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A review of microplastics in wastewater treatment plants in Türkiye: Characteristics, removal efficiency, mitigation strategies for microplastic pollution and future perspective

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ABSTRACT

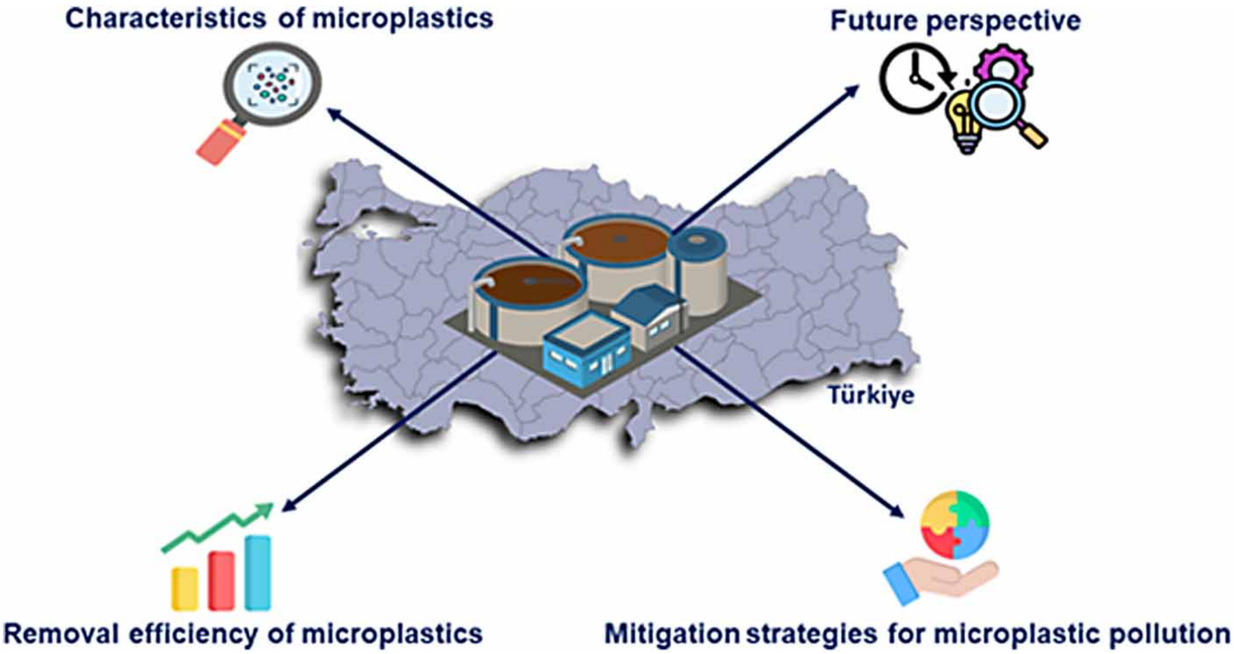
The effluent of WWTPs is an important source of microplastics (MP) for the aquatic environment. In this review study, MPs in wastewater treatment plants (WWTP) in Türkiye and their removal from WWTPs are reviewed for the first time. First, MP characteristics in the influent and effluent of WWTPs in Türkiye are discussed. In the next section, the abundance of MPs in the influent and effluent of WWTPs in Türkiye and the MP removal efficiency of WWTPs in Türkiye are evaluated. Then, the results of studies on MP abundance and characteristics in Türkiye's aquatic environments are presented and suggestions are made to reduce MPs released from WWTPs into the receiving environments. Strategies for reducing MPs released to the receiving environment from WWTPs of Türkiye are summarized. In the last section, research gaps regarding MPs in WWTPs in Türkiye are identified and suggestions are made for future studies. This review paper provides a comprehensive assessment of the abundance, dominant characteristics, and removal of MPs in WWTPs in Türkiye, as well as the current status and deficiencies in Türkiye. Therefore, this review can serve as a scientific guide to improve the MP removal efficiency of WWTPs in Türkiye.

Key words: aquatic environment, characteristic, microplastic, removal efficiency, Türkiye, wastewater treatment plant

HIGHLIGHTS

- Although WWTPs in Türkiye have high MP removal efficiencies, they cannot remove 100% of MP from wastewater.
- Millions of MPs are released into aquatic environments every day from WWTPs in Türkiye.
- In general, the dominant shape and size of MPs released to the aquatic environment from WWTPs in Türkiye are fiber and 0.5 mm, respectively.
- Both citizens and the government have responsibilities to reduce MP emissions from WWTPs in Türkiye.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Plastics are widely used around the world due to their properties such as easy manufacturing, low cost, flexibility, and lightness. According to Plastics Europe, world plastic production in 2021 is 390.7 million tonnes, of which 352.3, 32.5, and 5.9 million tonnes correspond to fossil-based plastics, post-consumer recycled plastics, and bio-based plastics, respectively (Plastics Europe 2022). The increasing use of plastic makes environmental plastic pollution a more serious problem. Microplastic (MP) pollution, which has become a threat to aquatic environments, is due to the increasing production and consumption of plastic, poor environmental awareness, poor plastic waste management, and the lack of water/wastewater treatment technologies that provide 100% efficiency.

MPs are plastics with dimensions less than 5 mm and larger than 1 μm. MPs are divided into two categories according to their sources: primary MPs and secondary MPs. Primary MPs are small-sized and properly shaped MPs generally produced for use in personal care products (toothpaste, facial cleansing gels, shower gel, etc.) and cosmetic products (Acarer 2023a). Secondary MPs are MPs formed by the fragmentation of large-sized plastics into smaller pieces as a result of physical, chemical and/or biological effects. Visibly large plastics left unconsciously in the aquatic environment and its surroundings break down through factors such as friction and sunlight and form secondary MPs (Lamichhane *et al.* 2023). Secondary MPs are released from synthetic clothes washed in washing machines due to friction and chemical effects, and such MPs constitute a significant part of MP pollution, especially in domestic wastewater (De Falco *et al.* 2019) MPs released into the environment due to abrasion from vehicle tires also reach wastewater treatment plants (WWTPs) through surface runoff and increase the secondary MP concentration in the influent (Tamis *et al.* 2021).

MPs are found in water and wastewater in various shapes such as fiber, fragment, film, foam, and granular (Ziajahromi *et al.* 2017; Pivokonsky *et al.* 2018; Liu *et al.* 2019; Acarer 2023a, 2023b). Polyethylene (PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), polyvinyl chloride (PVC), and polyamide (PA) are the most commonly detected polymer types of MPs in wastewaters (Magni *et al.* 2019; Bayo *et al.* 2020; Raju *et al.* 2020). PE, PP, and PS are widely used in the packaging of many products encountered in daily life (Acarer 2023a). PET is widely used in packaging and the textile industry (Periyasamy & Tehrani-Bagha 2022), while PVC is used in the manufacturing of water and wastewater pipes and coating various materials (Vahidi *et al.* 2015; Acarer 2023a). PA is generally used in the production of fiber for the textile industry and film for packaging (Tyuftin & Kerry 2020). In addition, domestic and industrial wastewater may also contain MP in different polymeric structures such as styrene-butadiene (SBR), polyethylene-vinyl acetate (PEVA), polymethyl methacrylate (PMMA), polyetheretherketone (PEEK), polycarbonate (PC) (Franco *et al.* 2020).

MPs found in domestic and industrial wastewater are removed in various treatment units in WWTPs. WWTP effluents with reduced MP concentration are discharged into the receiving aquatic environment. WWTPs, which are the last barrier between MPs in wastewater and receiving aquatic environments, are extremely important in minimizing the entry of MPs into the aquatic environment and their negative effects on aquatic biota. There are review papers covering the sources (Acarer 2023a), identification (Bakaraki Turan *et al.* 2021; Kong *et al.* 2023), occurrence (Ali *et al.* 2021; Kong *et al.* 2023), characteristics (Hamidian *et al.* 2021; Acarer 2023a), fate (Ali *et al.* 2021; Bakaraki Turan *et al.* 2021), effects on sewage sludge (Liu *et al.* 2023) and removal efficiency in different treatment units (Acarer 2023a; Ta & Promchan 2024) of MPs in various WWTPs around the world. To date, there is no review paper covering the characteristics and abundance of MPs in WWTPs of Türkiye and the MP removal efficiency of WWTPs of Türkiye. This paper is the first review on the abundance and characteristics of MPs in WWTPs of Türkiye and the removal of MPs from WWTPs in Türkiye.

The studies used in this review paper are collected from the Turkish Council of Higher Education Thesis Center, Google Scholar, and Scopus databases. The words 'microplastic' and 'wastewater treatment plant' are searched in the entire field at the Turkish Council of Higher Education Thesis Center and relevant studies are identified. The following expressions are searched separately in the article title, abstract and keywords section of the Scopus database: (1) 'microplastic' AND 'wastewater treatment plant' AND 'Turkey' and (2) 'microplastic' AND 'wastewater treatment plant' AND 'Türkiye'. Similarly, the words microplastic, wastewater treatment plant and Türkiye/Turkey are searched together on Google Scholar, and relevant articles are identified.

This review summarizes the abundance and dominant characteristics (polymer type, shape, and size) of MPs in the inlet effluent of WWTPs in Türkiye. Additionally, this review may serve as a scientific guide for the MP removal efficiency of WWTPs from wastewater in Türkiye. Moreover, this review provides the opportunity to compare the dominant MP characteristics in WWTPs in Türkiye, and the MP removal efficiency of WWTPs in Türkiye with results in different countries. Thus, this review may encourage cooperation between Türkiye and other countries at the international level to increase the MP removal efficiency of WWTPs.

2. NUMERICAL DATA ON WASTEWATER TREATMENT AND DISCHARGE IN TÜRKIYE

WWTPs ensure that wastewater is treated through various processes and discharged into receiving environments according to limit values to minimize the damage to human health and the environment. According to the information on the official website of the Ministry of Environment, Urbanisation and Climate Change of the Republic of Türkiye, the number of WWTPs in Türkiye is 1,068 at the end of 2020 (Ministry of Environment Urbanisation and Climate Change of the Republic of Türkiye 2023).

Data from the Türkiye Statistical Institute (TUIK) shows that 15.3 billion m^3 of wastewater was discharged directly into the receiving environment by thermal power plants, municipalities, manufacturing industries, organized industrial sites, mining industries, and villages in 2020. In 2020, 76.6, 19.3, 1.1, 1, 0.4, 0.2, and 1.4% of wastewater were discharged into seas, streams, dams, septic tanks, lakes/ponds, lands, and other receiving environments, respectively (Figure 1(a)). 52.2, 30.9, 13.4, 1.6, 1.1, and 0.8% of the total wastewater were discharged directly to the receiving environment by thermal power plants, municipalities, manufacturing industries, organized industrial sites, mining industries, and villages, respectively (Figure 1(b)). It is known that 4.4 billion m^3 of the 5 billion m^3, i.e. 88%, of wastewater discharged by municipalities into receiving environments are treated in WWTPs. Municipalities applied advanced treatment, biological treatment, physical treatment and natural treatment to 50.7, 27.1, 21.9 and 0.3% of wastewater, respectively (Figure 1(c)). A large portion of the wastewater treated by municipalities was discharged into rivers (46.4%) and seas (42.8%) (Figure 1(d)) (TUIK 2020).

3. CHARACTERISTICS OF MICROPLASTICS IN WASTEWATER TREATMENT PLANTS IN TÜRKIYE

MPs reaching WWTPs lead to the formation of an MP cocktail in various polymer types, shapes, sizes, and colors in the influent of WWTPs. The results of the studies investigating the characteristics of MPs in the influent and effluent of WWTPs in Türkiye are listed in Table 1.

Some studies have revealed that PE is the dominant MP polymer type in the influent of WWTPs in Türkiye (Üstün *et al.* 2022; Can *et al.* 2023; Kılıç *et al.* 2023). The fact that PE is the dominant MP polymer type in the influent of WWTPs in Türkiye can be explained by the fact that PE is widely used in many places in daily life, such as packaging, plastic bags, stretch film, cutting boards and pipes, due to its superior properties. On the other hand, some studies reported that polyester (PEST)

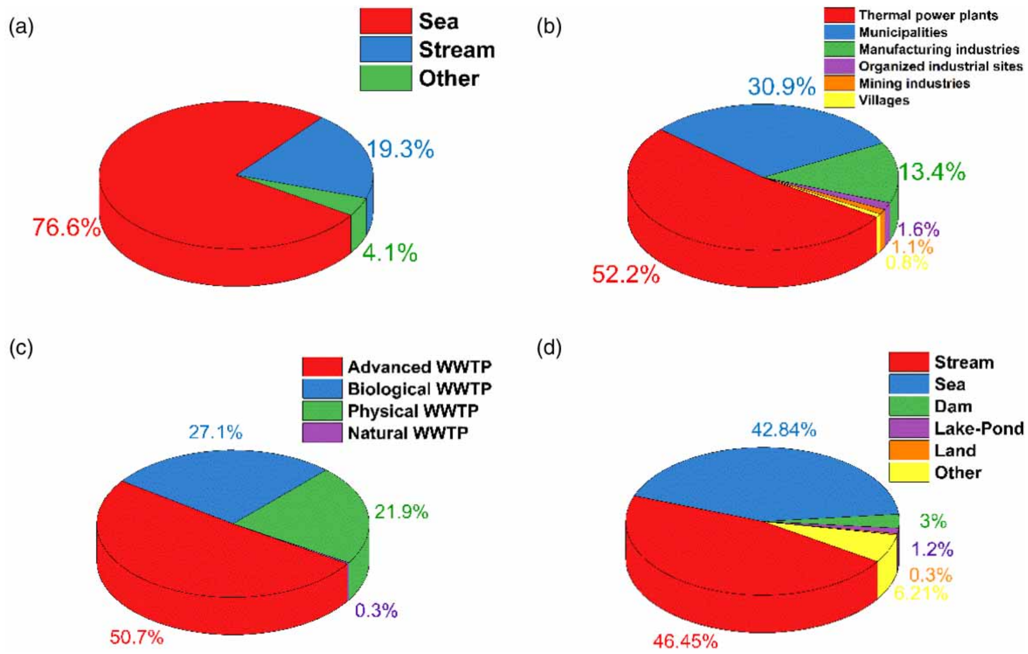


Figure 1 | (a) Distribution of discharged wastewater according to receiving environments, (b) Distribution of discharged wastewater according to dischargers, (c) Distribution of wastewater treated by municipalities according to the type of WWTP used in treatment, and (d) Distribution of wastewater treated by municipalities according to discharged receiving environments (TUIK 2020).

Table 1 | Results of studies investigating the characteristics of MPs in the influent and effluent of WWTPs in Türkiye

		Dominant MP Polymer Type		Dominant MP Shape		Dominant MP Size (μm)		
WWTP	**Treatment Stages**	**Influent**	**Effluent**	**Influent**	**Effluent**	**Influent**	**Effluent**	**Reference**
Hatay Antakya WWTP	Pre-, primary, and secondary	PET	PE	Fiber	Fiber	500–1,000	250–500	Kılıç *et al*. (2023)
Hatay Serinyol WWTP	Pre- and secondary	PE	PE	Fiber	Fiber	500–1,000	500–1,000	Kılıç *et al*. (2023)
Hatay Narlıca WWTP	Pre-, secondary and tertiary	PET	PE	Fiber	Fiber	500–1,000	<500	Kılıç *et al*. (2023)
Bursa WWTP	Pre- and secondary	PE	PE	Fiber	Fiber	500–1,000	500–300	Can *et al*. (2023)
Bursa WWTP	Pre- and secondary	PE	PP	Fragment	Fragment	500–1,000	300–500	Üstün *et al*. (2022)
İstanbul Ambarlı WWTP	Pre- and secondary	PC and PUR	PC, PUR and PES	Fiber	Fiber	500–1,000	500–1,000	Vardar *et al*. (2021)
Sakarya Karaman WWTP	Pre- and secondary	PE	PA	Film	Fiber	<1,000	<1,000	Bilgin *et al*. (2020)
Yozgat WWTP	-	-	-	Fiber	Fiber	200–500	200–500	Altuğ (2020)
Adaana Seyhan WWTP	Pre-, primary, and secondary	PEST	PEST	Fiber	Fiber	1,000–5,000	1,000–5,000 = 500–1,000	Gündoğdu *et al*. (2018)
Adana Yüreğir WWTP	Pre-, primary, and secondary	PEST	PEST	Fiber	Fiber	1,000–5,000	1,000–5,000	Gündoğdu *et al*. (2018)
Sakarya Karaman WWTP	Pre- and secondary	PA6 and PA66		Fiber	Fiber	–	–	Ceylan (2017)

and PET are the dominant MP types in the influent of WWTPs in Türkiye (Kılıç *et al*. 2023). PEST fiber-type MPs found in the influent of WWTPs originate from the wastewater of washing machines, especially where synthetic laundry is washed (Hernandez *et al*. 2017). Polymer types of MPs in the effluents of WWTs in Türkiye include PE, PP, PET, PVC, PA, PC, PS, acrylic, polyurethane (PUR), polyethersulfone (PES) and ethylene vinyl acetate (EVA) (Üstün *et al*. 2022; Can *et al*. 2023; Kılıç *et al*. 2023). MPs released from WWTPs into receiving aquatic environments can remain in the environment for hundreds of years without degrading, depending on the polymer type and thickness of the MP and environmental conditions (Chamas *et al*. 2020). MPs in polymer types with low density tend to float, and MPs in polymer types with high density tend to sink (Mehra *et al*. 2021). This indicates that MPs are ubiquitous throughout the water column in the aquatic environment and threaten the aquatic ecosystem.

Studies conducted in WWTPs of Türkiye have shown that MPs with fiber (Ceylan 2017; Gündoğdu *et al*. 2018; Altuğ 2020; Bilgin *et al*. 2020; Vardar *et al*. 2021; Üstün *et al*. 2022; Akdemir & Gedik 2023; Bağ 2023; Can *et al*. 2023), fragment (Ceylan 2017; Gündoğdu *et al*. 2018; Altuğ 2020; Bilgin *et al*. 2020; Vardar *et al*. 2021; Üstün *et al*. 2022; Akdemir & Gedik 2023; Bağ 2023; Can *et al*. 2023), film (Ceylan 2017; Gündoğdu *et al*. 2018; Altuğ 2020; Bilgin *et al*. 2020; Üstün *et al*. 2022; Akdemir & Gedik 2023; Can *et al*. 2023) pellet (Altuğ 2020) and granular (Üstün *et al*. 2022; Can *et al*. 2023) shapes are found in the influent and effluent of WWTPs. Fiber-shaped MPs in the influent of WWTPs generally originate from washing synthetic clothing and textiles (washing machine wastewater, textile industry wastewater, etc.) (De Falco *et al*. 2019). Fragments are mostly formed by breaking larger plastics (packaging, pipes, etc.) into smaller pieces. Film-shaped MPs in WWTPs have a slight thickness and usually result from the breaking of plastic bags or plastic packaging into smaller pieces. Since pellets and granular MPs are generally produced for use in plastic production and personal care products/cosmetic products, these are generally the sources of pellets and granular MPs in wastewater. The majority of studies conducted in Türkiye reported that fiber and fragment-shaped MPs are the dominant MP shape in the influent and effluent of WWTPs (Gündoğdu *et al*. 2018; Vardar *et al*. 2021; Üstün *et al*. 2022; Can *et al*. 2023). Studies have shown that small amounts of pellets and granular MPs are found in the influent and effluent of WWTPs compared to the sum of fibers and fragments. It has been reported that the dominant MP shape in the influents of WWTPs located in Adana (Gündoğdu *et al*. 2018), Bursa (Can *et al*. 2023), Hatay (Kılıç *et al*. 2023), Yozgat (Altuğ 2020), Sakarya (Bilgin *et al*. 2020) and İstanbul (Vardar *et al*. 2021) is fiber. Studies conducted in WWTPs located in China-Wuhan (Liu *et al*. 2019), China-Shandong (Cai *et al*. 2022), Canada/Vancouver (Gies *et al*. 2018), New South Wales/Australia (Raju *et al*. 2020) and Northern Italy (Magni *et al*. 2019) also reported that fibers are the dominant MP shape in the effluent of WWTPs.

The size of MPs is in the range of 1 μm–5 mm, and most of the studies conducted in Türkiye have shown that MPs smaller than 1 mm, especially 0.5–1 mm, are dominant in the influent of WWTPs (Vardar *et al*. 2021; Üstün *et al*. 2022; Can *et al*. 2023; Kılıç *et al*. 2023). On the other hand, it was determined by Gündoğdu *et al.* (2018) that MPs with a size of 1–5 mm were dominant in the influent of Yüreğir WWTP and Seyhan WWTP located in Adana, Türkiye. The size of MPs in the influent of WWTPs plays an important role in MP removal at different treatment stages of WWTPs. Generally, small-sized MPs are removed with lower efficiency than large-sized MPs in conventional WWTPs, and small-sized MPs are dominant in the effluent of WWTPs (Bayo *et al*. 2020; Üstün *et al*. 2022; Kılıç *et al*. 2023). In addition, the fragmentation of MPs in the influent of WWTPs into smaller-sized MPs during the treatment process is accepted as another reason for the small-sized MPs in the effluent of WWTPs (Lv *et al*. 2019). The size of MPs discharged into receiving environments from different WWTPs in Türkiye has been reported to be mostly <500 μm and 500–1,000 μm. Since the size of MPs in aquatic environments decreases and their surface areas increase, such MPs may create more worrying results by adsorbing different pollutants in the aquatic environment more (Acarer 2023a).

MPs found in wastewater have various colors such as transparent, white, black, blue, red, green, and yellow (Ceylan 2017; Altuğ 2020; Vardar *et al*. 2021; Üstün *et al*. 2022). In MP characterization studies, researchers examine the polymer type, shape, and size of MPs found in aquatic environments and wastewater, as well as the color distribution of MPs. Color can help predict the source of MPs. For instance, it can be predicted that film-shaped transparent, white, and black MPs in water originate from plastic shopping bags or transparent/white fragment-shaped MPs originate from plastic beverage bottles. Similarly, it can be estimated that fiber-shaped MPs with colors such as black, red, and blue in wastewater are caused by washing colored synthetic clothes. Size is not the only factor in the ingestion of MPs by aquatic organisms, color is also significant. Aquatic organisms swallow MPs similar in color to their prey, perceiving them as food, and the swallowed MPs accumulate in their bodies (Borriello *et al*. 2023). Kılıç *et al.* (2023) reported that blue (59%), black (28%), red (8%), green (3%), brown (1%), and yellow (1%) were found in the effluents of WWTPs in Hatay, Türkiye. Can *et al.* (2023) reported that the MPs in the effluent of the WWTP in Bursa-Türkiye, whose effluent is discharged into the Marmara Sea, are mostly transparent (35%) and black (28%). Altuğ (2020) stated that there were mostly black, blue, green, and red MPs in the effluent of Yozgat WWTP in March and September, respectively. Ceylan (2017) reported that dark navy blue-blue, purple, and black colored MPs were dominant, respectively, in the effluent of Karaman WWTP located in Sakarya, Türkiye. When the studies conducted in WWTPs of Türkiye are evaluated, it can be concluded that mostly black and blue MPs are discharged from WWTPs to the aquatic environments.

Although wastewater passes through various treatment units (preliminary, primary, secondary, and tertiary) in WWTP, MPs cannot be completely eliminated from wastewater. Possible reasons for the presence of MPs in WWTP effluents include the inability of current treatment processes to provide 100% efficient separation and the fragmentation of MPs into smaller pieces during treatment (Lv *et al.* 2019). Factors affecting the dominant MP characteristic in the effluent of WWTPs include the concentration of different MP types in the wastewater, the properties of MPs (density, size, shape, etc.), treatment processes in the WWTP, and the MP removal mechanisms of the treatment processes. For instance, washing machine wastewater has a significant share in the dominance of fiber in the influent of WWTPs. One reason for the dominance of fiber-shaped MPs in the effluent of WWTPs is that the fibers are not retained well enough in treatment processes due to their needle-like structures. A study conducted in recent years has shown that fibers, due to their shape, can easily pass even through reverse osmosis (RO) which provides effective treatment of water and wastewater (Cai *et al.* 2022). Therefore, fiber may be the dominant MP shape in both the influent and effluent of WWTPs. As another example, PE can dominate the influent of WWTPs because it is the most widely used plastic in the world. The reason for the dominance of PE in the effluent may be related to the high concentration of PE in the wastewater as well as the fact that PE does not settle well enough in the primary and secondary settling tanks due to its low density. It is quite difficult to understand the dominant MP characteristics in the effluents of WWTPs, since the concentration of MPs in the wastewater, the physical and chemical properties of MPs, and several treatment processes/mechanisms are all effective together.

4. MICROPLASTIC REMOVAL EFFICIENCY OF WASTEWATER TREATMENT PLANTS IN TÜRKIYE

Table 2 summarizes the results of studies examining the MP concentrations in the influent and effluent of WWTPs in Türkiye and the MP removal efficiencies of these WWTPs. According to the studies in Table 2, WWTPs of Türkiye provide MP removal efficiency in the range of 73%- 99%. Factors that play an effective role in the difference in the MP removal efficiencies of WWTPs can be listed as follows: (1) The population served by the WWTP, (2) consumption habits of the population, (3) MP abundance and characteristics in WWTP, (4) preliminary, primary, secondary and tertiary treatment stages in WWTP, (5) operation of treatment units in the WWTP, (6) the amount of surface runoff reaching the WWTP depending on the season, (7) the sampling volume taken for MP analysis, and (7) MP analysis methods. Although WWTPs are not specifically designed for the removal of MPs from wastewater, considering general MP removal rates, it is seen that WWTPs effectively remove MPs from wastewater (Table 2). MPs are separated from wastewater via various mechanisms in different treatment units in WWTPs (Figure 2). However, similar to the results of studies in Türkiye, studies conducted in different parts of the world show that WWTPs cannot provide 100% MP removal efficiency (Talvitie *et al.* 2017; Lares *et al.* 2018; Lv *et al.* 2019).

The MP removal efficiency of WWTPs is significantly related to the processes applied in the pre-, primary, secondary, and tertiary treatment stages in WWTPs. Coarse screens, fine screens, grit and oil chambers in WWTPs are pre-treatment units and most of the MPs are removed in the pre-treatment stages of WWTPs (Murphy *et al.* 2016; Bilgin *et al.* 2020). Plastics larger than the screen openings in WWTPs are separated from the wastewater by the screening mechanism (Badola *et al.* 2022). In addition, MPs are separated from the wastewater during the pre-treatment stage by adsorbing to the surface of other materials that are too large to pass through the screens. However, no study has been found in the literature examining the MP removal efficiency from wastewater with coarse screens and fine screens in any WWTP in Türkiye. Instead, the combined effect of pre-treatment units in WWTPs in Türkiye to remove MPs from the influents of WWTPs was investigated. For instance, Üstün *et al.* (2022) reported that the MP concentration in the influent (135.3 $\pm$ 28.0 MP/L) in a WWTP located in Bursa-Türkiye decreased to 78.3 $\pm$ 38.6 MP/L after the wastewater passed through the coarse screen, fine screen and grit chamber. Similarly, Can *et al.* (2023) reported that in a domestic WWTP in Bursa, the MP concentration of wastewater passing through the fine screen and grit chamber decreased from 107.1 $\pm$ 40.2 to 73.1 $\pm$ 40.6 MP/L. Bilgin *et al.* (2020) stated that the MP concentration in wastewater decreased from 30.7 to 21.7 MP/L through the coarse screen, fine screen, and aerated grit chamber in Karaman WWTP in Türkiye. Vardar *et al.* (2021) reported that in Ambarlı WWTP, approximately 55% of MPs in the wastewater were removed after the wastewater passed through the screens and the grit chamber.

The majority of MPs in WWTPs are retained in the primary and secondary sludge (Magni *et al.* 2019). Hydrophobic interactions and electrostatic interactions enable the sorption of MPs to the surface of the sludge particles (Rout *et al.* 2022).

Table 2 | MP concentrations in influent and effluent of WWTPs in Türkiye and the removal efficiency of WWTPs

WWTP	Treatment Units of WWTP	MP Concentration in the Influent (MP/L)	MP Concentration in the Effluent (MP/L)	Removal Efficiency	Reference
Bursa WWTP	Fine screen, grit chamber, A2O biological tank, secondary settling tank, and UV disinfection unit	107.1 ± 40.2	4.1 ± 1.1	96.1%	Can *et al.* (2023)
Hatay Antakya WWTP	Coarse and fine screens, grit chamber, primary settling tank, trickling filter, and secondary settling tank.	75.8 ± 5.1	1.3 ± 0.3	98%	Kılıç *et al.* (2023)
Hatay Serinyol WWTP	Coarse and fine screens, grit chamber, anaerobic tank, aerobic tank, and secondary settling tank	53.3 ± 6.6	4.5 ± 1.6	92%	Kılıç *et al.* (2023)
Hatay Narlıca WWTP	Coarse and fine screens, grit chamber, anaerobic tank, anoxic tank, aerobic tank and MBR	42.6 ± 3.5	0.6 ± 0.2	99%	Kılıç *et al.* (2023)
Bursa WWTP	Coarse and fine screens, grit chamber, anaerobic tank, anoxic tank, aerobic tank, and secondary settling tank	135.3 ± 28.0	8.5 ± 4.7	93.7%	Üstün *et al.* (2022)
İstanbul Ambarlı WWTP	Screens, grit chamber, phosphorus tank, biological tank, and secondary settling tank.	72.6	8.2	84.7%-93%	Vardar *et al.* (2021)
Yozgat WWTP	–	46.4 ± 11.5 61.4 ± 11.7	1.6 ± 0.7 2.1 ± 0.5	96.5% 96.5%	Altuğ (2020)
Sakarya Karaman WWTP	Coarse and fine screens, aerated grit chamber, aeration tank, and secondary settling tank	30.7	6.3	79.5%	Bilgin *et al.* (2020)
Adana Seyhan WWTP	Aerated grit-oil chamber, primary settling tank, aeration tank, and secondary settling tank	26,555 ± 3,175	6,999 ± 764	73%	Gündoğdu *et al.* (2018)
Adana Yüreğir WWTP	Grit-oil chamber, primary settling tank, aeration tank, and secondary settling tank	23,444 ± 4,100	4,111 ± 318	79%	Gündoğdu *et al.* (2018)

However, there is no study examining the effect of primary settling tanks on MP removal in WWTPs in Türkiye. Disposal of MPs separated from wastewater in WWTPs is another problem. Since MPs remain in the sludge even if various processes such as dewatering and stabilization are applied to the sludge, deficiencies in the management of sewage sludge and uncontrolled use of sludge in agricultural areas lead to a serious MP release into the environment (Ren *et al.* 2020; Harley-Nyang *et al.* 2022). Some studies conducted in recent years have shown that MPs separated from wastewater in WWTPs can be converted into economically valuable materials (Wang *et al.* 2022; Luo *et al.* 2023). Recycling MPs separated from wastewater and obtaining various materials from MPs not only reduces the environmental impacts of MPs but also contributes to sustainability and circular economy. However, there is no study on the transformation of MPs separated from wastewater in WWTPs into valuable products in Türkiye, and this issue deserves to be investigated.

In WWTPs, the tank where biological treatment takes place and the secondary settling tanks are within the scope of secondary treatment stages. The mechanisms for removing MPs in activated sludge systems are sorption, biodegradation, and biotransformation (Rout *et al.* 2022). MPs are digested by microorganisms and hydrolyzed by intracellular degradation, or MPs undergo extracellular degradation by extracellular enzymes secreted by microorganisms (Rout *et al.* 2022). In secondary treatment, MPs in wastewater are separated from wastewater by adsorption to activated sludge and precipitation by gravity in secondary settling tanks (Acarer 2023a). In other words, in secondary treatment, MPs in wastewater are trapped in the sludge in secondary settling tanks (Ren *et al.* 2020). Can *et al.* (2023) reported that MPs were removed with 87% efficiency through the A2/O biological tank and secondary settling tank in Bursa WWTP. Bilgin *et al.* (2020) found that the MP removal efficiency of the aeration tank and secondary settling tank from wastewater in Karaman WWTP was 71%. It is a good alternative for the treatment of wastewater compared to the conventional activated sludge system, which is widely used in

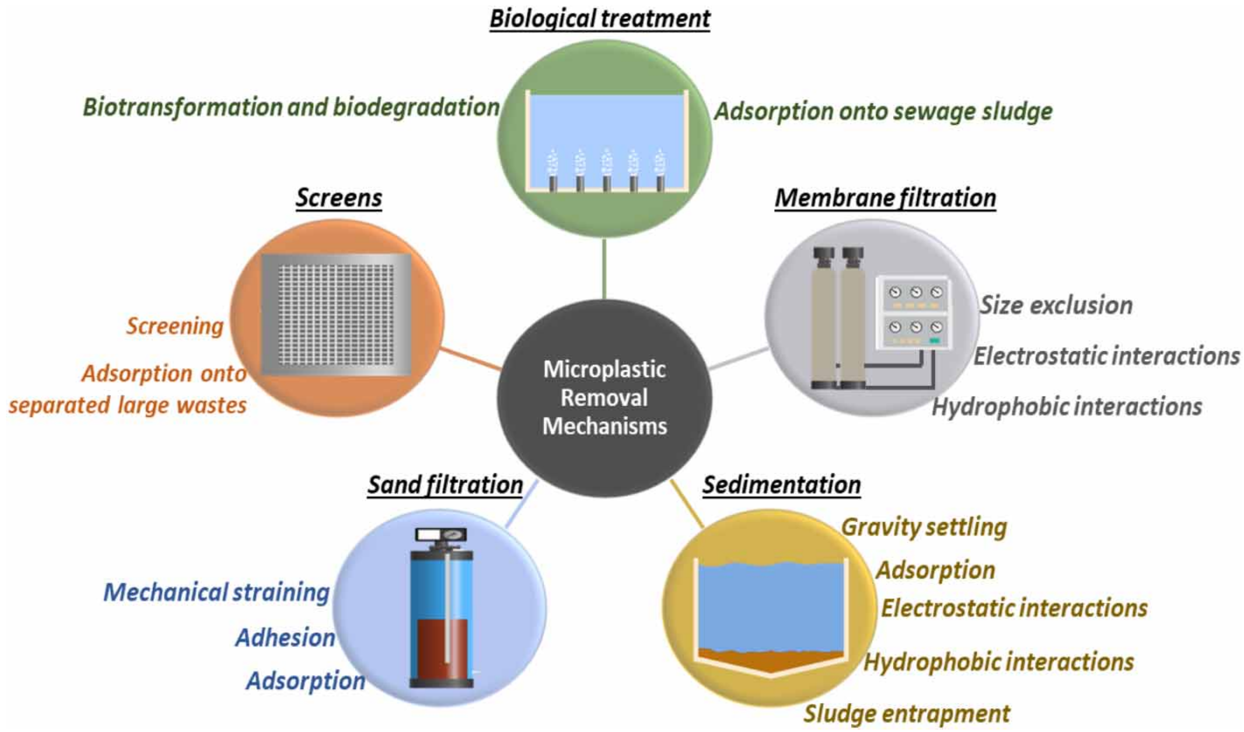


Figure 2 | Microplastic removal mechanisms in different treatment units of WWTPs.

the secondary treatment stage of WWTPs. Membrane bioreactors (MBRs) are a good alternative for treating wastewater compared to the conventional activated sludge system, which is widely used in the secondary treatment stage in WWTPs. Generally, microfiltration (MF) and ultrafiltration (UF) membranes are used in MBRs, and the pore size of both membranes is smaller than the size of MPs. An important advantage of MBRs is that they eliminate the need for secondary settling tanks in WWTPs. Since MP removal in secondary settling tanks depends on the density and shape of MPs, some MPs can be removed with high efficiency due to good settling, while some cannot be removed with high efficiency. Kılıç *et al.* (2023) reported that the MP removal efficiency was 98 and 92% in Antakya WWTP and Serinyol WWTP, where wastewater was secondary treated by trickling filter-secondary settling tank and A/O process-secondary settling tank, respectively.

Sand filtration and membrane filtration are the processes used in the tertiary treatment stage in WWTPs. Sand filters remove MPs from wastewater by trapping them between sand grains, that is, by mechanical straining mechanism (Singh *et al.* 2021). Adhesion is another mechanism that causes MPs to be retained in sand filter media (Sembiring *et al.* 2021). The tertiary treatment stage in WWTPs further increases the MP removal efficiency of the WWTP by providing greater removal of MPs in the secondary treated wastewater (Pittura *et al.* 2021). Although there are studies examining the MP removal efficiency of sand filtration (Ben-David *et al.* 2021; Bitter *et al.* 2022), the MP removal efficiency of sand filtration in WWTPs has not been reported in any study in Türkiye. Among the treatment technologies available today, membrane technologies are the most effective treatment technologies that exhibit the highest efficiency in MP removal from wastewater. The main mechanism for MP removal from wastewater by membrane processes is size exclusion, but adsorption and electrostatic interactions between the membrane surface and MPs are also effective (Acarer 2023a, 2023c). However, 100% MP removal from wastewater cannot be achieved even with membrane technologies (Luogo *et al.* 2022; Kara *et al.* 2023; Acarer 2023c). The reasons why MP cannot be removed from wastewater with 100% efficiency with membranes can be listed as follows: (1) the presence of deformations-openings in the membranes, (2) the possibility of MPs with sharp corners damaging the membrane structure, (3) low mechanical strength of the membrane and (4) MP release from the polymeric membrane material into water as a result of the structure of polymeric membranes being exposed to hydraulic impact during filtration/chemicals during membrane cleaning. It has been reported that the MP concentration decreased to 2 MP/L following the application of UF and nanofiltration (NF) after the bioreactor containing 196 MP/L MP in the leachate treatment plant located in

Istanbul, Türkiye (Kara *et al.* 2023). The study revealed that UF and NF removed MPs from the leachate with 96 and 99% efficiency, respectively, and the membranes contributed to a significant decrease in MP concentration (Kara *et al.* 2023).

5. DISCHARGE TO AQUATIC ENVIRONMENT FROM WASTEWATER TREATMENT PLANTS IN TÜRKIYE

MPs in aquatic environments such as rivers and seas originate from land-based sources or activities carried out in the aquatic environment. Sources of land-based MPs in aquatic environments include effluents of WWTPs. The effluents of WWTPs are an important source of MP for the aquatic environment. Studies conducted in Türkiye and in many parts of the world have reported the presence of MPs in various polymer types, sizes and shapes in the effluent of WWTPs. Considering the concentration of MP in the effluents of WWTPs and the effluent flow rate, a large amount of MP is discharged into the receiving aquatic environments even in a day. It has been reported that a total of 1,460 MPs were identified in the effluent of 15 different WWTPs located in Tekirdağ, Istanbul, Yalova, Bursa, Sakarya, Zonguldak, Kastamonu, Sinop, