and the prolonged residence of antibiotics in the anaerobic digester, which causes inhibition in antibiotic degradation (Zhu et al. 2018). Higher content of MPs in WAS causes inhibition of the hydrolysis stage of anaerobic digestion that results in the increased formation of dissolved organic matter (Chen et al. 2021). This further causes the inhibition of the acidogenesis stage that leads to lower methane production (Lin et al. 2020). In general, biodegradation of MPs in anaerobic digestion processes is difficult, and understanding the fate of MPs in the system is essential. The leaching of monomers during anaerobic digestion is another matter of concern, and the mechanisms involved in the anaerobic digestion of MPs are still not clearly understood.

5.2.2 Filtration

Rapid sand filtration (RSF) is the commonly adopted low-cost treatment method for the removal of MPs. The removal of MPs has been enhanced by incorporating RSF units as the last stage option in tertiary treatment (Padervand et al. 2020). After the systematic investigation of WWTPs in Finland, it was observed that RSF could remove 97% of MPs present in the effluent from the secondary treatment stage (Talvitie et al. 2017). Although higher removal efficiencies are being reported, the main demerit of such systems is that it causes fragmentation of MPs. Hence the magnitude as well the surface properties of the MPs are of great importance in this context, as these factors determine the extent of MPs and filter media interaction (Bhattacharjee 2016). A recent study in South Korea reported that RSF and coagulation units could be coupled together to achieve improved removal efficiency (Hidayaturrahman and Lee 2019). Investigation on the transport behavior of smaller fragments of MPs (0.02 μm and 2 μm) through sand and biochar medium has been evaluated in a recent study (Tong et al. 2020). The study also concluded that improvement in the surface roughness of the filter media has contributed to enhanced interaction between the polymer and caused better deposition of MPs in the filter media. In addition, the development of composite filter media such as biochar/Fe_3O_4-biochar having magnetic attraction can act as a permeable barrier and has great potential to immobilize the MPs fragments (Faisal et al. 2018). A study focused on the elucidation of the mechanism behind the immobilization of MPs (Fig. 5.3) in biochar media concluded that stuck, trapped, and entangled are the three factors that control MPs fate in biochar media (Wang et al. 2020d). The development of such cost-effective filter media can improve the overall performance of tertiary treatment systems.

5.2.3 Adsorption

Several studies have targeted the development of adsorbent media that can be used suitably to adsorb the MPs present in wastewater (Li et al. 2019; Nolte et al. 2017). In a recent study, the application of graphene oxide and chitin for the adsorption of MPs had been explored and identified to be an effective method (Sun et al. 2020). The adsorption of MPs to graphene-supported adsorbents is primarily due to the pie bond, H-bond, and electrostatic attraction. Three-dimensional graphene-based adsorbents can be used for the separation of MPs. The adherence and high sorption

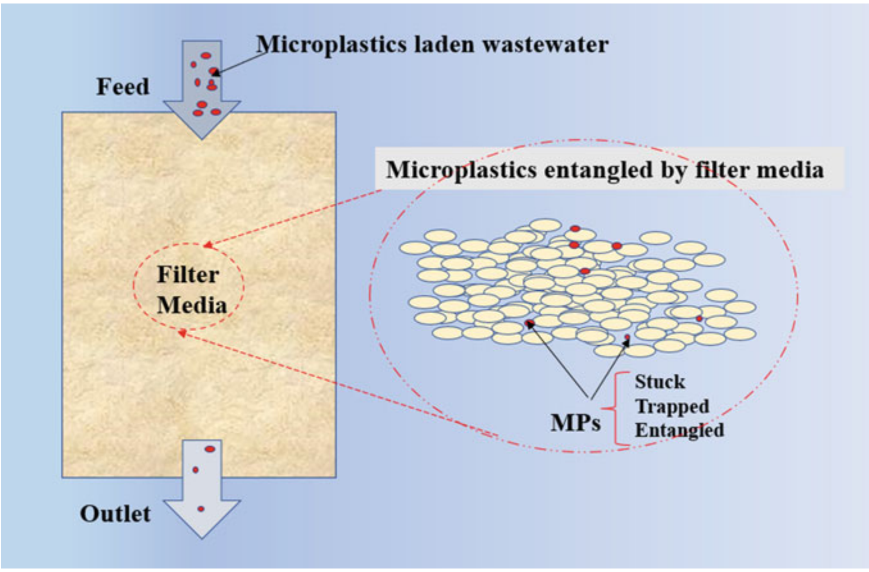

Fig. 5.3 Mechanisms involved in the removal of MPs using filtration (figure modified from Wang et al.(2020d))

of MPs to the surface of the marine microalgae and seaweed have been reported in a recent study (Sundbæk et al. 2018). The alginate released from the seaweed surfaces enhances the sorption capacity, and about 94% of MPs have been removed in that manner (Padervand et al. 2020). The effect of surface charges on MPs and microalgae in the adsorption process has been analyzed in a study conducted by Nolte et al. (2017). The study also concluded that the rate of adsorption of positively charged polystyrene is comparatively higher than the negatively charged MPs. Anionic polysaccharides present in the algal chemical structure enhanced the adsorption of MPs on the surface of algae (Dey et al. 2021). Hence the surface charge of the MPs is an important parameter that determines the rate of adsorption. A recent study shows effective MPs removal using granular activated carbon (GAC) adsorption with thermal regeneration. This study proposes to retrofit the existing STP with GAC combined with thermal regeneration as the process ensures more than 92% removal of MPs ranging from 20 to 50 µm (Kim & Park 2021).

5.2.4 Membrane Technologies

The application of membranes is highly effective for the treatment of MPs present in wastewater. Such membrane filtration units are reported to remove MPs with higher efficiency and maintain stable effluent quality and ease of treatment (Poerio et al. 2019). It is reported that the influent load and particle concentration are the critical parameters to be considered in the filtration of MPs (Li et al. 2018). The design of polymer coatings with elongated mesh is also found to be an effective method for the removal of MPs (Mohana et al. 2021). Size exclusion, electrostatic interaction, hydrophobic interaction, and biofilm formation are the basic mechanisms by which MPs are usually removed in a membrane technique (Joo et al. 2021).

