Cambridge Prisms: Plastics

www.cambridge.org/plc

An overview of the occurrence and distribution of plastics in wastewater treatment plants and the necessity of developing up-to-date management strategies

Overview Review

Cite this article: Akarsu C, Sönmez VZ and Sivri N (2023). An overview of the occurrence and distribution of plastics in wastewater treatment plants and the necessity of developing up-to-date management strategies. *Cambridge Prisms: Plastics*, **1**, e23, 1–18
https://doi.org/10.1017/plc.2023.23

Received: 19 June 2023
Revised: 01 November 2023
Accepted: 10 November 2023

Keywords:
plastics; wastewater treatment plants; waste management; marine pollution source; SDGs

Corresponding author:
Ceyhun Akarsu;
Email: ceyhunakarsu@iuc.edu.tr

Ceyhun Akarsu[1], Vildan Zülal Sönmez[2] and Nüket Sivri[1]

[1]Department of Environmental Engineering, İstanbul University-Cerrahpaşa, Istanbul, Turkey and [2]Department of Environmental Engineering, Duzce University, Duzce, Turkey

Abstract

Although studies suggest that wastewater treatment plants (WWTPs) are the main pathway for plastics into receiving waters, studies on the origin and fate of plastics entering WWTPs are imprecise and largely unexplored. The analysis of plastics in samples from WWTPs is also a relatively young and growing field compared with the marine environment. Furthermore, recent studies have shown that plastics are not uniformly distributed in WWTPs due to environmental factors and the inherent properties of plastics. Accordingly, this review article attempts to describe the current state of knowledge on plastic pollution in WWTPs and identify future research areas. In particular, this study describes the sources of plastics entering WWTPs and the analytical techniques used for the occurrence and properties of plastics in WWTPs. It also defines the role of these plastics as a possible source of microplastics and discusses the problems they can cause in WWTPs. The factors that can influence the variations in the number of plastics are defined. Furthermore, the policy needs for managing plastic pollution as a contribution to achieving the United Nations Sustainable Development Goals are assessed.

Impact statement

Plastic pollution is a global environmental problem that is becoming increasingly important. Wastewater treatment plants (WWTPs) are a significant source of plastic pollution as they receive a large amount of plastic waste from households and businesses. However, the literature on plastics entering WWTPs and their fate is insufficient and largely unexplored. This review article attempts to describe the current state of knowledge on plastic pollution in WWTPs and identify future research areas.

Introduction

Environmental pollution through chemicals is a global concern, specifically for aquatic ecosystems, threatening the water supplies and food production as they pose significant environmental risks due to their novelty or lack of information about their fate (Bashir et al., 2020). Even those chemicals that have been known for some time may only recently be identified as potentially hazardous to the environment (Bhat et al., 2022). Microplastics (MPs) classify under this category, with recorded data showing increasing concern, particularly in terms of pollution levels in aquatic systems (Andrady, 2011; Twiss, 2016; Blettler et al., 2018). These pollutants are chemicals with no legal status, and their effects on human health or the environment are unknown, according to government-related organizations (Deblonde et al., 2011; Yaşar et al., 2013). Plastic debris poses a particular threat because it is resistant to degradation processes, leading to ubiquitous accumulation in the environment, and because it is resistant to corrosion and damage from various factors (Hu et al., 2019). Furthermore, earlier studies also show that as the volume of this waste in water bodies increases, the amount of solar heat energy trapped in the water per unit volume decreases, resulting in additional energy escaping to the nearby environment and affecting global warming (Ford et al., 2022).

Plastic particles accumulate in wastewater treatment plants (WWTPs) from various sources such as domestic sewage, industrial effluents, rainwater and landfills (Okoffo et al., 2019). Therefore, they have been identified as major sources of plastic release into the environment. Due to primary MPs (PMPs) added to cosmetics and personal care products, and secondary MPs (SMPs) formed during the degradation of synthetic plastics after washing, MPs can be detected in wastewater (Lares et al., 2018). During rainy weather, urban storm water, which may contain MPs from traffic, airborne and synthetic degradation, enters the sewer system either independently or together with street runoff (Sugiura et al., 2021).

MPs pose the problems mentioned previously. Therefore, it is crucial to understand their likely sources and pathways in order to reduce their negative impacts on biotic and abiotic habitats. In addition to MPs, the presence of nanoplastics (NPs) resulting from fragmentation of MP in WWTPs also raises serious questions due to their physicochemical properties and potential damage to ecosystems (Twiss, 2016; Ali et al., 2021). Despite the growing awareness of the scale, nature and impact of MP pollution, there is still not enough information on how plastics enter WWTPs and what happens to them (Rasmussen et al., 2021). Therefore, the purpose of this study is to identify research gaps and provide a thorough overview of the current state of knowledge on plastic pollution in WWTPs. The study draws attention to the lack of knowledge about the sources of plastic inputs into WWTPs and emphasizes the need for further thorough research in this area. Additionally, the study investigates the function of plastics as a potential source of MPs and the difficulties they pose in wastewater treatment, as well as the analytical methods used to assess the presence and properties of plastics in WWTPs. The variables that affect the fluctuation of plastic content in WWTPs are being studied in order to gain a better understanding of the complicated dynamics of plastic pollution in these systems. In addition, the need for policies to effectively manage plastic pollution in line with the United Nations Sustainable Development Goals (SDGs) was assessed.

WWTPs as a potential source of plastic pollution in the environment

WWTPs are designed to effectively remove essential contaminants and purify water by removing debris, organic compounds and inorganic pollutants. Maintaining quality standards for wastewater from urban areas has been a critical aspect of wastewater management. However, the current treatment plants may not provide an adequate solution for the complete removal of plastics from domestic wastewater.

WWTPs usually involves several treatment steps, including screening, sedimentation, flocculation and aeration, which together contribute to the removal of various pollutants, including macroplastics (MaPs) and MPs (Ziajahromi et al., 2021; Keerthana Devi et al., 2022). The initial step of the treatment process usually involves screening of the influent wastewater to remove larger plastic debris, primarily MaPs. Subsequently, in the secondary treatment stage, advanced oxidation tanks ensure that dissolved organic wastes, including MPs, are eliminated through various mechanisms. To ensure the highest possible water quality, tertiary treatment protocols are often used in WWTPs following secondary treatment. Advanced treatment methods, such as activated sand filters, biofilm reactors and membrane bioreactors, are often used as part of tertiary treatment to provide additional purification and removal of MPs before the treated wastewater is discharged into nearby rivers or water bodies (Mahon et al., 2017). Typical processes of WWTP and indicated sources of plastics are schematically given in Figure 1.

Nevertheless, it has been found that the efficacy of treatment varies depending on the specific design and operating parameters of each WWTP. In particular, the accumulation of plastics in treatment units such as sedimentation tanks and pumps poses operational challenges, leading to increased maintenance and reduced efficiency. In addition, the accumulation of plastics in aeration tanks hinders oxygen transport and thus affects the performance of treatment processes (Rasmussen et al., 2021).

According to Karapanagioti (2017), there are two main pathways by which plastics can enter a WWTP. The first is direct exposure, which occurs when people intentionally or accidentally flush solid waste down toilets or sinks (Mattsson et al., 2015). The second is indirect introduction into combined sewer systems, where the sewer system carries both stormwater and wastewater (Di Nunno et al., 2021). In addition, WWTPs serving smaller towns and suburban areas are more likely to contain certain types of MaPs such as cotton buds, as well as other wastes such as condoms, wet wipes, sanitary pads and baby wipes (Alda-Vidal et al., 2020; Besley and Cassidy, 2022; Köklü et al., 2023). This suggests that people in urban areas are more environmentally aware and active than people in suburban areas. This difference could be related to a greater awareness of the functions of urban WWTPs and a greater commitment, sensitivity and responsibility for environmental protection (Mourgkogiannis et al., 2018). Items such as cotton buds, plastic caps and non-plastics such as condoms and baby wipes are common among the plastics found in various WWTPs (Besley and Cassidy, 2022). Due to the difficulty in identifying tiny plastic waste, these smaller plastics can pollute the environment in overflow situations when wastewater is discharged into water bodies (Akarsu et al., 2023).

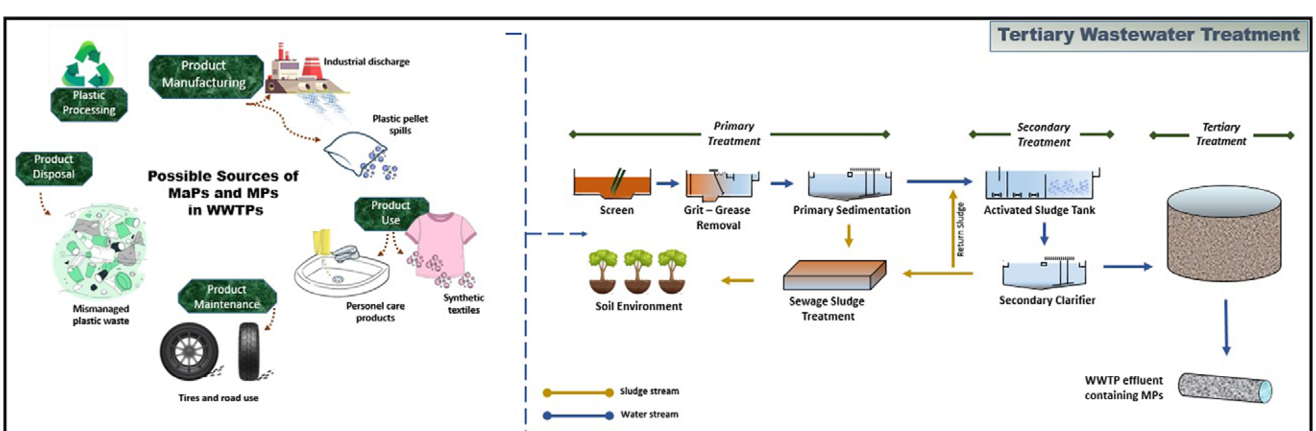

Figure 1. Typical processes of a tertiary WWTP (indicated sources of plastics in WWTP, and primary, secondary and tertiary processes).

https://doi.org/10.1017/plc.2023.23 Published online by Cambridge University Press

Both MPs and MaPs can also enter wastewater directly, for example, when products containing plastics are washed into wastewater (e.g., textile fibers released during laundry, microbeads in consumer goods, sanitary products or cotton buds), or indirectly via the combined sewer system from street debris and litter (Nunno et al., 2021). Although an average of 70% of wastewater is treated in high-income countries, only 20% of wastewater generated is treated worldwide (Duis and Coors, 2016). Furthermore, during periods of heavy rainfall or snowfall, overflows in combined sewers, together with the lack of functioning treatment plants, often result in MPs into the environment through the inefficient treatment of wastewater (Winton et al., 2020).

Some WWTPs should be known for the fact that their effluents flow directly into water bodies (Sun et al., 2023). The significant contribution of WWTP effluents to plastic pollution has been underlined by studies that estimate the daily release of millions or perhaps billions of plastic particles into receiving waters from WWTPs (Carr et al., 2016; Kalčíková et al., 2017; Leslie et al., 2017; Gündoğdu et al., 2018). For instance, one study found that a WWTP with a capacity of about 150,000 $m^3.d^{-1}$ discharges about 87.6 million MPs into the Mersin Bay (Akarsu et al., 2020). According to another study, more than 80% of the 210 trillion microbeads that enter the waters of mainland China each year originate from WWTP effluent (Cheung and Fok, 2017). Similarly, it is estimated that between 50,000 and 15 million plastic particles per day enter freshwater from some sewage treatment plants in the United States (Mason et al., 2016).

The transfer of plastic pollutants from aquatic to terrestrial ecosystems is primarily attributed to the use and disposal of sewage sludge from wastewater treatment. Sewage sludge, which is known to contain high levels of organic matter, nutrients and contaminants such as plastics, has been found to carry an average of 14,750 particles per kilogram (Ragoobur et al., 2021). Initial studies of plastic pollution from sewage sludge application have shown elevated concentration of MP in topsoil compared to non-fertilized soils (Corradini et al., 2019; Tagg et al., 2022; Hassan et al., 2023).

Restrictions such as the German regulation limiting the application of sewage sludge to 5 tons per hectare every 3 years have led to a decline in agricultural use, a trend that is expected to continue if regulations are tightened. Nonetheless, significant amounts of sewage sludge and associated plastics have been intentionally applied to soils in the past. Notably, MPs and NPs pose a significant threat to soil biota by affecting plant growth, organism reproduction and soil biodiversity (Hale et al., 2020). As soil is an important habitat for terrestrial organisms, its fauna is increasingly affected by the ecotoxicological impacts of MPs and NPs, which are ingested by soil invertebrates and poultry and potentially serve as entry points for humans and other animals (Cox et al., 2019). The leaching of additives such as bisphenol A and phthalates from MPs and NPs disrupts the endocrine system of vertebrates and has estrogenic effects (Zhang and Chen, 2020). Several factors, including sunlight, oxygen content, temperature, soil microorganisms and terrestrial biota, contribute to the rate of degradation of plastic waste in the upper soil layer (Wong et al., 2020).

Sources and pathways of plastic waste in wastewater treatment plants

MPs can be divided into two categories depending on their origin: PMPs and SMPs. PMPs, which account for an estimated 19–31% of MPs in the oceans, are plastics that enter the environment directly in the form of small particles. Examples of PMPs are plastics from the manufacture, use or maintenance of MaPs objects such as personal care products (facial cleansers, toothpaste, etc.), tire wear from driving and synthetic textile products from washing (Boucher and Friot, 2017).