Coupling the biological reactors with membrane units is another effective option for removing polymeric debris and MPs present in industrial wastewater (Talvitie et al. 2017). A simple schematic representing the removal of MPs while passing through the membrane modules (ultrafiltration unit) is presented in Fig. 5.4. The effective interaction between MPs and the ultrafiltration unit results in the complete removal of MPs (Enfrin et al. 2020). A comparison study was conducted by Lv et al. 2019 between MBR and oxidation ditch. The results revealed that MBR has exceptional efficiency over the oxidation ditch in the treatment of MPs. However, the limiting factors such as membrane congestion and control of biofilm reduce the efficiency of MBR in treating MPs (Lares et al. 2018; Nicolella et al. 2000). Studies have reported that smaller plastic fragments are very difficult to be removed in the tertiary treatment units and the treatment options such as biological filters and advanced separation systems are not effective as membrane bioreactors which ensures almost 99.9% removal efficiency (Mason et al. 2016; Talvitie et al. 2017). However, optimization of different parameters, including membrane surface charge, fouling phenomena, transmembrane pressure, membrane material, pore size, and hydraulic retention time are important for the effective removal of MPs.

A case study has showcased the capability of removing MPs in effluent at a WWTP using membrane process in Mikkeli, Finland (Hermabessiere et al. 2017). Dynamic membrane (DM) is considered an appealing membrane-based method for wastewater that works on the principle of cake layer-based formation (Poerio et al. 2019). In wastewater treatment, DM performs the function of a secondary membrane filter; however, compared to MF/UF, membrane performance is weakened due to dense fouling and thick layers (Baresel et al. 2019). The reverse osmosis (RO) process can also be effectively implemented in WWTPs to remove MPs. Tertiary treatment involving ultrafiltration and RO are reported to be efficient for removing MPs (Ziajahromi et al. 2017).

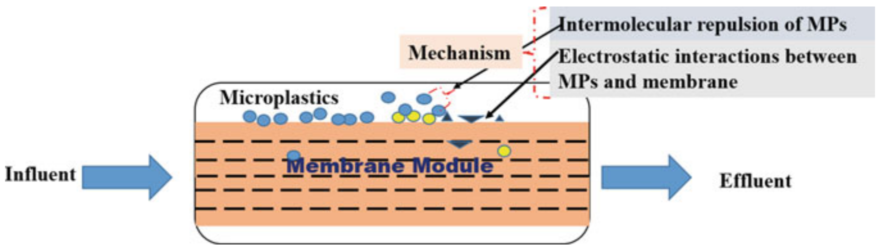

Fig. 5.4 Removal of MPs using ultrafiltration unit (figure modified from Enfrin et al. 2020)

5.2.5 Electrocoagulation

The electrocoagulation processes are considered to be an effective method for the removal of MPs as the coagulants produced from the metal electrodes are more likely to encounter the MPs present in wastewater with several advantages, including lower sludge production and minimal operating cost (Akarsu & Deniz, 2021; Elkhatib et al. 2021). The performance of electrocoagulation processes has been evaluated using a bench-scale electrocoagulation unit (Fig. 5.5) and found to be most effective in removing MPs at neutral pH as the rate of coagulant formation is higher at neutral pH (Perren et al. 2018).

In a recent study conducted by Ariza-Tarazona et al. (2019), the efficiency of iron and aluminum salt coagulants in removing polyethylene has been compared and concluded that aluminum-based coagulants had shown better removal efficiency than iron salt. This study also noted a reduction in the removal efficiency with the rise in pH, and the smaller plastic fragments below 0.5 mm are found to be hardly removed at a higher pH range. The study also inferred that an enhancing coagulation agent such as polyacrylamide had improved the removal efficiency of smaller MPs. Electrocoagulation processes have been successfully employed for the removal of microbeads using aluminum as the electrode material. Perren et al. (2018) investigated different parameters, including the effect of pH and electrode to electrode distance that affects the MPs removal rate. Higher removal efficiency (more than 90%) was reported over the lower pH values (pH 3). Kim et al. (2021) reported that about 90% of MPs were converted to separable flocs in the electrocoagulation unit, which would later be removed in any tertiary treatment unit.

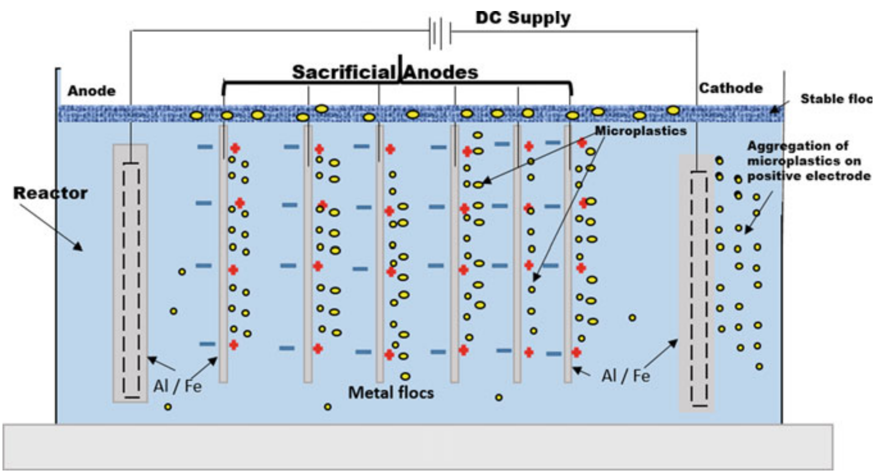

Fig. 5.5 Electrocoagulation unit adopted for the removal of MPs (figure modified from Perren et al. 2018)

5.2.6 Advanced Oxidation Processes

The applicability of the advanced oxidation process (AOP) has been explored as a tertiary treatment option for removing MPs. Recently, the combined influence of Fenton and heat-activated persulfate methods in the long-term degradation of polyethylene and polystyrene MPs have been studied (Liu et al. 2019c). The influence of the average size and oxygen to carbon ratio (O/C) ratio of MPs in the surface properties and the adsorption capacity was analyzed in this study, and concluded that these parameters have significantly changed the oxidation rate of MPs. The alterations in the surface of MPs in an advanced oxidation process are usually evaluated for the O/C ratio (Liu et al. 2019b). The morphological and structural variations of polyethylene MPs during the dark and UV light degradation have been evaluated in a recent study (Da Costa et al. 2018). It is observed that salinity increased the rate of degradation of MPs compared to UV irradiation (Suhrhoff et al. 2016). Hence the salinity of the surrounding media plays an important factor in the photodegradation of MPs as salts enhance the formation of oxidized sites (Vasile and Pascu 2005).

The disintegration of MPs by the photocatalytic method has been recently explored and reported as a potential treatment option for the mineralization of polymer (Tofa et al. 2019). The light source is chosen depending upon the type of photocatalyst and the amount of energy required for the extraction of electrons from the valence band of the photocatalyst. Many of the recent studies have effectively utilized photocatalysis for the effective degradation of MPs. The applicability of TiO_2 (Ariza-Tarazona et al. 2020; Luo et al. 2021) and ZnO (Uheida et al. 2021) photocatalysts for the photocatalytic degradation of MPs have been majorly explored in this field. Liang et al. (2013) reported improved photocatalytic degradation of low-density polyethylene by grafting hydrophilic polyacrylamide on the TiO_2 photocatalyst.

The apparent conditions of the degradation for polypropylene (PP), polystyrene (PS), and polyethylene (PE) are cracks/flakes and granular oxidation. However, the most vulnerable MPs that can change the configuration to a smaller range or even nano range are the ones that develop cracks and flakes (Cai et al. 2018). These fissures are referred to as stress concentrators and fractures, formed at the brittle or weak spots of MPs (Cooper, 2012). The application of UV irradiation initiates the splitting of C-H bonds and C–C bonds, which results in the formation of peroxy free radicals (Cai et al. 2018; Gewert et al. 2015). Furthermore, application of UV irradiation activates hydroxyl, carbonyl, hydroperoxide, and chromophore groups in the surface of MPs that causes the formation of free radicals and marks the beginning of chain reactions that ultimately leads to the complete mineralization of MPs. The removal efficiency reported with AOP is comparatively lower; however, these methods could achieve maximum mineralization of MPs (Lam et al. 2020).

The pros and cons of different technologies need to be evaluated for selecting the suitable treatment scheme for removing MPs. High energy demand, membrane fouling, sludge accumulation, microbial aggregation on the membrane surface are some of the inherent demerits encountered with conventional treatments and membrane processes that can be avoided by the extended application of photocatalytic processes with efficient utilization of solar energy. Filtration systems are a comparatively low-cost option for MPs mitigation. However, the lower removal rate of MPs has been reported with filtration units, and this might be due to the longitudinal movement of MPs fragments through the filter media (Sun et al. 2019). Hence additional final stage treatment units should be supported with filtration systems in WWTPs to remove smaller fragments of MPs. In most cases, during the backwashing of the filters, the solids removed may again be sent back to the beginning stage, adding the loading rate of MPs in the WWTPs.

The retention of a significant fraction of MPs in the sewage sludge limits the visibility of biological processes in the treatment of MPs. However, research focusing on the leaching of monomers from MPs during the biodegradation and studies focusing on the transformation of MPs in specific units of WWTPs are scanty. The interactions of MPs with the surface of the membrane are not clearly understood, and further studies need to be conducted in this area. The effect of other pollutants and the operating parameters on the fate of MPs in different treatment units should be investigated, and the underlying mechanisms of removal need to be substantiated. Future studies should also focus on the reaction intermediates generated during photocatalysis and other AOPs during the treatment of MPs.

5.3 Conclusions

Plastic polymers are inevitable in human lives due to their continued demand in all sectors. Though it seems a considerable removal, still WWTPs are majorly contributing to MPs contamination to the environment. The MPs-loaded effluent released from the WWTPs ultimately merges with waterbodies. Being an emerging contaminant, MPs serve as carriers of metals and organic contaminants. Bioaccumulation of MPs is inevitable considering the cumulative emission of MPs into the water bodies. Therefore, maximizing the removal of MPs in WWTPs would eliminate a possible pathway of MPs into the environment. However, there are uncertainties in comparing the removal efficiencies of MPs in WWTPs due to the multiple possible removal mechanisms and lack of standardized sampling/identification methods. Proper standardization and the periodic assessment of treatment units are required for a greater degree of evaluation of the fate of the MPs in WWTPs. Different technologies are being explored for the removal of MPs, such as adsorption, filtration, membrane technologies, electrocoagulation, and advanced oxidation processes such as photocatalysis. The coupling of different secondary and tertiary schemes would significantly reduce the MPs concentration in the treated effluent. Membrane filtration is reported to be a promising technology; however, further research is required to address the challenges related to membrane fouling issues. Ample attention should be given to the development of treatment methods that focus on the complete mineralization of the MPs to curb the emission, and further studies are needed in this direction.

References

Abbasi S, Keshavarzi B, Moore F, Turner A, Kelly FJ, Dominguez AO, Jaafarzadeh N (2019) Distribution and potential health impacts of microplastics and micro rubbers in air and street dusts from Asaluyeh County, Iran. Environ Pollut 244:153–164. https://doi.org/10.1016/j.envpol.2018.10.039

Akarsu C, Deniz F (2021) Electrocoagulation/electroflotation process for removal of organics and microplastics in laundry wastewater. Clean: Soil, Air, Water. https://doi.org/10.1002/clen.202000146

Alia JM, Herrmann KMK, Rakestrawb MJ, Alan S, Coady K (2016) Learned discourses: timely scientific opinions learned discourse: timely scientific opinions 12(2), 397–406. https://doi.org/10.1002/ieam.1732

Andrady AL (2011) Microplastics in the marine environment. Mar Pollut Bull 62(8):1596–1605. https://doi.org/10.1016/j.marpolbul.2011.05.030

Andrady AL (2017) The plastic in microplastics: a review. Mar Pollut Bull 119(1):12–22

Ariza-Tarazona MC, Villarreal-Chiu JF, Barbieri V, Siligardi C, Cedillo-González EI (2019) New strategy for microplastic degradation: green photocatalysis using a protein-based porous N-TiO_2 semiconductor. Ceram Int 45(7):9618–9624

Ariza-Tarazona MC, Villarreal-Chiu JF, Hernández-López JM, De la Rosa JR, Barbieri V, Siligardi C, Cedillo-González EI (2020) Microplastic pollution reduction by a carbon and nitrogen-doped TiO_2: effect of pH and temperature in the photocatalytic degradation process. J Hazard Mater 395:122632

Bakaraki Turan N, Sari Erkan H, Onkal Engin G (2021) Microplastics in wastewater treatment plants: occurrence, fate and identification. Process Saf Environ Prot. https://doi.org/10.1016/j.psep.2020.08.039

Baldwin V, Bhatia M, Luckey M (2011) Folding studies of purified LamB protein, the maltoporin from the Escherichia coli outer membrane: trimer dissociation can be separated from unfolding. Biochim Biophys Acta (BBA)—Biomembranes 1808(9):2206–2213. https://doi.org/10.1016/j.bbamem.2011.05.013

Baresel C, Harding M, Fang J (2019) Ultrafiltration/granulated active carbon-biofilter: efficient removal of a broad range of micropollutants. Appl Sci (Switzerland). https://doi.org/10.3390/app9040710

Bayo J, Olmos S, López-Castellanos J (2020) Microplastics in an urban wastewater treatment plant: the influence of physicochemical parameters and environmental factors. Chemosphere 238:124593

Bhattacharjee S (2016) DLS and zeta potential—what they are and what they are not? J Control Release. https://doi.org/10.1016/j.jconrel.2016.06.017

Bond T, Ferrandiz-Mas V, Felipe-Sotelo M, Van Sebille E (2018) The occurrence and degradation of aquatic plastic litter based on polymer physicochemical properties: a review. Crit Rev Environ Sci Technol 48(7–9):685–722

Bretas Alvim C, Castelluccio S, Ferrer-Polonio E, Bes-Piá MA, Mendoza-Roca JA, Fernández-Navarro J, Alonso JL, Amorós I (2021) Effect of polyethylene microplastics on activated sludge process—accumulation in the sludge and influence on the process and on biomass characteristics. Process Saf Environ Prot. https://doi.org/10.1016/j.psep.2020.10.014

Bretas Alvim C, Mendoza-Roca JA, Bes-Piá A (2020) Wastewater treatment plant as microplastics release source—quantification and identification techniques. J Environ Manage 255, 109739. https://doi.org/10.1016/j.jenvman.2019.109739

Browne MA, Crump P, Niven SJ, Teuten E, Tonkin A, Galloway T, Thompson R (2011) Accumulation of microplastic on shorelines woldwide: sources and sinks. Environ Sci Technol 45(21):9175–9179. https://doi.org/10.1021/es201811s

Cai L, Wang J, Peng J, Wu Z, Tan X (2018) Observation of the degradation of three types of plastic pellets exposed to UV irradiation in three different environments. Sci Total Environ 628:740–747

Carr SA, Liu J, Tesoro AG (2016) Transport and fate of microplastic particles in wastewater treatment plants. Water Res. https://doi.org/10.1016/j.watres.2016.01.002

Chang M (2015) Reducing microplastics from facial exfoliating cleansers in wastewater through treatment versus consumer product decisions. Mar Pollut Bull 101(1):330–333. https://doi.org/10.1016/j.marpolbul.2015.10.074

Chen H, Tang M, Yang X, Tsang YF, Wu Y, Wang D, Zhou Y (2021) Polyamide 6 microplastics facilitate methane production during anaerobic digestion of waste activated sludge. Chem Eng J. https://doi.org/10.1016/j.cej.2020.127251

Chesters SP, Pena N, Gallego S, Fazel M, Armstrong MW, del Vigo F (2013) Results from 99 seawater RO membrane autopsies. IDA J Desalin Water Reuse 5(1):40–47

Cooper DA (2012) Effects of chemical and mechanical weathering processes on the degradation of plastic debris on marine beaches

Dey TK, Uddin ME, Jamal M (2021) Detection and removal of microplastics in wastewater: evolution and impact. Environ Sci Pollut Res 1–23

Dris R, Gasperi J, Rocher V, Saad M, Renault N, Tassin B (2015a) Microplastic contamination in an urban area: a case study in Greater Paris. Environ Chem 12(5):592–599

Dris R, Imhof H, Sanchez W, Gasperi CJ (2015) Special front issue beyond the ocean: contamination of freshwater ecosystems with (micro-) plastic particles, 539–550

Dussud C, Ghiglione JF (2014) Bacterial degradation of synthetic plastics. In: CIESM workshop monogr 46:49–54

Edo C, González-Pleiter M, Leganés F, Fernández-Piñas F, Rosal R (2020) Fate of microplastics in wastewater treatment plants and their environmental dispersion with effluent and sludge. Environ Pollut 259. https://doi.org/10.1016/j.envpol.2019.113837

Elkhatib D, Oyanedel-Craver V, Carissimi E (2021) Electrocoagulation applied for the removal of microplastics from wastewater treatment facilities. Sep Purif Technol. https://doi.org/10.1016/j.seppur.2021.118877

Enfrin M, Lee J, Le-Clech P, Dumée LF (2020) Kinetic and mechanistic aspects of ultrafiltration membrane fouling by nano- and microplastics. J Membr Sci. https://doi.org/10.1016/j.memsci.2020.117890

Eriksen M, Lebreton LCM, Carson HS, Thiel M, Moore CJ, Borerro JC, Galgani F, Ryan PG, Reisser J (2014) Plastic pollution in the world's oceans: more than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. PLoS ONE. https://doi.org/10.1371/journal.pone.0111913

Ezel ANVANW, Aris INEZC, Ools STAEK (2016) Plastic debris in the aquatic environment release of primary microplastics from consumer products to wastewater in The Netherlands. Environ Toxicol 35(7):1627–1631. https://doi.org/10.1002/etc.3316

Faisal AAH, Sulaymon AH, Khaliefa QM (2018) A review of permeable reactive barrier as passive sustainable technology for groundwater remediation. Int J Environ Sci Technol. https://doi.org/10.1007/s13762-017-1466-0

Fendall LS, Sewell MA (2009) Contributing to marine pollution by washing your face: microplastics in facial cleansers. Mar Pollut Bull 58(8):1225–1228

Foerster KH (2018) Plastics-the facts 2017. Association of Plastic Manufacturers, Brussels

Frias JPGL, Nash R (2019) Microplastics: finding a consensus on the definition. Mar Pollut Bull 138:145–147. https://doi.org/10.1016/j.marpolbul.2018.11.022

Gewert B, Plassmann MM, Macleod M (2015) Pathways for degradation of plastic polymers floating in the marine environment. Environ Sci Process Impacts 17(9):1513–1521. https://doi.org/10.1039/c5em00207a

Gies EA, LeNoble JL, Noël M, Etemadifar A, Bishay F, Hall ER, Ross PS (2018) Retention of microplastics in a major secondary wastewater treatment plant in Vancouver, Canada. Mar Pollut Bull 133:553–561

Golwala H, Zhang X, Iskander SM, Smith AL (2021) Solid waste: An overlooked source of microplastics to the environment. Sci Total Environ. https://doi.org/10.1016/j.scitotenv.2020.144581

González-Pleiter M, Tamayo-Belda M, Pulido-Reyes G, Amariei G, Leganés F, Rosal R, Fernández-Piñas F (2019) Secondary nanoplastics released from a biodegradable microplastic severely impact freshwater environments. Environ Sci Nano 6(5):1382–1392. https://doi.org/10.1039/c8en01427b

Gregory MR (2009) Environmental implications of plastic debris in marine settings—entanglement, ingestion, smothering, hangers-on, hitch-hiking and alien invasions. Philos Trans R Soc B Biol Sci 364(1526):2013–2025

Guo J-J, Huang X-P, Xiang L, Wang Y-Z, Li Y-W, Li H, Cai Q-Y, Mo C-H, Wong M-H (2020) Source, migration and toxicology of microplastics in soil. Environ Int 137:105263. https://doi.org/10.1016/j.envint.2019.105263

Guo W, Ngo H-H, Li J (2012) A mini-review on membrane fouling. Bioresour Technol 122:27–34. https://doi.org/10.1016/j.biortech.2012.04.089

Habib RZ, Thiemann T, Al Kendi R (2020) Microplastics and wastewater treatment plants—a review. J Water Resour Prot. https://doi.org/10.4236/jwarp.2020.121001

Han M, Niu X, Tang M, Zhang B-T, Wang G, Yue W, Kong X, Zhu J (2020) Distribution of microplastics in surface water of the lower Yellow River near estuary. Sci Total Environ 707:135601. https://doi.org/10.1016/j.scitotenv.2019.135601

Hartline NL, Bruce NJ, Karba SN, Ruff EO, Sonar SU, Holden PA (2016) Microfiber masses recovered from conventional machine washing of new or aged garments. Environ Sci Technol 50(21):11532–11538

Hartmann NB, Hüffer T, Thompson RC, Hassellöv M, Verschoor A, Daugaard AE, Rist S, Karlsson T, Brennholt N, Cole M, Herrling MP, Hess MC, Ivleva NP, Lusher AL, Wagner M (2019) Are we speaking the same language? Recommendations for a definition and categorization framework for plastic debris. Environ Sci Technol 53(3):1039–1047. https://doi.org/10.1021/acs.est.8b05297

He D, Bristow K, Filipović V, Lv J, He H (2020) Microplastics in terrestrial ecosystems: a scientometric analysis. Sustainability (Switzerland). https://doi.org/10.3390/su12208739

Hermabessiere L, Dehaut A, Paul-Pont I, Lacroix C, Jezequel R, Soudant P, Duflos G (2017) Occurrence and effects of plastic additives on marine environments and organisms: a review. Chemosphere 182:781–793

Hidayaturrahman H, Lee TG (2019) A study on characteristics of microplastic in wastewater of South Korea: identification, quantification, and fate of microplastics during treatment process. Mar Pollut Bull. https://doi.org/10.1016/j.marpolbul.2019.06.071

Hou L, Kumar D, Yoo CG, Gitsov I, Majumder ELW (2021) Conversion and removal strategies for microplastics in wastewater treatment plants and landfills. Chem Eng J. https://doi.org/10.1016/j.cej.2020.126715

Hurley RR, Lusher AL, Olsen M, Nizzetto L (2018) Validation of a method for extracting microplastics from complex, organic-rich, environmental matrices. Environ Sci Technol. https://doi.org/10.1021/acs.est.8b01517

Iyare PU, Ouki SK, Bond T (2020) Microplastics removal in wastewater treatment plants: a critical review. Environ Sci: Water Res Technol 6(10):2664–2675. https://doi.org/10.1039/d0ew00397b

Jain S, Mishra D, Khare P (2021) Microplastics as an emerging contaminant in environment: occurrence, distribution, and management strategy. In: Management of contaminants of emerging concern (CEC) in environment. https://doi.org/10.1016/b978-0-12-822263-8.00010-5

Jeong CB, Won EJ, Kang HM, Lee MC, Hwang DS, Hwang UK, Lee JS (2016) Microplastic size-dependent toxicity, oxidative stress induction, and p-JNK and p-p38 activation in the monogonont rotifer (Brachionus koreanus). Environ Sci Technol 50(16):8849–8857

Jiang J, Wang X, Ren H, Cao G, Xie G, Xing D, Liu B (2020) Investigation and fate of microplastics in wastewater and sludge filter cake from a wastewater treatment plant in China. Science Total Environ 746:141378. https://doi.org/10.1016/j.scitotenv.2020.141378

Joo SH, Liang Y, Kim M, Byun J, Choi H (2021) Microplastics with adsorbed contaminants: mechanisms and treatment. Environ Challenges 100042

Kalčíková G, Alič B, Skalar T, Bundschuh M, Gotvajn AŽ (2017) Wastewater treatment plant effluents as source of cosmetic polyethylene microbeads to freshwater. Chemosphere. https://doi.org/10.1016/j.chemosphere.2017.08.131

Kaliszewicz A, Winczek M, Karaban K, Kurzydłowski D, Górska M, Koselak W, Romanowski J (2020) The contamination of inland waters by microplastic fibres under different anthropogenic pressure: preliminary study in Central Europe (Poland) 1–8. https://doi.org/10.1177/0734242X20938448

Kärrman A, Schönlau C, Engwall M (2016) Exposure and effects of microplastics on wildlife: a review of existing data
Kim KT, Park S (2021) Enhancing microplastics removal from wastewater using electrocoagulation and granule-activated carbon with thermal regeneration. Processes. https://doi.org/10.3390/pr9040617
Kuoppamäki K, Pflugmacher Lima S, Scopetani C, Setälä H (2021) The ability of selected filter materials in removing nutrients, metals, and microplastics from stormwater in biofilter structures. J Environ Qual. https://doi.org/10.1002/jeq2.20201
Lambert S, Sinclair C, Boxall A (2014) Occurrence, degradation, and effect of polymer-based materials in the environment. Rev Environ Contam Toxicol 227:1–53
Lares M, Ncibi MC, Sillanpää M, Sillanpää M (2018) Occurrence, identification and removal of microplastic particles and fibers in conventional activated sludge process and advanced MBR technology. Water Res 133:236–246
Lee H, Kim Y (2018) Treatment characteristics of microplastics at biological sewage treatment facilities in Korea. Mar Pollut Bull 137:1–8. https://doi.org/10.1016/j.marpolbul.2018.09.050
Lee J, Enfrin M, Dum LF (2019) Nano/microplastics in water and wastewater treatment processes—origin, impact and potential solutions. Water Res 161. https://doi.org/10.1016/j.watres.2019.06.049
Li L, Xu G, Yu H, Xing J (2018) Dynamic membrane for micro-particle removal in wastewater treatment: performance and influencing factors. Sci Total Environ 627:332–340
Li X, Mei Q, Chen L, Zhang H, Dong B, Dai X, Zhou J (2019) Enhancement in adsorption potential of microplastics in sewage sludge for metal pollutants after the wastewater treatment process. Water Res 157:228–237
Liang W, Luo Y, Song S, Dong X, Yu X (2013) High photocatalytic degradation activity of polyethylene containing polyacrylamide grafted TiO_2. Polym Degrad Stab 98(9):1754–1761
Lin X, Su C, Deng X, Wu S, Tang L, Li X, Liu J, Huang X (2020) Influence of polyether sulfone microplastics and bisphenol A on anaerobic granular sludge: performance evaluation and microbial community characterization. Ecotoxicol Environ Saf. https://doi.org/10.1016/j.ecoenv.2020.111318
Liu G, Zhu Z, Yang Y, Sun Y, Yu F, Ma J (2019a) Sorption behavior and mechanism of hydrophilic organic chemicals to virgin and aged microplastics in freshwater and seawater. Environ Pollut 246:26–33. https://doi.org/10.1016/j.envpol.2018.11.100
Liu P, Qian L, Wang H, Zhan X, Lu K, Gu C, Gao S (2019b) New Insights into the aging behavior of microplastics accelerated by advanced oxidation processes. Environ Sci Technol 53(7):3579–3588. https://doi.org/10.1021/acs.est.9b00493
Liu X, Yuan W, Di M, Li Z, Wang J (2019c) Transfer and fate of microplastics during the conventional activated sludge process in one wastewater treatment plant of China. Chem Eng J 362:176–182
Liu F, Nord NB, Bester K, Vollertsen J (2020) Microplastics removal from treated wastewater by a biofilter. Water (switzerland) 12(4):1–11. https://doi.org/10.3390/W12041085
Liu W, Zhang J, Liu H, Guo X, Zhang X, Yao X, Cao Z, Zhang T (2021) A review of the removal of microplastics in global wastewater treatment plants: characteristics and mechanisms. Environ Int 146:106277
Luo H, Xiang Y, Li Y, Zhao Y, Pan X (2021) Photocatalytic aging process of Nano-TiO_2 coated polypropylene microplastics: combining atomic force microscopy and infrared spectroscopy (AFM-IR) for nanoscale chemical characterization. J Hazard Mater 404:124159
Lv X, Dong Q, Zuo Z, Liu Y, Huang X, Wu WM (2019) Microplastics in a municipal wastewater treatment plant: fate, dynamic distribution, removal efficiencies, and control strategies. J Clean Prod 225:579–586
Ma J, Zhao J, Zhu Z, Li L, Yu F (2019) Effect of microplastic size on the adsorption behavior and mechanism of triclosan on polyvinyl chloride. Environ Pollut 254:113104. https://doi.org/10.1016/j.envpol.2019.113104
Magni S, Binelli A, Pittura L, Avio CG, Della Torre C, Parenti CC, Gorbi S, Regoli F (2019) The fate of microplastics in an Italian Wastewater Treatment Plant. Sci Total Environ 652:602–610. https://doi.org/10.1016/j.scitotenv.2018.10.269

Magnusson K, Norén F (2014) Screening of microplastic particles in and down-stream a wastewater treatment plant
Mammo FK, Amoah ID, Gani KM, Pillay L, Ratha SK, Bux F, Kumari S (2020) Microplastics in the environment: interactions with microbes and chemical contaminants. Sci Tot Environ 140518
Mason SA, Garneau D, Sutton R, Chu Y, Ehmann K, Barnes J, Fink P, Papazissimos D, Rogers DL (2016) Microplastic pollution is widely detected in US municipal wastewater treatment plant effluent. Environ Pollut 218:1045–1054. https://doi.org/10.1016/j.envpol.2016.08.056
Michielssen MR, Michielssen ER, Ni J, Duhaime MB (2016) Fate of microplastics and other small anthropogenic litter (SAL) in wastewater treatment plants depends on unit processes employed. Environ Sci Water Res Technol 2(6):1064–1073
Miller ME, Hamann M, Kroon FJ (2020) Bioaccumulation and biomagnification of microplastics in marine organisms: a review and meta-analysis of current data. PLoS ONE. https://doi.org/10.1371/journal.pone.0240792
Mintenig SM, Int-Veen I, Löder MGJ, Primpke S, Gerdts G (2017) Identification of microplastic in effluents of waste water treatment plants using focal plane array-based micro-Fourier-transform infrared imaging. Water Res 108:365–372
Miri S, Saini R, Davoodi SM, Pulicharla R, Brar SK, Magdouli S (2021) Biodegradation of microplastics: better late than never. Chemosphere 131670
Miri S, Saini R, Davoodi SM, Pulicharla R, Brar SK, Magdouli S (2022) Biodegradation of microplastics: better late than never. Chemosphere. https://doi.org/10.1016/j.chemosphere.2021.131670
Mohana AA, Farhad SM, Haque N, Pramanik BK (2021) Understanding the fate of nano-plastics in wastewater treatment plants and their removal using membrane processes. Chemosphere 284:131430
Murphy F, Ewins C, Carbonnier F, Quinn B (2016) Wastewater treatment works (WwTW) as a source of microplastics in the aquatic environment. Environ Sci Technol 50(11):5800–5808
Napper IE, Bakir A, Rowland SJ, Thompson RC (2015) Characterisation, quantity and sorptive properties of microplastics extracted from cosmetics. Mar Pollut Bull 99(1–2):178–185
Ngo PL, Pramanik BK, Shah K, Roychand R (2019) Pathway, classification and removal efficiency of microplastics in wastewater treatment plants. Environ Pollut. https://doi.org/10.1016/j.envpol.2019.113326
Niaounakis M (2017) Management of marine plastic debris. William Andrew
Nicolella C, Van Loosdrecht MCM, Heijnen JJ (2000) Wastewater treatment with particulate biofilm reactors. J Biotechnol 80(1):1–33
Nolte TM, Hartmann NB, Kleijn JM, Garnæs J, Van De Meent D, Hendriks AJ, Baun A (2017) The toxicity of plastic nanoparticles to green algae as influenced by surface modification, medium hardness and cellular adsorption. Aquat Toxicol 183:11–20
Oberbeckmann S, Löder MG, Labrenz M (2015) Marine microplastic-associated biofilms–a review. Environ Chem 12(5):551–562
Ou H, Zeng EY (2018) Occurrence and fate of microplastics in wastewater treatment plants. In: Microplastic contamination in aquatic environments: an emerging matter of environmental urgency. Elsevier Inc. https://doi.org/10.1016/B978-0-12-813747-5.00010-2
Padervand M, Lichtfouse E, Robert D, Wang C (2020) Removal of microplastics from the environment. A review. Environ Chem Lett 1–22
Perren W, Wojtasik A, Cai Q (2018) Removal of microbeads from wastewater using electrocoagulation. ACS Omega 3(3):3357–3364
Poerio T, Piacentini E, Mazzei R (2019) Membrane processes for microplastic removal. Molecules 24(22):4148
Raju S, Carbery M, Kuttykattil A, Senathirajah K, Subashchandrabose SR, Evans G, Thavamani P (2018) Transport and fate of microplastics in wastewater treatment plants: implications to environmental health. Rev Environ Sci Biotechnol. https://doi.org/10.1007/s11157-018-9480-3
Rummel CD, Jahnke A, Gorokhova E, Kühnel D, Schmitt-Jansen M (2017) Impacts of biofilm formation on the fate and potential effects of microplastic in the aquatic environment. Environ Sci Technol Lett 4(7):258–267

Salmi P, Ryymin K, Karjalainen AK, Mikola A, Uurasjärvi E (2021) Uncorrected proof particle balance and return loops for microplastics in a tertiary-level wastewater treatment plant. Uncorrected Proof 1–12. https://doi.org/10.2166/wst.2021.209

Singla M, Díaz J, Broto-Puig F, Borrós S (2020) Sorption and release process of polybrominated diphenyl ethers (PBDEs) from different composition microplastics in aqueous medium: solubility parameter approach. Environ Pollut 262:114377. https://doi.org/10.1016/j.envpol.2020.114377

Skariyachan S, Patil AA, Shankar A, Manjunath M, Bachappanavar N, Kiran S (2018) Enhanced polymer degradation of polyethylene and polypropylene by novel thermophilic consortia of Brevibacillus sps. and Aneurinibacillus sp. screened from waste management landfills and sewage treatment plants. Polym Degrad Stab. https://doi.org/10.1016/j.polymdegradstab.2018.01.018

Sol D, Laca A, Laca A, Díaz M (2020) Approaching the environmental problem of microplastics: Importance of WWTP treatments. Sci Total Environ 740:140016. https://doi.org/10.1016/j.scitotenv.2020.140016

Sørensen L, Rogers E, Altin D, Salaberria I, Booth AM (2020) Sorption of PAHs to microplastic and their bioavailability and toxicity to marine copepods under co-exposure conditions. Environ Pollut 258:113844. https://doi.org/10.1016/j.envpol.2019.113844

Suhrhoff TJ, Scholz-Böttcher BM (2016) Qualitative impact of salinity, UV radiation and turbulence on leaching of organic plastic additives from four common plastics—a lab experiment. Mar Pollut Bull 102(1):84–94

Sun J, Dai X, Wang Q, Van Loosdrecht MCM, Ni B (2019) Microplastics in wastewater treatment plants: detection, occurrence and removal. Water Res 152:21–37. https://doi.org/10.1016/j.watres.2018.12.050

Sun Q, Ren SY, Ni HG (2020) Incidence of microplastics in personal care products: an appreciable part of plastic pollution. Sci Total Environ 742:140218

Sundbæk KB, Koch IDW, Villaro CG, Rasmussen NS, Holdt SL, Hartmann NB (2018) Sorption of fluorescent polystyrene microplastic particles to edible seaweed Fucus vesiculosus. J Appl Phycol 30(5):2923–2927

Tagg AS, Sapp M, Harrison JP, Ojeda JJ (2015) Identification and quantification of microplastics in wastewater using focal plane array-based reflectance micro-FT-IR imaging. Anal Chem 87(12):6032–6040. https://doi.org/10.1021/acs.analchem.5b00495

Talvitie J, Mikola A, Koistinen A, Setälä O (2017) Solutions to microplastic pollution–removal of microplastics from wastewater effluent with advanced wastewater treatment technologies. Water Res 123:401–407

Tang N, Liu X, Xing W (2020a) Microplastics in wastewater treatment plants of Wuhan, Central China: abundance, removal, and potential source in household wastewater. Sci Total Environ 745:141026

Tang W, Li X, Liu H, Wu S, Zhou Q, Du C, Teng Q, Zhong Y, Yang C (2020b) Sequential vertical flow trickling filter and horizontal flow multi-soil-layering reactor for treatment of decentralized domestic wastewater with sodium dodecyl benzene sulfonate. Biores Technol. https://doi.org/10.1016/j.biortech.2019.122634

Thompson RC, Olsen Y, Mitchell RP, Davis A, Rowland SJ, John AWG, McGonigle D, Russell AE (2004) Lost at sea: where is all the plastic? Science(Washington) 304(5672):838

Thuptimdang P, Siripattanakul-Ratpukdi S, Ratpukdi T, Youngwilai A, Khan E (2021) Biofiltration for treatment of recent emerging contaminants in water: current and future perspectives. Water Environ Res. https://doi.org/10.1002/wer.1493

Tofa TS, Kunjali KL, Paul S, Dutta J (2019) Visible light photocatalytic degradation of microplastic residues with zinc oxide nanorods. Environ Chem Lett. https://doi.org/10.1007/s10311-019-00859-z

Tong M, He L, Rong H, Li M, Kim H (2020) Transport behaviors of plastic particles in saturated quartz sand without and with biochar/Fe_3O_4-biochar amendment. Water Res. https://doi.org/10.1016/j.watres.2019.115284

Uheida A, Mejía HG, Abdel-Rehim M, Hamd W, Dutta J (2021) Visible light photocatalytic degradation of polypropylene microplastics in a continuous water flow system. J Hazard Mater 406:124299

Vasile C, Pascu M (2005) Practical guide to polyethylene. iSmithers Rapra Publishing

Viveknand AC, Mohapatra S, Tyagi VK (2021) Microplastics in aquatic environment: challenges and perspectives. ECSN 131151. https://doi.org/10.1016/j.chemosphere.2021.131151
Wang J, Liu X, Dai Y, Ren J, Li Y, Wang X, Zhang P, Peng C (2020a) Effects of co-loading of polyethylene microplastics and ciprofloxacin on the antibiotic degradation efficiency and microbial community structure in soil. Sci Total Environ. https://doi.org/10.1016/j.scitotenv.2020.140463
Wang Q, Zhang Y, Wangjin X, Wang Y, Meng G, Chen Y (2020b) The adsorption behavior of metals in aqueous solution by microplastics effected by UV radiation. J Environ Sci 87:272–280
Wang S, Chen H, Zhou X, Tian Y, Lin C, Wang W, Zhou K, Zhang Y, Lin H (2020c) Microplastic abundance, distribution and composition in the mid-west Pacific Ocean. Environ Pollut 264:114125. https://doi.org/10.1016/j.envpol.2020.114125
Wang Z, Sedighi M, Lea-Langton A (2020d) Filtration of microplastic spheres by biochar: removal efficiency and immobilisation mechanisms. Water Res. https://doi.org/10.1016/j.watres.2020.116165
Wang C, Zhao J, Xing B (2021) Environmental source, fate, and toxicity of microplastics. J Hazard Mater. https://doi.org/10.1016/j.jhazmat.2020.124357
Wei W, Huang QS, Sun J, Dai X, Ni BJ (2019) Revealing the mechanisms of polyethylene microplastics affecting anaerobic digestion of waste activated sludge. Environ Sci Technol. https://doi.org/10.1021/acs.est.9b02971
Wright SL, Ulke J, Font A, Chan KLA, Kelly FJ (2020) Atmospheric microplastic deposition in an urban environment and an evaluation of transport. Environ Int 136:105411. https://doi.org/10.1016/j.envint.2019.105411
Xu Z, Bai X, Ye Z (2021) Removal and generation of microplastics in wastewater treatment plants: a review. J Clean Prod. https://doi.org/10.1016/j.jclepro.2021.125982
Yang L, Zhang Y, Kang S, Wang Z, Wu C (2021) Microplastics in soil: a review on methods, occurrence, sources, and potential risk. Sci Total Environ. https://doi.org/10.1016/j.scitotenv.2021.146546
Yazdani Foshtomi M, Oryan S, Taheri M, Darvish Bastami K, Zahed MA (2019) Composition and abundance of microplastics in surface sediments and their interaction with sedimentary heavy metals, PAHs and TPH (total petroleum hydrocarbons). Mar Pollut Bull 149:110655. https://doi.org/10.1016/j.marpolbul.2019.110655
Yoshida S, Hiraga K, Takehana T, Taniguchi I, Yamaji H, Maeda Y, Toyohara K, Miyamoto K, Kimura Y, Oda K (2016) A bacterium that degrades and assimilates poly(ethylene terephthalate). Science. https://doi.org/10.1126/science.aad6359
Yuan J, Ma J, Sun Y, Zhou T, Zhao Y, Yu F (2020) Microbial degradation and other environmental aspects of microplastics/plastics. Sci Total Environ 715:136968
Zhang J, Ma L (2020) Environmental sustainability assessment of a new sewage treatment plant in China based on infrastructure construction and operation phases emergy analysis. Water 12(2):484
Zhang J, Zhao M, Li C, Miao H, Huang Z, Dai X, Ruan W (2020) Evaluation the impact of polystyrene micro and nanoplastics on the methane generation by anaerobic digestion. Ecotoxicol Environ Saf. https://doi.org/10.1016/j.ecoenv.2020.111095
Zhu D, Chen QL, An XL, Yang XR, Christie P, Ke X, Wu LH, Zhu YG (2018) Exposure of soil collembolans to microplastics perturbs their gut microbiota and alters their isotopic composition. Soil Biol Biochem. https://doi.org/10.1016/j.soilbio.2017.10.027
Ziajahromi S, Neale PA, Leusch FDL (2016). Wastewater treatment plant ef fl uent as a source of microplastics: review of the fate, chemical interactions and potential risks to aquatic organisms. Water Sci Technol. https://doi.org/10.2166/wst.2016.414
Ziajahromi S, Neale PA, Rintoul L, Leusch FD (2017) Wastewater treatment plants as a pathway for microplastics: development of a new approach to sample wastewater-based microplastics. Water Res 112:93–99
Ziajahromi S, Neale PA, Telles Silveira I, Chua A, Leusch FDL (2021) An audit of microplastic abundance throughout three Australian wastewater treatment plants. Chemosphere 263:128294. https://doi.org/10.1016/j.chemosphere.2020.128294