On the other hand, SMPs, which is estimated to account for 69–81% of MPs in the oceans (Evangeliou et al., 2022), is formed by the degradation of MaP- and mesoplastic into smaller dimensions. SMPs can enter the marine environment from both terrestrial and marine sources. A major terrestrial source of SMPs is WWTPs, which receive a variety of primary plastic wastes, such as wet wipes, plastic gloves, bandages, diapers, feminine hygiene products and plastic medical consumables (Figure 2). These items are often improperly disposed of in toilets, where they can cause blockages, clogs and overflows and disrupt biological treatment processes in WWTPs. In addition, these items can cause unpleasant odors in sewage systems, pumping stations and treatment plant pipes. Approximately, 75–90% of plastic in the marine environment comes from land-based sources transported via rivers (1.4 Mt/year) and coastal areas (5.1 Mt/year), whereas 10–25% comes from activities such as commercial fishing, maritime transport and sea travel (Belzagui Elder, 2017). Improper disposal of plastic waste is a major contributor to the accumulation of SMPs in the marine environment (Pandey et al., 2022).

The presence of MPs in the influent and effluent of WWTP has been reported in several countries, including the United States (Mason et al., 2016; Ridall et al., 2023), the Netherlands (Leslie et al., 2017), Germany (Mintenig et al., 2017; Barkmann-Metaj et al., 2023), England (Murphy et al., 2016), Sweden (Magnusson and Noren, 2014), Australia (Ziajahromi et al., 2017) and Turkey (Akarsu et al., 2020; Vardar et al., 2021; Koyuncuoğlu and Erden, 2023). Despite the high efficiency of WWTPs in removing of MPs, significant amounts of MPs can still enter into receiving waters. For example, one WWTP serving 650,000 residents was found to have an MP removal efficiency of 98.41%, yet an estimated 65 million MPs were discharged daily (Murphy et al., 2016). Similarly, a study conducted at 17 WWTPs in the United States reported releases of over 4 million MPs per plant per day (Mason et al., 2016). Another example is a WWTP in northern Italy with a population of about 1,200,000 that had a MP removal efficiency of 84%, but still released an estimated 160,000,000 MPs per day (Magni et al., 2019). In a study by Vardar et al., (2021), it was predicted that Ambarlı Advanced Biological WWTP contributes approximately $2,934 \times 10^6$ MPs per day into the Sea of Marmara. These results highlight that despite their treatment efforts, WWTPs can be a significant source of MP pollution, as they continuously discharge large amounts of effluent into the aquatic environment (Bozdaş et al., 2020).

Sampling, sample pre-treatment and analytical methodologies

Sampling and description of WWTP

MPs in WWTPs show heterogeneous distribution in both effluent and sludge (Gao et al., 2023). Although there are no standardized methods for sampling MPs in WWTPs, several successful approaches have been used. These include non-discrete techniques such as continuous pumping combined with *in situ* filtration and discrete sampling methods such as manual sampling or the use of an auto-sampler (Üstün et al., 2022). These different sampling

https://doi.org/10.1017/plc.2023.23 Published online by Cambridge University Press

Figure 2. Visual data depicting the MaPs wastes found within a WWTP (with Prof. Dr. Mustafa Öztürk's permission and consent).

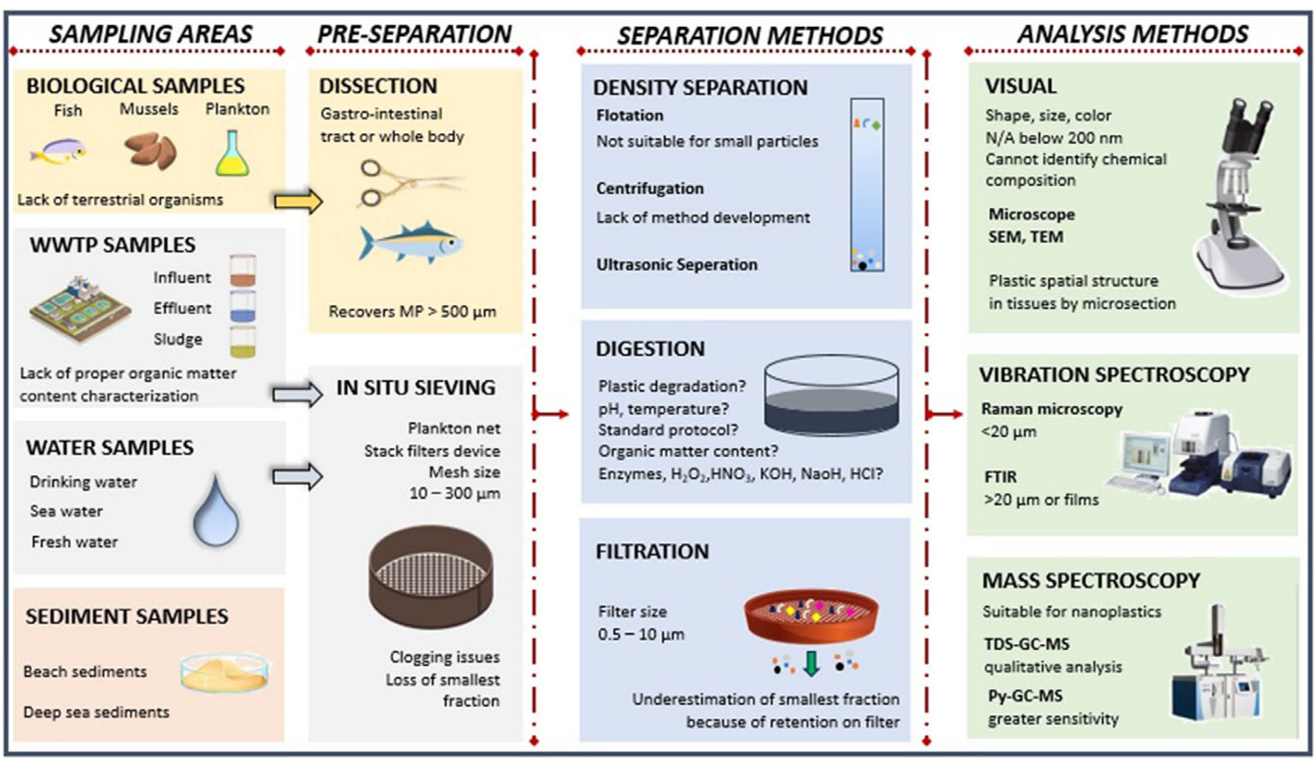

Figure 3. Classification, measurement method and some typical apparatuses (adapted from Ye et al., 2022).

methods allow researchers to effectively detect MP and investigate its presence in different parts of the WWTP (Figure 3).

Among them, grab sampling is the most common method for collecting water, sediment or other environmental matrices to quantify the presence and concentration of MPs (Sönmez et al., 2023). There are a number of different methods for conducting grab sampling, but the most common method is to use a container to collect a set amount of samples (Green et al., 2018). Various sample volumes have been reported for collecting samples from organically contaminated wastewater, ranging from 0.1 L to 50 L (Michielssen et al., 2016; Leslie et al., 2017; Mintenig et al., 2017). These samples are usually taken from both the influent and the biological unit of the WWTP (Table 1).

Sample preparation

MPs found in the environmental matrix have the ability to absorb various pollutants and may also have altered density due to biofilm layers covering its surface (Tu et al., 2020). Therefore, it is important to wash the collected particles several times with distilled water

https://doi.org/10.1017/plc.2023.23 Published online by Cambridge University Press

Table 1. A summary of commonly applied sampling approaches (adapted from Gao et al., 2023)

Sampling method	Volume (L)	Advantages	Disadvantages	References
Wastewater				
Manually grabbing	1–50	■ Simple, fast and easy to perform	■ Limited volume of wastewater	Michielssen et al., 2016
		■ Collecting organic-rich samples	■ Transportation of water samples to the lab	Mintenig et al., 2017
		■ Analyzing MPs down to 1 µm	■ Possibility of false positive data	Leslie et al., 2017
Grabbing with autosamplers	1–360	■ Time-proportional or flow-proportional wastewater	■ Require specialized equipment	Simon et al., 2018)
			■ Highly depend on the place where the equipment is installed	Conley et al., 2019
Surface filtration	Up to 2.32×10^5	■ Easy to use	■ A practical limitation	Carr et al., 2016
		■ Sample large volumes of wastewater	■ Relatively large mesh size should be chosen due to the easy clogging	
			■ Open to fugitive airborne contamination	
			■ May underestimate the MPs with high density	
Separate pumping coupled *in situ* filtration	Up to $4\text{x}10^4$	■ Sample large volumes of wastewater	■ Requires energy to work	Mason et al., 2016
		■ Effortless	■ Potential contamination by apparatus	Talvitie et al., 2017a
		■ Allows choice of mesh size	■ Time consuming depending on mesh size	Talvitie et al., 2017b
			■ Variation with sampled depth	Ziajahromi et al., 2017
Sludge				
Manually grabbing	Up to 60 L	■ Easy to implement	■ Variation with sampled area and depth	Raju et al., 2020
		■ Rapid sampling		Alavian Petroody et al., 2020; Alavian Petroody et al., 2021
		■ Allow replicates		
Grabbing with autosamplers	Up to 5 L	■ Obtain representative samples	■ Requires specialized equipment	Pittura et al., 2021
			■ Highly depend on the place where the equipment is installed	

before determining the morphological characteristics and performing the chemical structure analysis. This washing procedure effectively removes potential contaminants and impurities that could interfere with the subsequent analysis. In some cases, the MaPs and MPs are analyzed directly without undergoing additional processes to detect contaminants or organisms that may be adsorbed on their surface. In the case of water matrices, the separation of MPs is usually done with a series of screens or filters with different mesh or pore sizes through which the collected wastewater is passed (Costa et al., 2021). For example, Ziajahromi et al. (2017) developed a method using a large-volume sampling device with multiple mesh screens to effectively separate various size of MPs from wastewater. This method showed high efficiency with a retention efficiency of 92% for the 25 μm mesh screen and 99% for the 500 μm mesh screen. As an alternative, Besley et al. (2017) proposed a slightly different approach using a fully saturated NaCl solution in combination with filtration for MP extraction. This method allows the quantification of MPs in the size range of 0.3–5 mm.

Filtration is also used to separate them from the aqueous environment to determine the abundance and characterize the morphological properties of MPs. Various filter paper pore sizes have been used in different studies, including 0.2 μm (alumina oxide), 0.45 μm (GF/C), 1.2 μm (GF/C) and 5 μm (silicone, silver) (Robertson, 2018). Among the filter options, glass fiber filters have been widely used in MP research (Hanvey et al., 2017). These filters are commonly selected due to their suitability for capturing MPs and their compatibility with subsequent analysis techniques.

On the other hand, density fractionation methods are widely used to extract MPs from a complex soil matrix. The methods are based on the principle of combining the sample with a saturated salt solution of known density, followed by separation of the MP from its environment after a certain retention time (Sönmez et al., 2022). Retention times for MPs can vary considerably, ranging from 5 min to 48 h (Fries et al., 2013). After the specified retention time, the MPs are separated from the supernatant of the separating funnel so that they are available for subsequent analysis. Sodium chloride (NaCl), sodium iodide (NaI) and zinc chloride ($ZnCl_2$) are commonly used salts in the density-based separation process (Nabi et al., 2022). Among them, NaCl with a density of 1.2 $g.L^{-1}$ is preferred because of its affordability and nontoxic properties (Li et al., 2020). The saturated salt solution with NaCl creates a density gradient that floats the MP particles, which makes the separation process. Using the density separation method with NaCl provides a cost-effective and safe approach to isolate MP based on their density properties (Parashar and Hait, 2023).

Following the separation process, a clean-up procedure to remove microbes and various organic deposits is frequently used (Li et al., 2020). In the literature, various approaches including peroxide digestion (H_2O_2), alkaline digestion (NaOH) and acid digestion (HNO_3 and H_2SO_4) have been used to degrade organic matter in wastewater samples and sewage sludge (Sönmez et al., 2022). Sewage sludge is a more challenging sample than other environmental matrices, especially sediment, as it contains a mixture of organic material from human waste, inorganic solids, food waste, trace chemicals, heavy metals, microbes, pharmaceuticals and other micropollutants (Zhang and Chen, 2020; Gao et al., 2023). Several extraction techniques including oxidative digestion (Bretas Alvim et al., 2020; Cunsolo et al., 2021), alkaline treatment (Mintenig et al., 2017) and acid-based digestion (Hernández-Arenas et al., 2021) have been proposed to remove organics efficiently with minimal impact on MPs. The applicability of Fenton's reagent in the extraction of plastics from environmental matrices such as sludge and soil in combination with density separation has been confirmed (Hurley et al., 2018). Oxidation with hydrogen peroxide coupled with density separation has been shown to reduce chemical consumption, sample pretreatment time and cost by adjusting the reaction temperature (Sujathan et al., 2017; Zhang and Chen, 2020). For samples with high organic content, a mixture of 30% H_2O_2 and 0.05 M Fe(II), known as Fenton reagent, is commonly used. The temperature is usually increased to 50°C to promote decomposition of the organic compounds during the oxidation process (Hurley et al., 2018).

Enzymatic treatments with enzymes such as amylase, lipase, chitinase, proteinase and fibers have also been used to remove organic matter from MPs (Cole et al., 2014; Parashar and Hait, 2023). However, it should be noted that enzymatic treatments can be costly and may have limitations in terms of MP processing efficiency (Zhu and Wang, 2020). In addition, acid and alkali treatments can be used to remove organic matter. However, care should be taken as they can potentially damage certain MP species that are sensitive to pH changes (Sönmez et al., 2022). Among the various isolation methods, the peroxide oxidation is considered effective for MP extraction and offers advantages over other methods.

Analytical methods

Previous studies on MaPs and MPs have performed abundance, enumeration and identification using stereomicroscopy and visual identification based on their physical characterization of type, morphology and color (Derraik, 2002; Andrady, 2011) (Figure 3). However, with increasing number of studies, this method has been found to have more drawbacks. There is a risk of up to 70% in the visual identification of possible plastic particles under the stereomicroscope (Hidalgo-Ruz et al., 2012). To overcome this problem, the use of selected dyes to determine the abundance and types of MPs has become popular (Hurley et al., 2018). However, it is not feasible to find a single dye that is suitable for all types of polymers. While staining remains an effective technique for quantifying and distinguishing different types of MPs, it is not sufficient to determine the colors of MPs, as shown by the research of Tu et al. (2020). When a thorough knowledge of the surface structure of MPs is required, for example, in a study of weathering mechanisms or confirmation of plastisphere potential, the limitations of optical microscopy become apparent. Scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM-EDX) is a useful technique in such situations (Huang et al., 2023). SEM is a very useful tool for the morphological analysis of MPs, as shown by Wagner et al. (2017).

By comparing the characteristic chemical fingerprints of novel particles with a database of spectra of known materials, vibrational spectroscopy is a useful method for detecting unknown particles (Vianello et al., 2013). To identify possible MPs, this method first examines the particles visually. If MP are found, this is then confirmed using methods such as Raman spectroscopy or attenuated total internal reflection Fourier transform infrared spectroscopy (ATR-FTIR) (Yang et al., 2021; De Frond et al., 2023). According to Chalmers (2000), the spectrum of a polymer in ATR-FTIR represents the link between the observed infrared intensity and the wavelength of light. However, it is important to note that FT-IR can identify polar groups more accurately (Silva et al., 2018). While manual processing of particles larger than 500 μm is relatively easy, this method becomes increasingly impractical as particle size decreases (Sönmez et al., 2022).

https://doi.org/10.1017/plc.2023.23 Published online by Cambridge University Press

https://doi.org/10.1017/plc.2023.23 Published online by Cambridge University Press

Table 2. MPs sampling, sample processing, occurrence and identification methods for wastewater and sludge in various WWTPs

Location	Sampling method	MPs: Count: Influent	MPs: Count: Effluent	Size range (μm)	Type	Identification method: MS	Identification method: FTIR	Identification method: Other	References
Wastewater (MPs/L)									
Sweden	Ruttner sampler	15,000	1,800	≥300	Fragments, fibers and flakes	+	+	–	Magnusson and Noren, 2014
United Kingdom	Grab sampler	120	–	–	PE, PP, PVC and Nylon-6	–	+	–	Tagg et al., 2015
United States	Tyler sieves	–	0.004–0.195	125–355	Fibers, fragments, films, foams and beads	+	–	–	Mason et al., 2016
Scotland	Steel buckets	15.70	0.25 ± 0.04	–	–	+	+	–	Murphy et al., 2016
Southern California	SS sieve pans	0.0009	–	>100	PE and microbeads	+	–	–	Carr et al., 2016
Netherlands	Grab Sampling	68–910	51–81	10–5,000	Fibers, spheres and foils	+	+	–	Leslie et al., 2017
Germany	Mobile pump device	–	750.42	20–500	PS, PP, PES, PA, PVC, PET and PVA	+	+	–	Mintenig et al., 2017
Finland	*In situ* filtering	0.3 ± 0.1	0.005 ± 0.004	>20	PES, PE, PP, PS, PU, PVC and PA	+	+	–	Talvitie et al., 2017a
South Korea	Grab sampling	13,813	132	–	Microbeads, fibers, sheet and fragments	+	–	–	Hidayaturrahman and Lee, 2019
Italy	Grab sampling	2.5 ± 0.3	0.4 ± 0.1	100–500	PES and PA	+	+	–	Magni et al., 2019
China	Stainless steel sieves	196 ± 11.89	9.04 ± 1.12	100–500	PET and rayon	+	+	–	Xu et al., 2019b
Korea	Grab sampling	10–470	0.004–0.51	20–45	PP, PE and PET	+	+	–	Park et al., 2020
Spain	Steel scuttle	645.03 ± 182.24–1567.49 ± 413.18	16.40 ± 7–131.35 ± 95.36	100–1,000	PVC, PE and HDPE	+	+	–	Franco et al., 2021
United Kingdom	Grab sampling	955–17,214	2–54	25–178	PE, PP and PET	–	+	–	Jenner et al., 2021
South Korea	Grab sampling	114 ± 17–216 ± 65	0.26 ± 0.29–0.48 ± 0.11	20–200	PP, PE, PVC, PS, PA, PES, PET and PU	+	+	–	Kim et al., 2022
Thailand	Grab sampling	77 ± 7.21	2.33 ± 1.53	50–5,000	PET, PP and PE	+	+	–	Tadsuwan and Babel, 2022
Turkey	Automatic sampler	135.3 ± 28.0	8.5 ± 4.7	500–1000	PP, PE, PS and PA	–	–	–	Üstün et al., 2022
China	Grab sampling	80.3	9.3	<500–2,000	PP, PET, PE, PS and PVC	+	–	–	Yang et al., 2023
Wastewater sludge (MPs/kg)									
Ireland	–	–	0.004	45–250	HDPE	–	–	+	Mahon et al., 2017

(*Continued*)

Table 2. (*Continued*)

		MPs							
		Count				Identification method			
Location	Sampling method	Influent	Effluent	Size range (μm)	Type	MS	FTIR	Other	References
Norway	Metal spoon	–	0.0017–0.0198	54–4,987	PE, PET, PP, PU, PA, PVC and PMMA	+	+	–	Lusher et al., 2017
China	–	–	2,403 ± 0.0314	200–1,000	Fiber, shaft and film	+	+	+	Li et al., 2018b
Spain	Grab sampling	–	0.133 ± 0.059	25–5,000	Fragment, fiber, PE, PET, PP, PMMA, PU, PES and cellophane	+	+	–	Edo et al., 2020
Morocco	Grab sampling	–	0.0405 ± 0.0119	<500–>2,000	PP, PE and PES	+	+	+	El Hayany et al., 2020
Australia	Grab sampling	–	0.0079 ± 0.0004	1.5–>1,000	PET, Nylon, PES, PP, PU, PMMA and PVC	+	+	–	Raju et al., 2020
China	Shovel	–	0.0029 ± 0.0006–0.0053 ± 0.0015	192.84–1,104.41	PBA, rayon, PA, PE, PET, PP, PVC and PS	–	+	+	Xu et al., 2020
United Kingdom	Metal trowel	–	0.214 ± 0.016	25–178	PET, PE, PP, PA, PMMA, PU, PVC and PS	+	+	–	Horton et al., 2021
Iran	Metal shovel	–	0.129 ± 0.017	–	PES, PET, PP, PA, PC, PS and PE	–	+	+	Alavian Petroody et al., 2021
China	Steel shovel	–	0.00023–0.0069	500–5,000	PP, PET and PE	+	+	–	Zhang et al., 2021a

On the other hand, Raman spectroscopy offers several advantages over FTIR, such as better resolution and response to nonpolar symmetric bonds, by exposing the sample to a monochromatic light source, typically a laser (Imhof et al., 2016; Ivleva et al., 2017; Yang et al., 2021). By exciting the molecules with a laser of a single wavelength, the interaction between the radiation and the sample is detected (Li et al., 2018a). The spatial resolution of the Raman microscope improves as the excitation wavelength of the laser decreases (Anger et al., 2018). As another vibrational spectroscopic technique in the analysis of MPs, Raman spectroscopy decodes the molecular vibrations of MPs, provides their vibrational spectrum and gives information about the different components present in the sample (Ribeiro-Claro et al., 2017). Raman spectroscopy allows the characterization of MPs ranging in size from 1 to 20 μm, with no limitations on sample size and thickness (Li et al., 2018a). However, interference from the presence of microorganisms or organic or inorganic contaminants can cause interference with the fluorescence signal (Li et al., 2018a). Despite its advantages, Raman spectroscopy has some known disadvantages, including a long processing time, potential polymer degradation and interference from fluorescence (Parashar and Hait, 2023).

Gas chromatography is widely recognized as one of the most popular and efficient chromatographic methods for the characterization of MPs, despite its destructive nature (Gniadek and Dąbrowska, 2019). Gas chromatography allows the separation and identification of volatile organic compounds (VOCs) released from MPs. Pyrolysis gas chromatography–mass spectrometry (Pyr-GC–MS) and thermal extraction–desorption gas chromatography–mass spectrometry (TED-GC–MS) are two promising approaches to obtain accurate information on polymers, additives and contaminants (Pipkin et al., 2021). Pyr-GC–MS can analyze the chemical composition and structural properties of high molecular weight polymers. This method provides a detailed description of the sample as well as an accurate assessment of its chemical properties (Tianniam et al., 2010). TED-GC–MS, on the other hand, is a more advanced thermal analysis method that combines thermogravimetric analytical solid-phase extraction (TGA-SPE) with thermal desorption gas chromatography–mass spectrometry (TDS-GC–MS) (Dümichen et al., 2015).

Occurrence and characteristics of plastics in WWTPs influents

In numerous investigations, plastics have been found in both influent and effluent samples from WWTPs. Reported concentrations of plastic particles in influent samples ranged from 0.0009 to 15,000 particles/L, while in effluent samples they ranged from 0.004 to 1,800 particles/L (Table 2). The use of different sampling methods, sample pretreatment techniques and analytical methods could be responsible for these differences in particle counts (Sönmez et al., 2022). Most of the plastic particles found were larger than 500 μm in the influent samples, while most of them were smaller than 500 μm in the effluent samples (Bayo et al., 2020; Üstün et al., 2022). However, in some studies, plastic particles smaller than 100 μm were also found in effluent samples (Jiang et al., 2022). In particular, with regard to samples with a mesh size of 10 μm, which mainly contained millimeter-sized debris, there are not many studies specifically address the presence of nano-sized plastics in wastewater samples (Okoffo et al., 2019). This discrepancy can be explained by a lack of information or evidence on the presence of nanoscale plastics in wastewater, as well as inadequate sampling procedures at WWTPs (Lehner et al., 2019). However, due to the environmental impacts associated with nano-sized plastics, it is essential to consider them in future studies focusing on WWTPs.

It has been shown that when a storm sewer is connected to a WWTP, the amount of plastics in the influent of the treatment plant generally increases (Sun et al., 2019). This leads to an increase in the amount of plastics associated with the wastewater system due to the release of plastics from brake and tire wear, which eventually enter the sewer system via road runoff (Mason et al., 2016; Michielssen et al., 2016; Wagner et al., 2018). Plastics in the influent not only affect the technologies and processes used in the WWTP, but also the amount of plastics that end up in the effluent (Sun et al., 2019). It should be mentioned that some wastewater pipes are made of PVC polymers, the abrasion of which can increase the total amount of plastics in the WWTP (Xu et al., 2019a).

Plastic particles have been identified in the influent and effluent of WWTP as spherical beads, microbeads, pellets, fibers, particles, flakes, films, fragments, foams, paint chips, nurdles, foils, spheres, sheets, granules, lines and irregular shapes (Hamidian et al., 2021). Fibers have been found to be the most common form with an average of 65.4% of the wastewater samples. Irregular pieces came second with an average of 42.6% (Lv et al., 2019). According to the study by Mason et al. (2016), the most common plastic particles in 17 wastewater samples from effluent treatment plants were microfibers (59%), followed by fragments (33%), films (5%), foams (2%) and pellets (1%). These results indicate that the main sources of plastics entering WWTPs are secondary plastics that have been degraded and synthetic fibers (Kang et al., 2018). There is a possibility that natural fibers such as cotton have been misrecorded or classified as synthetic fibers during identification and quantification, and it is important to consider that current sampling and analytical techniques may not be sufficient to fully capture and identify plastics in effluents (Talvitie et al., 2017b; Sun et al., 2019).

The predominant polymer types in the influent and effluent of the WWTP were polyethersulfone (PES, ca. 30–90%), polyethylene (PE, ca. 6–60%), polyethylene terephthalate (PET, ca. 5–40%), polyamide (PA, ca. 5–35%), acrylate (ca. 4–31%), polypropylene (PP, ca. 4–27%), alkyds (ca. 4–25%), polystyrene (PS, ca. 4–25%), polyurethane (PU, ca. 3–25%), polyvinyl acetate (PVA, ca. 3–20%), polylactic acid (PLA, ca. 2–18%) and polytetrafluoroethylene (PTFE, ca. 2–8%) (Hurley et al., 2018; Long et al., 2019; Wolff et al., 2019). Since PES, PET and PA are commonly used in synthetic garments, laundry effluents could be the reason for their presence in wastewater. PE, on the other hand, the most commonly produced plastic in the world, is used in personal care products such as toothpaste, body and facial cleansers, water bottles and food packaging films (Alavian Petroody et al., 2020). A recent study in a Finnish WWTP found that MP dominate in the following order: PET > PE > PAR > PVC > PS > PP (Talvitie et al., 2017a). Another study conducted in three Australian WWTPs found that the concentrations of different types of polymers (PET, PE, PVC, PP, PS and nylon) varied, with PET and PE being the predominant polymers (Ziajahromi et al., 2017). It is crucial to focus research efforts on the identification and quantification of these polymers in influent and effluent samples, as they are known to be generated by routine human activities, even though the exact sources and pathways by which plastics enter WWTPs are not yet fully known.

Fate of plastics in WWTPs

Plastics not only accumulate in the natural environment, but also enter WWTPs via domestic and industrial wastewater discharges

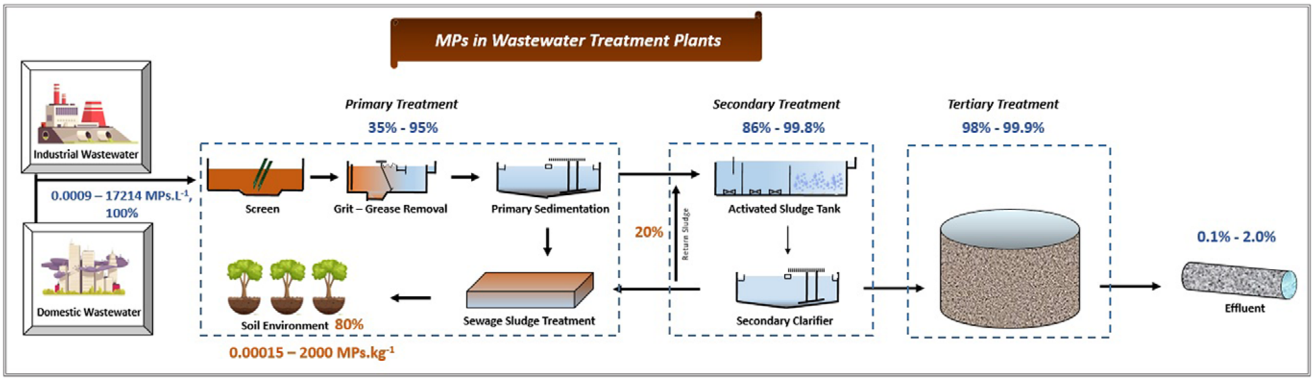

Figure 4. MPs removal efficiency in different treatment stages.

(Hajji et al., 2023; Ruffell et al., 2023) (Figure 4). Concentrations of MP in these environments have been shown to range from 0.0009 to 15 MPs/L. It is estimated that nearly 520,000 tons of MPs are discharged from WWTPs into freshwater rivers in Europe (Hajji et al., 2023). For these reasons, the numerous studies that have been conducted to investigate the fate of plastics in WWTPs have mainly focused on three key aspects: removal efficiency, fate of MPs and impacts on treatment processes (Carr et al., 2016; Ziajahromi et al., 2017). But the main focus, the fate of plastics in WWTPs is a complex issue that is influenced by various factors such as size, composition and treatment processes. MPs can take different pathways after their release into the environment and enter the three main environmental compartments: water, air and soil. There are many variables that influence the behavior of MP in the different environments. The physico-chemical properties of MP, such as size and density, as well as environmental conditions, such as temperature and solar radiation, play a crucial role. According to Gkika et al. (2023), the unique properties of MPs polymers have a significant impact on their durability, fate, degradation and ability to absorb or release organic pollutants.

Several studies have investigated the removal efficiency of MP at different treatment stages in different WWTPs and identified their removal mechanisms. In a study by Iyare et al. (2020), it was found that although WWTPs are not designed to remove MPs, an average removal value of 88% was achieved at secondary treatment and 94% removal efficiency at tertiary treatment. The authors also reported that most of the MPs, 72% on average, were removed during the pre- and primary treatment steps. Similarly, Parashar and Hait (2023) reported that the overall removal efficiency of MPs during primary, secondary and tertiary treatment in WWTPs ranged from 57% to 99%, 78.1% to 99.4% and 90% to 99.2%, respectively. Furthermore, Gkika et al. (2023) found that the efficiency of MP removal in primary treatment may depend on several variables. A key factor is the presence of an aerated grit chamber, which plays a role in improving removal efficiency. The exact categories of polymers present in the influent also influence removal rates. Studies in the literature have shown that removal efficiencies vary widely, ranging from 40.7% to 91.7%. The study also highlighted the influence of the different treatment steps on the relative size distribution of the MPs. Pre-treatments were found to have a significant impact on the removal of larger particles. For the secondary treatments, such as activated sludge and sedimentation, their configuration and retention time played a role in determining the removal efficiency, which ranged from 28.1% to 66.7%. These results show the importance of considering different treatment strategies and their specific configurations in order to effectively reduce MP pollution during wastewater treatment.

Numerous studies have reported that the conventional treatment process are not always effective in removing MPs larger than 500 μm resulting discharge of MPs into aquatic environments along with the effluent (Bilgin et al., 2020; Schmidt et al., 2020; Xu et al., 2021).

While typical WWTPs are capable of removing up to 90% of MPs from wastewater, it is important to consider that smaller MPs, such as the microbeads in facial cleansers and synthetic textile fibers, may escape from these treatment processes (Ziajahromi et al., 2017; Raju et al., 2020; Funck et al., 2021). This highlights the need for improved treatment steps and the application of state-of-the-art technologies to address the problem of tiny MPs escaping conventional treatment processes. Advanced wastewater treatment methods, including membrane bioreactors, are mentioned in the literature as possible options to increase effectiveness in removing small size MPs (less than 100 μm). However, research on the fate of MPs in WWTPs has shown that they can interact with the solid fraction of wastewater treatment, causing them to accumulate in the sludge (Mahon et al., 2017). If the sludge is subsequently used in agriculture or disposed of in landfills, MPs can enter terrestrial habitats (Zettler et al., 2013). However, little is known about the fate of MPs when used in agriculture (Tu et al., 2020; Casella et al., 2023). The use of sewage sludge as an additive in agriculture is considered an important source of MP in soil matrices. Similarly, MP can serve as colonization sites for specific microorganisms in both terrestrial and aquatic ecosystems (Zettler et al., 2013). Recent research has shown that MP in soil matrices have the potential to disrupt fungal community diversity (Zhang et al., 2021b). Moreover, the favorable growth of *Actinobacteria* and *Bacteroidetes* was found on polyethylene (PE) surfaces (Zhang et al., 2019, 2021b; Ren et al., 2020). Indeed, the potential transfer of MPs through the application of sewage sludge in agriculture still raises questions about the long-term consequences for soil health and crop safety (Zhang et al., 2020; Weber et al., 2022).

Possible strategies for robust management plan

The global campaign against MP pollution has gained significant momentum in recent years. Calls have been made to strengthen the capacity to manage plastic waste, particularly through increased recycling initiatives (Diggle and Walker, 2022). While effective recycling can help address the broader problem of plastic pollution, its impact on reducing MP pollution remains rather limited (Kumar et al., 2021). This study highlights the critical shortcomings of the current waste management system that allow MP to escape. Given the inability of the existing waste management system to adequately address the scale and severity of MP pollution, it is unrealistic to expect significant improvements without fundamental changes. It is unlikely that simply intensifying efforts under the existing framework will lead to significantly better results. There is therefore an urgent need to re-evaluate and adapt current waste management practices to effectively block the pathways through which MP escapes into the receiving environment.

In order to prevent ecosystems degradation, the implementation of strong legislative measures to monitor and regulate the overuse of plastics is essential (Prata et al., 2019). Effective management, recycling practices and the establishment of environmentally friendly disposal systems are crucial in the pursuit of a plastic-free environment. Developing countries have introduced extensive measures to combat the proliferation of plastics, including comprehensive bans on plastic bags and bottles and the imposition of fines for plastic violations (Gopinath et al., 2020). Over the past three decades, global efforts have led to the formulation of laws aimed at addressing the hazards and impacts of increasing plastic consumption and waste (Table 3) (Bhardwaj et al., 2020; Wen et al., 2021; Usman et al., 2022). As can be seen from the previous discussion and highlighted in Table 3, many international laws lack a comprehensive framework and the necessary global mechanisms to effectively monitor and evaluate progress toward the established goals. Although these legal frameworks often include sound governance strategies, they generally rely on individual countries to design and develop their own strategies for implementation. The effectiveness of these strategies in turn depends on a country's political will and allocation of resources to address the problem. The United Nations (UN) has recognized the problem of plastic pollution by including it in 11 SDGs alongside SDG-14 (Walker, 2021). However, the fact that only one indicator out of a total of 247 is dedicated to the impact of plastic in the ocean is woefully inadequate given the alarming rate at which plastic pollution is increasing globally. This allocation urgently needs to be reconsidered. Moreover, the European Parliament and the Council have failed to include MPs in their directives, while the measures proposed by WHO to mitigate the problem remain out of reach in many countries (Usman et al., 2022). This underline the need for a concerted commitment to provide resources that can support research efforts and the development of practical, measurable tools to comprehensively address this pressing global problem.

A comprehensive global assessment of national laws and regulations introduced by countries to restrict the production, import, use and disposal of single-use plastics and MPs, which contribute significantly to the spread of marine pollution, found that in 2018, about 60% (127 out of 192) of countries had enacted various forms of legislation concerning plastic bags (Xanthos and Walker, 2017). These laws specifically aim to regulate aspects such as production, distribution, use, trade, taxation, levies and disposal. While landfills remain the primary method of disposing of plastic waste, the gradual release of MPs and toxic additives poses a significant threat to the environment, inevitably leading to a phase-out of traditional landfill practices (Shen et al., 2022). Although incineration is an option for the disposal of plastic waste, the significant release of greenhouse gases remains a critical issue. With approximately, 79% combustible carbon per ton, this method generates an estimated 2.9 tons of CO_2 emissions, highlighting the environmental impacts associated with this approach (Hamilton et al., 2019).

In this context, recycling is widely recognized as the optimal long-term solution to address the current MP problem and ensure sustainable plastic use (Kassab et al., 2023). Reusing 1 ton of plastic waste by recycling instead of producing new materials can save approximately 130 million kilojoules of energy (Ramirez and George, 2019). However, the recycling rate for plastic waste, especially for secondary (recycled) plastics, remains low. Therefore, promoting environmentally friendly and cost-effective alternatives to plastics is essential in the long term. Researchers also need to explore methods to break down the basic components of plastics so they can be converted into new materials. Researchers have discovered a mutant enzyme capable of breaking down plastic bottles in days –a significant improvement over the centuries it takes in the oceans (Lamichhane, 2023).

In recent years, several studies have underlined the effectiveness of plastic-degrading bacteria. In particular, *Ideonella sakaiensis*, a member of the *Ideonella* genus and *Comamonadaceae* family, has shown that it is able to consume plastic polyethylene terephthalate (PET) as a sole source of carbon and energy, effectively contributing to plastic recycling (Yoshida et al., 2016). With the help of two successive enzymes, these bacteria can break down PET into terephthalic acid and ethylene glycol, both environmentally friendly substances (Bornscheuer, 2016). Similarly, research by Gao and Sun showed that a mixed culture of *Exiguobacterium* sp., *Halomonas* sp. and *Ochrobactrum* sp. degrades both PET and PE films better than individual isolates, as evidenced by observations with SEM (Gao and Sun, 2021).

Given the ubiquitous presence of plastic, there is an urgent need for more than one alternative solution that is renewable, environmentally sound and biodegradable. Unregulated and poorly managed bioplastics could potentially lead to environmental damage comparable to that of conventional plastics. It is therefore crucial that legislators set strict criteria with high standards for the classification of bioplastics to promote consumer and business confidence (Bhagwat et al., 2020). Biodegradable plastics based on cellulose and polyolefins should be actively promoted due to their cost-effectiveness, high mechanical strength and ease of decomposition in the environment (Ammala et al., 2011). Recent advances have led to the development of plant-based materials capable of replacing single-use plastics in various consumer products and a polymer film that mimics the properties of spider silk. This innovative material has comparable durability to conventional plastics and can be produced on an industrial scale from sustainable components thanks to an energy-efficient technology that fuses plant proteins into silk-like materials (Kamada et al., 2021). Most importantly, this substance is compostable at home, so no special industrial composting facilities are required. Furthermore, due to its natural composition, the material can be safely biodegraded in most natural environments, providing a promising alternative to single-use plastics and MPs on the commercial market.

Future perspectives and conclusions

Aquatic ecosystems play a crucial role in the transport and deposition of plastic waste from terrestrial storage to surface waters (Margenat et al., 2021). All recent studies consistently identify urban areas, transportation, infrastructure and WWTPs as major sources of micro-, meso- and macroplastics (van Emmerik, 2021; Cowger et al., 2022). Recent scientific articles have shown that the movement of plastics over land and rivers is influenced by human activities, flood and storm events, hydrodynamics and their

Table 3. Different governance strategies to control MP pollution (adapted from Usman et al., 2022)

International and regional strategies Organization	Law	Strategies
EU	Sustainable sewage sludge management strategy	■ Review directive 86/278/EEc on SS & include MPs control ■ Prohibits SS disposal on land ■ Provides alternative to SS management ■ To use high tech in sewage treatment plant ■ Research and development to support high-tech processes ■ To actualize circular economy
United Nations SDGs	Target 14.1 of SDG 14 on plastic pollution	■ To prevent and reduce all forms of marine pollution ■ To prevent land based activities polluting the oceans by 2025 ■ To measure the impact through index of coastal eutrophication and floating plastic debris
UNEP	Resolution on: ■ Marine plastic litter ■ Single-use plastic ■ Innovative pathways	■ Control release of plastics and MPs ■ Provides alternatives ■ Stop and reverse plastic pollution ■ Sustainable management of plastics ■ Circular economy ■ Technology innovation ■ Control single-use plastics ■ Community education ■ Research and development ■ Funding policies in developing countries
UNEP, IUCN and life cycle initiative	National guidance for plastic pollution hotspotting and shaping	■ Provide framework to countries and regions ■ Enable identification of plastics leakage ■ Trace impacts of leakage along the value chain ■ Make provisions for priority actions ■ Set benchmark for assessing progress of intervention ■ Provides methods, tools and resources for assessment
ASEAN	Regional action plan for combatting marine debris	■ To harmonize strategies ■ To allocate resources to strengthen existing actions ■ To reduce plastic release ■ To increase plastics clean-up ■ To enhance plastic re-use ■ To phase out single-use plastics ■ To monitor and measure plastic debris ■ To improve innovation, investment and training
WHO	Call for plastics and MPs impact on health and environment	■ Standardization of MPs measuring methods in water ■ Research on MPs occurrence ■ Testing efficacy of water treatment methods ■ To prioritize chemical and pathogen removal in water, which will remove 90% of MPs

combinations. Interestingly, the majority of plastics do not reach the open sea but end up on beaches, float in coastal waters or accumulate on land and in river systems (Köklü et al., 2023; Sönmez et al., 2023). To address this problem, several innovative technologies have been developed and deployed to reduce pollution from MaPs. These technologies mainly include innovative devices placed along rivers and streams to effectively collect MaPs and other litter. Prominent examples include the Ocean Cleanup Foundation's Interceptor Project, which has been successfully implemented in Indonesia, Malaysia and the Dominican Republic (The Ocean Cleanup, 2021). The Bubble Barrier, which Waternet has installed in a number of Amsterdam canals, is another notable tool (Waternet Annual Report, 2021). This bubble barrier diverts floating litter, such as MaPs, so that it can be cleaned up on the riverbank.

Further research needs to focus on the pragmatic use of area-specific expertise on rivers, with particular attention to the collection and examination of extensive and original datasets. In addition, it is essential to identify the origins and entry points of plastic pollution and to understand the basic mechanisms of transport. This priority issue not only offers new perspectives on the production, distribution, fate and impact of plastics, but also highlights the urgent need for a thorough investigation of plastic pollution in the aquatic environment. Furthermore, there is a notable lack of comparative research between technology-based enhanced treatment strategies and conventional treatment methods (Iyare et al., 2020).

In addition, the accumulation of plastics in WWTPs can lead to operational challenges and potential environmental impacts. Further research and the development of innovative treatment technologies are needed to effectively address the challenges posed by plastics in WWTPs effectively. Understanding the fate of plastics in WWTPs is critical to developing strategies to contain their presence and minimize their potential negative impacts on the environment. The United Nations Environment Programme considers plastic pollution to be a major environmental problem that, along with climate change, is becoming a threat to biodiversity and human health. Metrics such as models or ecological footprints can be useful tools for decision-making, public engagement and policy development. Nevertheless, contingency plans should be continuously adapted and developed to consider the future of waste management and plastics (Klemeš et al., 2020). For example, to achieve the best environmental performance through recycling, it is important to improve pre-treatment methods in line with the most appropriate recycling technology for a given polymer. Some of the studies emphasize the importance of polymer quality (e.g., mixed origin and mixed materials), which affects the overall environmental performance of a technology, but does not change the performance rating of the technology (Schwarzer et al., 2022).

Effective waste management is critical to achieving the SDGs that aim to address environmental, social and economic challenges. Governments and organizations around the world have adopted waste management plans that are aligned with the SDGs and emphasize the need for sustainable waste management practices. Under the SDGs, waste management plans and regulatory improvements focus on several key areas. These include reducing waste generation through waste prevention and promoting sustainable consumption patterns. Recycling and recovery efforts aim to increase waste prevention, conserve resources and reduce greenhouse gas emissions. Above all, improving regulation plays a crucial role in creating a regulatory framework that supports sustainable waste management. By adopting comprehensive waste management policies that include waste prevention, recycling and safe disposal, countries can minimize environmental impacts, conserve resources and contribute to the achievement of the SDGs. These regulations cover the classification, collection, treatment and disposal of waste, as well as extended producer responsibility (EPR). EPR requires producers to take responsibility for the entire life cycle of their products, including the disposal of post-consumer waste.

To further advance waste management in line with the SDGs, cooperation and knowledge sharing between countries and stakeholders is crucial. Sharing best practices, innovative technologies and scientific research can improve waste management systems and promote sustainable solutions worldwide. In addition, financial incentives, capacity building and public awareness campaigns are integral components to drive behavioral change and ensure the successful implementation of waste management plans.

Open peer review. To view the open peer review materials for this article, please visit http://doi.org/10.1017/plc.2023.23.

Acknowledgments. The authors would like to thank the Scientific and Technological Research Council of Turkey (TÜBİTAK) for their support in this publication, which was prepared using the outputs of the preliminary work packages of the 118C556 project.

References

Akarsu C (2023) Cotton buds: The new villain of the litter story in coastal area. *Ocean and Coastal Research* **71**(34), 1–18. https://doi.org/10.1590/2675-2824071.22119ca

Akarsu C, Kumbur H, Gökdağ K, Kıdeyş AE and Sanchez-Vidal A (2020) Microplastics composition and load from three wastewater treatment plants discharging into Mersin Bay, north eastern Mediterranean Sea. *Marine Pollution Bulletin* **150**, 110776. https://doi.org/10.1016/j.marpolbul.2019.110776

Alavian Petroody SS, Hashemi SH and van Gestel CAM (2020) Factors affecting microplastic retention and emission by a wastewater treatment plant on the southern coast of Caspian Sea. *Chemosphere* **261**, 128179. https://doi.org/10.1016/j.chemosphere.2020.128179

Alavian Petroody SS, Hashemi SH and van Gestel CAM (2021) Transport and accumulation of microplastics through wastewater treatment sludge processes. *Chemosphere* **278**, 130471. https://doi.org/10.1016/j.chemosphere.2021.130471

Alda-Vidal C, Hoolohan C, Dyson R, Danino V and Browne A (2020) Unflushables: Designing new intervention pathways for sewer blockages and environmental pollution in the Anglian Water region, UK. Commissioned Report. University of Manchester.

Ali I, Ding T, Peng C and Liu J (2021) Micro- and nanoplastics in wastewater treatment plants: Occurrence, removal, fate, impacts and remediation technologies – A critical review. *Chemical Engineering Journal* **423**, 130205. https://doi.org/10.1016/j.cej.2021.130205

Ammala A, Bateman S, Dean K, Petinakis E, Sangwan P, Wong S, Yuan Q, Yu L, Patrick C and Leong KH (2011) An overview of degradable and biodegradable polyolefins. *Progress in Polymer Science* **36**(8), 1015–1049.

Andrady AL (2011) Microplastics in the marine environment. *Marine Pollution Bulletin* **62**(8), 1596–1605. https://doi.org/10.1016/j.marpolbul.2011.05.030

Anger PM, von der Esch E, Baumann T, Elsner M, Niessner R and Ivleva NP (2018) Raman microspectroscopy as a tool for microplastic particle analysis. *TrAC Trends in Analytical Chemistry* **109**, 214–226. https://doi.org/10.1016/j.trac.2018.10.010

Barkmann-Metaj L, Weber F, Bitter H and Engelhart M (2023) Quantification of microplastics in wastewater systems of German industrial parks and their wastewater treatment plants. *Science of the Total Environment* **881**, 163349. https://doi.org/10.1016/j.scitotenv.2023.163349

Bashir I, Lone FA, Bhat RA, Mir SA, Dar ZA and Dar SA (2020) Concerns and threats of contamination on aquatic ecosystems. In Hakeem KR, Bhat RA and Qadri H (eds.), *Bioremediation and Biotechnology*, Cham: Springer International Publishing, pp. 1–26. https://doi.org/10.1007/978-3-030-35691-0_1

Bayo J, Olmos S and López-Castellanos J (2020) Microplastics in an urban wastewater treatment plant: The influence of physicochemical parameters and environmental factors. *Chemosphere* **238**, 124593. https://doi.org/10.1016/j.chemosphere.2019.124593

Belzagui Elder F (2017) Microplastics' state of the art & presentation of a method to quantify textile microfibers, olitècnica de Catalunya University, Barcelona.

Besley A, Vijver MG, Behrens P and Bosker T (2017) A standardized method for sampling and extraction methods for quantifying microplastics in beach sand. *Marine Pollution Bulletin* **114**(1), 77–83. https://doi.org/10.1016/j.marpolbul.2016.08.055

Besley CH and Cassidy M (2022) The composition of gross pollutants contained in wet weather overflows for different locations, spill frequencies and discharge volumes. *Journal of Environmental Management* **303**, 114256. https://doi.org/10.1016/j.jenvman.2021.114256

Bhagwat G, Gray K, Wilson SP, Muniyasamy S, Vincent SGT, Bush R and Palanisami T (2020) Benchmarking bioplastics: A natural step towards a sustainable future. *Journal of Polymer Environment* **28**(12), 3055–3075. https://doi.org/10.1007/s10924-020-01830-8

Bhardwaj N, Kumar B and Verma P (2020) Microwave-assisted pretreatment using alkali metal salt in combination with orthophosphoric acid for generation of enhanced sugar and bioethanol. *Biomass Conversation and Biorefinery* **12**, 1069–1076. https://doi.org/10.1007/s13399-020-00640-1

Bhat RA, Beigh BA, Mir SA and Lone R (2022) Biopesticide techniques to remediate pesticides in polluted ecosystems. In Khosrow-Pour M (ed.), *Research Anthology on Emerging Techniques in Environmental Remediation*, Pennsylvania: IGI Global, pp. 336–356. https://doi.org/10.4018/978-1-6684-3714-8.ch017

Bilgin M, Yurtsever M and Karadagli F (2020) Microplastic removal by aerated grit chambers versus settling tanks of a municipal wastewater treatment plant. *Journal of Water Process Engineering* **38**, 101604. https://doi.org/10.1016/j.jwpe.2020.101604

Blettler MCM, Abrial E, Khan FR, Sivri N and Espinola LA (2018) Freshwater plastic pollution: Recognizing research biases and identifying knowledge gaps. *Water Research* **143**, 416–424. https://doi.org/10.1016/j.watres.2018.06.015

Bornscheuer UT (2016) Feeding on plastic. *Science* **351**(6278), 1154–1155. https://doi.org/10.1126/science.aaf2853

Boucher J and Friot D (2017) Primary microplastics in the oceans: A global evaluation of sources. IUCN (International Union for Conservation of Nature). https://doi.org/10.2305/IUCN.CH.2017.01.en

Bozdaş K, **Üstün GE and Aygün A** (2020) Atiksu Aritma Tesislerinde Mikro Plastikler Ve Giderim Yöntemleri. *Uludağ University Journal of the Faculty of Engineering* **25**(3), 1577–1592. https://doi.org/10.17482/uumfd.758523

Bretas Alvim C, **Bes-Piá MA and Mendoza-Roca JA** (2020) Separation and identification of microplastics from primary and secondary effluents and activated sludge from wastewater treatment plants. *Chemical Engineering Journal* **402**, 126293. https://doi.org/10.1016/j.cej.2020.126293

Carr SA, **Liu J and Tesoro AG** (2016) Transport and fate of microplastic particles in wastewater treatment plants. *Water Research* **91**, 174–182. https://doi.org/10.1016/j.watres.2016.01.002

Casella C, **Sol D**, **Laca A and Díaz M** (2023) Microplastics in sewage sludge: A review. *Environmental Science and Pollution Research* **30**(23), 63382–63415. https://doi.org/10.1007/s11356-023-27151-6

Chalmers JM (2000) Infrared spectroscopy in analysis of polymers and rubbers. In Meyers RA (ed.), *Encyclopedia of Analytical Chemistry*, New Jersey:Wiley. https://doi.org/10.1002/9780470027318.a2015

Cheung PK and Fok L (2017) Characterisation of plastic microbeads in facial scrubs and their estimated emissions in Mainland China. *Water Research* **122**, 53–61. https://doi.org/10.1016/j.watres.2017.05.053

Cole M, **Webb H**, **Lindeque PK**, **Fileman ES**, **Halsband C and Galloway TS** (2014) Isolation of microplastics in biota-rich seawater samples and marine organisms. *Scientific Reports* **4**(1), 4528. https://doi.org/10.1038/srep04528

Conley K, **Clum A**, **Deepe J**, **Lane H and Beckingham B** (2019) Wastewater treatment plants as a source of microplastics to an urban estuary: Removal efficiencies and loading per capita over one year. *Water Research X* **3**, 100030. https://doi.org/10.1016/j.wroa.2019.100030

Corradini F, **Meza P**, **Eguiluz R**, **Casado F**, **Huerta-Lwanga E and Geissen V** (2019) Evidence of microplastic accumulation in agricultural soils from sewage sludge disposal. *Science of the Total Environment* **671**, 411–420. https://doi.org/10.1016/j.scitotenv.2019.03.368

Costa CQV, **Cruz J**, **Martins J and Da Silva JP** (2021) Fluorescence sensing of microplastics on surfaces. *Environmental Chemistry Letters* **19**(2), 1797–1802. https://doi.org/10.1007/s10311-020-01136-0

Cowger W, **Gray A**, **Hapich H and Ajami H** (2022) Litter origins, accumulation rates, and hierarchical composition on urban roadsides of the Inland Empire, California. *Environmental Research Letters* **17**(1), 015007. https://doi.org/10.1088/1748-9326/ac3c6a

Cox KD, **Covernton GA**, **Davies HL**, **Dower JF**, **Juanes F and Dudas SE** (2019) Human consumption of microplastics. *Environmental Science & Technology* **53**(12), 7068–7074. https://doi.org/10.1021/acs.est.9b01517

Cunsolo S, **Williams J**, **Hale M**, **Read DS and Couceiro F** (2021) Optimising sample preparation for FTIR-based microplastic analysis in wastewater and sludge samples: Multiple digestions. *Analytical and Bioanalytical Chemistry* **413**(14), 3789–3799. https://doi.org/10.1007/s00216-021-03331-6

De Frond H, **Cowger W**, **Renick V and Christiansen S** (2023) What determines accuracy of chemical identification when using microspectroscopy for the analysis of microplastics? *Chemosphere* **313**, 137300. https://doi.org/10.1016/j.chemosphere.2022.137300

Deblond T, **Cossu-Leguille C and Hartemann P** (2011) Emerging pollutants in wastewater: A review of the literature. *International Journal of Hygiene and Environmental Health* **214**(6), 442–448. https://doi.org/10.1016/j.ijheh.2011.08.002

Derraik JG (2002) The pollution of the marine environment by plastic debris: A review. *Marine Pollution Bulletin* **44**(9), 842–852. https://doi.org/10.1016/S0025-326X(02)00220-5

Di Nunno F, **Granata F**, **Parrino F**, **Gargano R and de Marinis G** (2021) Microplastics in combined sewer overflows: An experimental study. *Journal of Marine Science and Engineering* **9**(12), 1415. https://doi.org/10.3390/jmse9121415

Diggle A and Walker TR (2022) Environmental and economic impacts of mismanaged plastics and measures for mitigation. *Environments* **9**(2), 15. https://doi.org/10.3390/environments9020015

Duis K and Coors A (2016) Microplastics in the aquatic and terrestrial environment: Sources (with a specific focus on personal care products), fate and effects. *Environmental Sciences Europe* **28**(1), 2. https://doi.org/10.1186/s12302-015-0069-y

Dümichen E, **Barthel AK**, **Braun U and Senz R** (2015) Analysis of polyethylene microplastics in environmental samples, using a thermal decomposition method. *Water Research* **85**, 451–457. https://doi.org/10.1016/j.watres.2015.09.002

Edo C, **González-Pleiter M**, **Leganés F**, **Fernández-Piñas, F and Rosal R** (2020) Fate of microplastics in wastewater treatment plants and their environmental dispersion with effluent and sludge. *Environmental Pollution* **259**, 113837. https://doi.org/10.1016/j.envpol.2019.113837

El Hayany B, **El Fels L**, **Quénéa K and Hafidi M** (2020) Microplastics from lagooning sludge to composts as revealed by fluorescent staining-image analysis, Raman spectroscopy and pyrolysis-GC/MS. *Journal of Environmental Management* **275**, 111249. https://doi.org/10.1016/j.jenvman.2020.111249

Evangeliou N, **Tichý O**, **Eckhardt S**, **Zwaaftink CG and Brahney J** (2022) Sources and fate of atmospheric microplastics revealed from inverse and dispersion modelling: From global emissions to deposition. *Journal of Hazardous Materials* **432**, 128585. https://doi.org/10.1016/j.jhazmat.2022.128585

Ford HV, **Jones NH**, **Davies AJ and Koldewey HJ** (2022) The fundamental links between climate change and marine plastic pollution. *Science of the Total Environment* **806**, 150392. https://doi.org/10.1016/j.scitotenv.2021.150392

Franco AA, **Arellano JM**, **Albendín G**, **Rodríguez-Barroso R**, **Quiroga JM and Coello MD** (2021) Microplastic pollution in wastewater treatment plants in the city of Cádiz: Abundance, removal efficiency and presence in receiving water body. *Science of the Total Environment* **776**, 145795. https://doi.org/10.1016/j.scitotenv.2021.145795

Fries E, **Dekiff JH**, **Willmeyer J**, **Nuelle MT**, **Ebert M and Remy D** (2013) Identification of polymer types and additives in marine microplastic particles using pyrolysis-GC/MS and scanning electron microscopy. *Environmental Science: Processes & Impacts* **15**(10), 1949. https://doi.org/10.1039/c3em00214d

Funck M, **Al-Azzawi MS**, **Yildirim A and Tuerk J** (2021) Release of microplastic particles to the aquatic environment via wastewater treatment plants: The impact of sand filters as tertiary treatment. *Chemical Engineering Journal* **426**, 130933. https://doi.org/10.1016/j.cej.2021.130933

Gao R and Sun C (2021) A marine bacterial community capable of degrading poly(ethylene terephthalate) and polyethylene. *Journal of Hazardous Materials* **416**, 125928. https://doi.org/10.1016/j.jhazmat.2021.125928

Gao Z, **Chen L**, **Cizdziel J and Huang Y** (2023) Research progress on microplastics in wastewater treatment plants: A holistic review. *Journal of Environmental Management* **325**, 116411. https://doi.org/10.1016/j.jenvman.2022.116411

Gkika DA, **Tolkou AK**, **Evgenidou E and Kyzas GZ** (2023) Fate and removal of microplastics from industrial wastewaters. *Sustainability* **15**(8), 6969. https://doi.org/10.3390/su15086969

Gniadek M and Dąbrowska A (2019) The marine nano- and microplastics characterisation by SEM-EDX: The potential of the method in comparison with various physical and chemical approaches. *Marine Pollution Bulletin* **148**, 210–216. https://doi.org/10.1016/j.marpolbul.2019.07.067

Gopinath KP, **Nagarajan VM**, **Krishnan A and Malolan R** (2020) A critical review on the influence of energy, environmental and economic factors on various processes used to handle and recycle plastic wastes: Development of a comprehensive index. *Journal of Cleaner Production* **274**, 123031. https://doi.org/10.1016/j.jclepro.2020.123031

Green DS, **Kregting L**, **Boots B**, **Crowley Q** (2018) A comparison of sampling methods for seawater microplastics and a first report of the microplastic litter in coastal waters of Ascension and Falkland Islands. *Marine Pollution Bulletin* **137**, 695–701. https://doi.org/10.1016/j.marpolbul.2018.11.004

Gündoğdu S, **Çevik C**, **Güzel E and Kilercioğlu S** (2018) Microplastics in municipal wastewater treatment plants in Turkey: A comparison of the influent and secondary effluent concentrations. *Environmental Monitoring and Assessment* **190**(11), 626. https://doi.org/10.1007/s10661-018-7010-y

Hajji S, **Ben-Haddad M**, **Abelouah MR**, **De-la-Torre GE and Alla AA** (2023) Occurrence, characteristics, and removal of microplastics in wastewater treatment plants located on the Moroccan Atlantic: The case of Agadir metropolis. *Science of the Total Environment* **862**, 160815. https://doi.org/10.1016/j.scitotenv.2022.160815

Hale RC, **Seeley ME**, **La Guardia MJ**, **Mai L and Zeng EY** (2020) A global perspective on microplastics. *Journal of Geophysical Research: Oceans* **125**(1), e2018JC014719. https://doi.org/10.1029/2018JC014719

Hamidian AH, **Ozumchelouei EJ**, **Feizi F**, **Wu C**, **Zhang Y and Yang M** (2021) A review on the characteristics of microplastics in wastewater treatment plants: A source for toxic chemicals. *Journal of Cleaner Production* **295**, 126480. https://doi.org/10.1016/j.jclepro.2021.126480

Hamilton LA, **Feit S**, **Muffett C**, **Kelso M**, **Rubright SM**, **Bernhardt C**, **Schaeffer E**, **Moon D**, **Morris J and Labbe-Bellas R** (2019) Plastic & climate: The hidden costs of a plastic planet. Center for International Environmental Law (CIEL). https://www.ciel.org/plasticandclimate

Hanvey JS, **Lewis PJ**, **Lavers JL**, **Crosbie ND**, **Pozo K and Clarke BO** (2017) A review of analytical techniques for quantifying microplastics in sediments. *Analytical Methods* **9**(9), 1369–1383. https://doi.org/10.1039/C6AY02707E

Hassan F, **Prasetya KD**, **Hanun JN and Jiang JJ** (2023) Microplastic contamination in sewage sludge: Abundance, characteristics, and impacts on the environment and human health. *Environmental Technology & Innovation* **31**, 103176. https://doi.org/10.1016/j.eti.2023.103176

Hernández-Arenas R, **Beltrán-Sanahuja A**, **Navarro-Quirant P and Sanz-Lazaro C** (2021) The effect of sewage sludge containing microplastics on growth and fruit development of tomato plants. *Environmental Pollution* **268**, 115779. https://doi.org/10.1016/j.envpol.2020.115779

Hidalgo-Ruz V, **Gutow L**, **Thompson RC and Thiel M** (2012) Microplastics in the marine environment: A review of the methods used for identification and quantification. *Environmental Science & Technology* **46**(6), 3060–3075. https://doi.org/10.1021/es2031505

Hidayaturrahman H and Lee TG (2019) A study on characteristics of microplastic in wastewater of South Korea: Identification, quantification, and fate of microplastics during treatment process. *Marine Pollution Bulletin* **146**, 696–702. https://doi.org/10.1016/j.marpolbul.2019.06.071

Horton AA, **Cross RK**, **Read DS and Johnson AC** (2021) Semi-automated analysis of microplastics in complex wastewater samples. *Environmental Pollution* **268**, 115841. https://doi.org/10.1016/j.envpol.2020.115841

Hu Y, **Gong M**, **Wang J and Bassi A** (2019) Current research trends on microplastic pollution from wastewater systems: A critical review. *Reviews in Environmental Science and Bio/Technology* **18**(2), 207–230. https://doi.org/10.1007/s11157-019-09498-w

Huang Z, **Hu B and Wang H** (2023) Analytical methods for microplastics in the environment: A review. *Environmental Chemistry Letters* **21**(1), 383–401. https://doi.org/10.1007/s10311-022-01525-7

Hurley RR, **Lusher AL**, **Olsen M and Nizzetto L** (2018) Validation of a method for extracting microplastics from complex, organic-rich, environmental matrices. *Environmental Science & Technology* **52**(13), 7409–7417. https://doi.org/10.1021/acs.est.8b01517

Imhof HK, **Laforsch C**, **Wiesheu AC and Ivleva NP** (2016) Pigments and plastic in limnetic ecosystems: A qualitative and quantitative study on microparticles of different size classes. *Water Research* **98**, 64–74. https://doi.org/10.1016/j.watres.2016.03.015

Ivleva NP, **Wiesheu AC and Niessner R** (2017) Microplastic in aquatic ecosystems. *Angewandte Chemie International Edition* **56**(7), 1720–1739. https://doi.org/10.1002/anie.201606957

Iyare PU, **Ouki SK and Bond T** (2020) Microplastics removal in wastewater treatment plants: A critical review. *Environmental Science: Water Research & Technology* **6**(10), 2664–2675. https://doi.org/10.1039/D0EW00397B

Jenner LC, **Sadofsky LR**, **Danopoulos E and Rotchell JM** (2021) Household indoor microplastics within the Humber region (United Kingdom): Quantification and chemical characterisation of particles present. *Atmospheric Environment* **259**, 118512. https://doi.org/10.1016/j.atmosenv.2021.118512

Jiang F, **Wang M**, **Ding J**, **Cao W and Sun C** (2022) Occurrence and seasonal variation of microplastics in the effluent from wastewater treatment plants in Qingdao, China. *Journal of Marine Science and Engineering* **10**(1), 58. https://doi.org/10.3390/jmse10010058

Kalčíková G, **Alič B**, **Skalar T**, **Bundschuh M and Gotvajn AŽ** (2017) Wastewater treatment plant effluents as source of cosmetic polyethylene microbeads to freshwater. *Chemosphere* **188**, 25–31. https://doi.org/10.1016/j.chemosphere.2017.08.131

Kamada A, **Rodriguez-Garcia M**, **Ruggeri FS**, **Shen Y**, **Levin A and Knowles TPJ** (2021) Controlled self-assembly of plant proteins into high-performance multifunctional nanostructured films. *Nature Communications* **12**(1), 3529. https://doi.org/10.1038/s41467-021-23813-6

Kang HJ, **Park HJ**, **Kwon OK and Kwon JH** (2018) Occurrence of microplastics in municipal sewage treatment plants: A review. *Environmental Health and Toxicology* **33**(3), e2018013. https://doi.org/10.5620/eht.e2018013

Karapanagioti HK (2017) Microplastics and synthetic fibers in treated wastewater and sludge. In *Wastewater and Biosolids Management*. International Water Association, pp. 77–88. https://doi.org/10.2166/9781780408231_0077

Kassab A, **Al Nabhani D**, **Mohanty P**, **Pannier C and Ayoub GY** (2023) Advancing plastic recycling: Challenges and opportunities in the integration of 3D printing and distributed recycling for a circular economy. *Polymers* **15**(19), 3881. https://doi.org/10.3390/polym15193881

Keerthana D M, **Karmegam N**, **Manikandan S and Govarthanan M** (2022) Removal of nanoplastics in water treatment processes: A review. *Science of the Total Environment* **845**, 157168. https://doi.org/10.1016/j.scitotenv.2022.157168

Kim MJ, **Na SH**, **Batool R**, **Byun IS and Kim EJ** (2022) Seasonal variation and spatial distribution of microplastics in tertiary wastewater treatment plant in South Korea. *Journal of Hazardous Materials* **438**, 129474. https://doi.org/10.1016/j.jhazmat.2022.129474

Klemeš JJ, **Fan Y**, **Van Tan RR and Jiang P** (2020) Minimising the present and future plastic waste, energy and environmental footprints related to COVID-19. *Renewable and Sustainable Energy Reviews* **127**, 109883. https://doi.org/10.1016/j.rser.2020.109883

Köklü R, **Ateş A**, **Deveci EÜ and Sivri N** (2023) Generic foresight model in changing hygiene habits with the pandemic: Use of wet wipes in next generations. *Journal of Material Cycles and Waste Management* **25**(1), 74–85. https://doi.org/10.1007/s10163-022-01515-5

Koyuncuoğlu P and Erden G (2023) Microplastics in municipal wastewater treatment plants: A case study of Denizli/Turkey. *Frontiers of Environmental Science & Engineering* **17**(8), 99. https://doi.org/10.1007/s11783-023-1699-8

Kumar R, **Verma A**, **Shome A**, **Sinha R**, **Sinha S**, **Jha PK**, **Kumar R**, **Kumar P and Shubham Das S** (2021) Impacts of plastic pollution on ecosystem services, sustainable development goals, and need to focus on circular economy and policy interventions. *Sustainability* **13**(17), 9963. https://doi.org/10.3390/su13179963

Lamichhane G, **Acharya A**, **Marahatha R**, **Modi B**, **Paudel R**, **Adhikari A**, **Raut BK**, **Aryal S and Parajuli N** (2023) Microplastics in environment: Global concern, challenges, and controlling measures. *International Journal of Environmental Science and Technology* **20**(4), 4673–4694. https://doi.org/10.1007/s13762-022-04261-1

Lares M, **Ncibi MC**, **Sillanpää M and Sillanpää M** (2018) Occurrence, identification and removal of microplastic particles and fibers in conventional activated sludge process and advanced MBR technology. *Water Research* **133**, 236–246. https://doi.org/10.1016/j.watres.2018.01.049

Lehner R, **Weder C**, **Petri-Fink A and Rothen-Rutishauser B** (2019) Emergence of nanoplastic in the environment and possible impact on human health. *Environmental Science & Technology* **53**(4), 1748–1765. https://doi.org/10.1021/acs.est.8b05512

Leslie HA, **Brandsma SH**, **van Velzen MJM and Vethaak AD** (2017) Microplastics en route: Field measurements in the Dutch river delta and Amsterdam canals, wastewater treatment plants, North Sea sediments and biota. *Environment International* **101**, 133–142. https://doi.org/10.1016/j.envint.2017.01.018

Li J, **Liu H and Paul Chen J** (2018a) Microplastics in freshwater systems: A review on occurrence, environmental effects, and methods for microplastics detection. *Water Research* **137**, 362–374. https://doi.org/10.1016/j.watres.2017.12.056

Li J, **Song Y and Cai Y** (2020) Focus topics on microplastics in soil: Analytical methods, occurrence, transport, and ecological risks. *Environmental Pollution* **257**, 113570. https://doi.org/10.1016/j.envpol.2019.113570

Li X, **Chen L**, **Mei Q and Zeng EY** (2018b) Microplastics in sewage sludge from the wastewater treatment plants in China. *Water Research* **142**, 75–85. https://doi.org/10.1016/j.watres.2018.05.034

Long Z, Pan Z, Wang W and Jin X (2019) Microplastic abundance, characteristics, and removal in wastewater treatment plants in a coastal city of China. *Water Research* **155**, 255–265. https://doi.org/10.1016/j.watres.2019.02.028

Lusher AL, Hurley RC, Vogelsang L and Nizzetto MO (2017) Mapping microplastics in sludge. Report. Norwegian Institute for Water Research. https://niva.brage.unit.no/ni

Lv X, Dong Q, Zuo Z, Liu Y, Huang X and Wu WM (2019) Microplastics in a municipal wastewater treatment plant: Fate, dynamic distribution, removal efficiencies, and control strategies. *Journal of Cleaner Production* **225**, 579–586. https://doi.org/10.1016/j.jclepro.2019.03.321

Magni S, Binelli A, Pittura L and Regoli F (2019) The fate of microplastics in an Italian wastewater treatment plant. *Science of the Total Environment* **652**, 602–610. https://doi.org/10.1016/j.scitotenv.2018.10.269

Magnusson K and Noren F (2014) Screening of microplastic particles in and down-stream a wastewater treatment plant.

Mahon AM, O'Connell B, Healy MG, O'Connor I, Officer R, Nash R and Morrison L (2017) Microplastics in sewage sludge: Effects of treatment. *Environmental Science & Technology* **51**(2), 810–818. https://doi.org/10.1021/acs.est.6b04048

Margenat H, Nel HA, Stonedahl SH, Krause S, Sabater F and Drummond JD (2021) Hydrologic controls on the accumulation of different sized microplastics in the streambed sediments downstream of a wastewater treatment plant (Catalonia, Spain). *Environmental Research Letters* **16**(11), 115012. https://doi.org/10.1088/1748-9326/ac3179

Mason SA, Garneau D, Sutton R, Chu Y, Ehmann K, Barnes J, Fink P, Papazissimos D and Rogers DL (2016) Microplastic pollution is widely detected in US municipal wastewater treatment plant effluent. *Environmental Pollution* **218**, 1045–1054. https://doi.org/10.1016/j.envpol.2016.08.056

Mattsson J, Hedström A, Ashley RM and Viklander M (2015) Impacts and managerial implications for sewer systems due to recent changes to inputs in domestic wastewater – A review. *Journal of Environmental Management* **161**, 188–197. https://doi.org/10.1016/j.jenvman.2015.06.043

Michielssen MR, Michielssen ER, Ni J and Duhaime MB (2016) Fate of microplastics and other small anthropogenic litter (SAL) in wastewater treatment plants depends on unit processes employed. *Environmental Science: Water Research & Technology* **2**(6), 1064–1073. https://doi.org/10.1039/C6EW00207B

Mintenig SM, Int-Veen I, Löder MGJ, Primpke S and Gerdts G (2017) Identification of microplastic in effluents of waste water treatment plants using focal plane array-based micro-Fourier-transform infrared imaging. *Water Research* **108**, 365–372. https://doi.org/10.1016/j.watres.2016.11.015

Mourgkogiannis N, Kalavrouziotis IK and Karapanagioti HK (2018) Questionnaire-based survey to managers of 101 wastewater treatment plants in Greece confirms their potential as plastic marine litter sources. *Marine Pollution Bulletin* **133**, 822–827. https://doi.org/10.1016/j.marpolbul.2018.06.044

Murphy F, Ewins C, Carbonnier F and Quinn B (2016) Wastewater treatment works (WwTW) as a source of microplastics in the aquatic environment. *Environmental Science & Technology* **50**(11), 5800–5808. https://doi.org/10.1021/acs.est.5b05416

Nabi I, Bacha AUR and Zhang L (2022) A review on microplastics separation techniques from environmental media. *Journal of Cleaner Production* **337**, 130458. https://doi.org/10.1016/j.jclepro.2022.130458

Okoffo ED, O'Brien S, O'Brien JW, Tscharke BJ and Thomas KV (2019) Wastewater treatment plants as a source of plastics in the environment: A review of occurrence, methods for identification, quantification and fate. *Environmental Science: Water Research & Technology* **5**(11), 1908–1931. https://doi.org/10.1039/C9EW00428A

Pandey B, Pathak J, Singh P, Kumar R, Kumar A, Kaushik S and Thakur TK (2022) Microplastics in the ecosystem: An overview on detection, removal, toxicity assessment, and control release. *Water* **15**(1), 51. https://doi.org/10.3390/w15010051

Parashar N and Hait S (2023) Recent advances on microplastics pollution and removal from wastewater systems: A critical review. *Journal of Environmental Management* **340**, 118014. https://doi.org/10.1016/j.jenvman.2023.118014

Park HJ, Oh MJ, Kim PG, Kim G, Jeong DH, Ju BK, Lee WS, Chung HM, Kang HJ and Kwon JH (2020) National reconnaissance survey of microplastics in municipal wastewater treatment plants in Korea. *Environmental Science & Technology* **54**(3), 1503–1512. https://doi.org/10.1021/acs.est.9b04929.

Pipkin W, Belganeh R, Robberson W, Allen HL, Cook A and Watanabe A (2021) Identification of microplastics in environmental monitoring using pyrolysis-GC-MS analysis. *LCGC North America* **39**(4):179–186.

Pittura L, Foglia A, Akyol Ç, Cipolletta G, Benedetti M, Regoli F, Eusebi AL, Sabbatini S, Tseng LY, Katsou E, Gorbi S and Fatone F (2021) Microplastics in real wastewater treatment schemes: Comparative assessment and relevant inhibition effects on anaerobic processes. *Chemosphere* **262**, 128415. https://doi.org/10.1016/j.chemosphere.2020.128415

Prata JC, Silva ALP, da Costa JP, Mouneyrac C, Walker TR, Duarte AC and Rocha-Santos T (2019) Solutions and integrated strategies for the control and mitigation of plastic and microplastic pollution. *International Journal of Environmental Research and Public Health* **16**(13), 2411. https://doi.org/10.3390/ijerph16132411

Ragoobur D, Huerta-Lwanga E and Somaroo GD (2021) Microplastics in agricultural soils, wastewater effluents and sewage sludge in Mauritius. *Science of the Total Environment* **798**, 149326. https://doi.org/10.1016/j.scitotenv.2021.149326

Raju S, Carbery M, Kuttykattil A, Senthirajah K, Lundmark A, Rogers Z, SCB S, Evans G and Palanisami T (2020) Improved methodology to determine the fate and transport of microplastics in a secondary wastewater treatment plant. *Water Research* **173**, 115549. https://doi.org/10.1016/j.watres.2020.115549

Ramirez A and George B (2019) Plastic recycling and waste reduction in the hospitality industry: Current challenges and some potential solutions. *Economics, Management and Sustainability* **4**(1), 6–20. https://doi.org/10.14254/jems.2019.4-1.1

Rasmussen LA, Iordachescu L, Tumlin S and Vollertsen J (2021) A complete mass balance for plastics in a wastewater treatment plant – Macroplastics contributes more than microplastics. *Water Research* **201**, 117307. https://doi.org/10.1016/j.watres.2021.117307

Ren X, Sun Y, Wang Z, Barceló D, Wang Q, Zhang Z and Zhang Y (2020) Abundance and characteristics of microplastic in sewage sludge: A case study of Yangling, Shaanxi province, China. *Case Studies in Chemical and Environmental Engineering* **2**, 100050. https://doi.org/10.1016/j.cscee.2020.100050.

Ribeiro-Claro P, Nolasco MM and Araújo C (2017) Characterization of microplastics by Raman spectroscopy. In Rocha-Santos TAP and Duarte AC (eds.), Comprehensive Analytical Chemistry, Amsterdam: Elsevier, pp. 119–151. https://doi.org/10.1016/bs.coac.2016.10.001

Ridall A, Farrar E, Dansby M and Ingels J (2023) Influence of wastewater treatment plants and water input sources on size, shape, and polymer distributions of microplastics in St. Andrew Bay, Florida, USA. *Marine Pollution Bulletin* **187**, 114552. https://doi.org/10.1016/j.marpolbul.2022.114552

Robertson I (2018) Optimising the workflow for microplastic analysis by FTIR microscopy. In *MICRO 2018. Fate and Impact of Microplastics: Knowledge, Actions and Solutions*. Massachusetts: MSFS-RBLZ, p. 151.

Ruffell H, Pantos O, Northcott G and Gaw S (2023) Wastewater treatment plant effluents in New Zealand are a significant source of microplastics to the environment. *New Zealand Journal of Marine and Freshwater Research* **57**, 336–352. https://doi.org/10.1080/00288330.2021.1988647

Schmidt C, Kumar R, Yang S and Büttner O (2020) Microplastic particle emission from wastewater treatment plant effluents into river networks in Germany: Loads, spatial patterns of concentrations and potential toxicity. *Science of the Total Environment* **737**, 139544. https://doi.org/10.1016/j.scitotenv.2020.139544

Schwarzer M, Brehm J, Vollmer M, Jasinski J, Xu C, Zainuddin S, Fröhlich T, Schott M, Greiner A, Scheibel T and Laforsch C (2022) Shape, size, and polymer dependent effects of microplastics on *Daphnia magna*. *Journal of Hazardous Materials* **426**, 128136. https://doi.org/10.1016/j.jhazmat.2021.128136.

Shen M, Xiong W, Song B, Zhou C, Almatrafi E, Zeng G and Zhang Y (2022) Microplastics in landfill and leachate: Occurrence, environmental behavior and removal strategies. *Chemosphere* **305**, 135325. https://doi.org/10.1016/j.chemosphere

Silva AB, Bastos AS, Justino CIL, da Costa JP, Duarte AC and Rocha-Santos TAP (2018) Microplastics in the environment: Challenges in analytical chemistry – A review. *Analytica Chimica Acta* **1017**, 1–19. https://doi.org/10.1016/j.aca.2018.02.043

Simon M, van Alst N and Vollertsen J (2018) Quantification of microplastic mass and removal rates at wastewater treatment plants applying Focal Plane Array (FPA)-based Fourier Transform Infrared (FT-IR) imaging. *Water Research* **142**, 1–9. https://doi.org/10.1016/j.watres.2018.05.019

Sönmez VZ, Akarsu C, Cumbul Altay M and Sivri N (2022) Extraction, enumeration, and identification methods for monitoring microplastics in the aquatic environment. In Hashmi MZ (ed.), *Microplastic Pollution. Emerging Contaminants and Associated Treatment Technologies*. Cham: Springer, pp. 21–66. https://doi.org/10.1007/978-3-030-89220-3_2

Sönmez VZ, Akarsu C, and Sivri N (2023) Impact of coastal wastewater treatment plants on microplastic pollution in surface seawater and ecological risk assessment. *Environmental Pollution* **318**, 120922. https://doi.org/10.1016/j.envpol.2022.120922

Sugiura M, Takada H, Takada N, Mizukawa K, Tsuyuki S and Furumai H (2021) Microplastics in urban wastewater and estuarine water: Importance of street runoff. *Environmental Monitoring and Contaminants Research* **1**, 54–65. https://doi.org/10.5985/emcr.20200006

Sujathan S, Kniggendorf AK, Kumar A, Roth B, Rosenwinkel KH and Nogueira R (2017) Heat and bleach: A cost-efficient method for extracting microplastics from return activated sludge. *Archives of Environmental Contamination and Toxicology* **73**(4), 641–648. https://doi.org/10.1007/s00244-017-0415-8

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

Sun X, Jia Q, Ye J, Zhu Y, Song Z, Guo Y and Chen H (2023) Real-time variabilities in microplastic abundance and characteristics of urban surface runoff and sewer overflow in wet weather as impacted by land use and storm factors. *Science of the Total Environment* **859**, 160148. https://doi.org/10.1016/j.scitotenv.2022.160148

Tadsuwan K and Babel S (2022) Microplastic abundance and removal via an ultrafiltration system coupled to a conventional municipal wastewater treatment plant in Thailand. *Journal of Environmental Chemical Engineering* **10**(2), 107142. https://doi.org/10.1016/j.jece.2022.107142

Tagg AS, Brandes E, Fischer F, Fischer D, Brandt J and Labrenz M (2022) Agricultural application of microplastic-rich sewage sludge leads to further uncontrolled contamination. *Science of the Total Environment* **806**, 150611. https://doi.org/10.1016/j.scitotenv.2021.150611

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

Talvitie J, Mikola A, Koistinen A and Setälä O (2017a) Solutions to microplastic pollution – Removal of microplastics from wastewater effluent with advanced wastewater treatment technologies. *Water Research* **123**, 401–407. https://doi.org/10.1016/j.watres.2017.07.005

Talvitie J, Mikola A, Setälä O, Heinonen M and Koistinen A (2017b) How well is microlitter purified from wastewater? – A detailed study on the stepwise removal of microlitter in a tertiary level wastewater treatment plant. *Water Research* **109**, 164–172. https://doi.org/10.1016/j.watres.2016.11.046

The Ocean Cleanup (2021) Retrieved from https://theoceancleanup.com/updates/.

Tianniam S, Bamba T and Fukusaki E (2010) Pyrolysis GC-MS-based metabolite fingerprinting for quality evaluation of commercial *Angelica acutiloba* roots. *Journal of Bioscience and Bioengineering* **109**(1), 89–93. https://doi.org/10.1016/j.jbiosc.2009.06.025

Tu C, Chen T, Zhou Q, Liu Y, Wei J, Waniek JJ and Luo Y (2020) Biofilm formation and its influences on the properties of microplastics as affected by exposure time and depth in the seawater. *Science of the Total Environment* **734**, 139237. https://doi.org/10.1016/j.scitotenv.2020.139237

Twiss MR (2016) Standardized methods are required to assess and manage microplastic contamination of the Great Lakes system. *Journal of Great Lakes Research* **42**(5), 921–925. https://doi.org/10.1016/j.jglr.2016.07.032

Usman S, Abdull Razis AF, Shaari K, Azmai MNA, Saad MZ, Mat Isa N and Nazarudin MF (2022) The burden of microplastics pollution and contending policies and regulations. *International Journal of Environmental Research and Public Health* **19**(11), 6773. https://doi.org/10.3390/ijerph19116773

Üstün GE, Bozdaş K and Can T (2022) Abundance and characteristics of microplastics in an urban wastewater treatment plant in Turkey. *Environmental Pollution* **310**, 119890. https://doi.org/10.1016/j.envpol.2022.119890

Van Emmerik T (2021) Macroplastic research in an era of microplastic. *Microplastics and Nanoplastics* **1**(1), 4. https://doi.org/10.1186/s43591-021-00003-1

Vardar S, Onay TT, Demirel B and Kideys AE (2021) Evaluation of microplastics removal efficiency at a wastewater treatment plant discharging to the Sea of Marmara. *Environmental Pollution* **289**, 117862. https://doi.org/10.1016/j.envpol.2021.117862

Vianello A, Boldrin A, Guerriero P, Moschino V, Rella R, Sturaro A and da Ros L (2013) Microplastic particles in sediments of Lagoon of Venice, Italy: First observations on occurrence, spatial patterns and identification. *Estuarine, Coastal and Shelf Science* **130**, 54–61. https://doi.org/10.1016/j.ecss.2013.03.022

Wagner J, Wang ZM, Ghosal S, Rochman C, Gassel M and Wall S (2017) Novel method for the extraction and identification of microplastics in ocean trawl and fish gut matrices. *Analytical Methods* **9**(9), 1479–1490. https://doi.org/10.1039/C6AY02396G

Wagner S, Hüffer T, Klöckner P, Wehrhahn M, Hofmann T and Reemtsma T (2018) Tire wear particles in the aquatic environment –A review on generation, analysis, occurrence, fate and effects. *Water Research* **139**, 83–100. https://doi.org/10.1016/j.watres.2018.03.051

Walker TR (2021) (Micro)plastics and the UN sustainable development goals. *Current Opinion in Green and Sustainable Chemistry* **30**, 100497. https://doi.org/10.1016/j.cogsc.2021.100497

Waternet Annual Report (2021) Retrieved from https://www.wereldwaternet.nl/en/reports–publications/annual-report-2021/.

Weber CJ, Santowski A and Chifflard P (2022) Investigating the dispersal of macro- and microplastics on agricultural fields 30 years after sewage sludge application. *Scientific Reports* **12**(1), 6401. https://doi.org/10.1038/s41598-022-10294-w

Wen Z, Xie Y, Chen M and Dinga CD (2021) China's plastic import ban increases prospects of environmental impact mitigation of plastic waste trade flow worldwide. *Nature Communications* **12**(1), 425. https://doi.org/10.1038/s41467-020-20741-9

Winton DJ, Anderson LG, Rocliffe S and Loiselle S (2020) Macroplastic pollution in freshwater environments: Focusing public and policy action. *Science of the Total Environment* **704**, 135242. https://doi.org/10.1016/j.scitotenv.2019.135242

Wolff S, Kerpen J, Prediger J, Barkmann L and Müller L (2019) Determination of the microplastics emission in the effluent of a municipal waste water treatment plant using Raman microspectroscopy. *Water Research X* **2**, 100014. https://doi.org/10.1016/j.wroa.2018.100014

Wong JKH, Lee KK, Tang KHD and Yap PS (2020) Microplastics in the freshwater and terrestrial environments: Prevalence, fates, impacts and sustainable solutions. *Science of the Total Environment* **719**, 137512. https://doi.org/10.1016/j.scitotenv.2020.137512

Xanthos D and Walker TR (2017) International policies to reduce plastic marine pollution from single-use plastics (plastic bags and microbeads): A review. *Marine Pollution Bulletin* **118**, 17–26. https://doi.org/10.1016/j.marpolbul.2017.02.048

Xu Q, Gao Y, Xu L, Shi W, Wang F, LeBlanc GA, Cui S, An L and Lei K (2020) Investigation of the microplastics profile in sludge from China's largest Water reclamation plant using a feasible isolation device. *Journal of Hazardous Materials* **388**, 122067. https://doi.org/10.1016/j.jhazmat.2020.122067

Xu X, Jian Y, Xue Y, Hou Q and Wang L (2019b) Microplastics in the wastewater treatment plants (WWTPs): Occurrence and removal. *Chemosphere* **235**, 1089–1096. https://doi.org/10.1016/j.chemosphere.2019.06.197

Xu X, Zhang L, Jian Y, Xue Y, Gao Y, Peng M, Jiang S and Zhang Q (2021) Influence of wastewater treatment process on pollution characteristics and fate of microplastics. *Marine Pollution Bulletin* **169**, 112448. https://doi.org/10.1016/j.marpolbul.2021.112448

Xu Y, He Q, Liu C and Huangfu X (2019a) Are micro- or nanoplastics leached from drinking water distribution systems? *Environmental Science & Technology* **53**(16), 9339–9340. https://doi.org/10.1021/acs.est.9b03673

Yang J, **Song K**, **Tu C**, **Li L**, **Feng Y**, **Li R**, **Xu H and Luo Y** (2023) Distribution and weathering characteristics of microplastics in paddy soils following long-term mulching: A field study in Southwest China. *Science of the Total Environment* **858**, 159774. https://doi.org/10.1016/j.scitotenv.2022.159774

Yang L, **Zhang Y**, **Kang S**, **Wang Z and Wu C** (2021) Microplastics in freshwater sediment: A review on methods, occurrence, and sources. *Science of the Total Environment* **754**, 141948. https://doi.org/10.1016/j.scitotenv.2020.141948

Yaşar A, **Can Doğan E and Arslan A** (2013) Macro and micro pollutants and treatment options in hospital wastewaters. *Erciyes University Graduate School of Natural and Applied Sciences Journal* **29**(2), 144–158. Retrieved from https://dergipark.org.tr/en/pub/erciyesfen/issue/25561/269634.

Ye Y, **Yu K and Zhao Y** (2022) The development and application of advanced analytical methods in microplastics contamination detection: A critical review. *Science of the Total Environment* **818**, 151851. https://doi.org/10.1016/j.scitotenv.2021.151851

Yoshida S, **Hiraga K**, **Takehana T**, **Taniguchi I**, **Yamaji H**, **Maeda Y**, **Toyohara K**, **Miyamoto K**, **Kimura Y and Oda K** (2016) A bacterium that degrades and assimilates poly(ethylene terephthalate). *Science* **351**(6278), 1196–1199. https://doi.org/10.1126/science.aad6359

Zettler ER, **Mincer TJ and Amaral Zettler LA** (2013) Life in the "plastisphere": Microbial communities on plastic marine debris. *Environmental Science & Technology* **47**(13), 7137–7146. https://doi.org/10.1021/es401288x

Zhang J, **Wang L**, **Halden RU and Kannan K** (2019) Polyethylene terephthalate and polycarbonate microplastics in sewage sludge collected from the United States. *Environmental Science & Technology Letters* **6**(11), 650–655. https://doi.org/10.1021/acs.estlett.9b00601

Zhang L, **Liu J**, **Xie Y**, **Zhong S and Gao P** (2021a) Occurrence and removal of microplastics from wastewater treatment plants in a typical tourist city in China. *Journal of Cleaner Production* **291**, 125968. https://doi.org/10.1016/j.jclepro.2021.125968

Zhang L, **Xie Y**, **Liu J**, **Zhong S**, **Qian Y and Gao P** (2020) An overlooked entry pathway of microplastics into agricultural soils from application of sludge-based fertilizers. *Environmental Science & Technology* **54**(7), 4248–4255. https://doi.org/10.1021/acs.est.9b07905

Zhang Y, **Wu D**, **Su Y and Xie B** (2021b) Occurrence, influence and removal strategies of mycotoxins, antibiotics and microplastics in anaerobic digestion treating food waste and co-digestive biosolids: A critical review. *Bioresource Technology* **330**, 124987. https://doi.org/10.1016/j.biortech.2021.124987

Zhang Z and Chen Y (2020) Effects of microplastics on wastewater and sewage sludge treatment and their removal: A review. *Chemical Engineering Journal* **382**, 122955. https://doi.org/10.1016/j.cej.2019.122955

Zhu J and Wang C (2020) Recent advances in the analysis methodologies for microplastics in aquatic organisms: Current knowledge and research challenges. *Analytical Methods* **12**(23), 2944–2957. https://doi.org/10.1039/D0AY00143K

Ziajahromi S, **Neale PA**, **Rintoul L and Leusch FDL** (2017) Wastewater treatment plants as a pathway for microplastics: Development of a new approach to sample wastewater-based microplastics. *Water Research* **112**, 93–99. https://doi.org/10.1016/j.watres.2017.01.042

Ziajahromi S, **Neale PA**, **Telles Silveira I**, **Chua A and 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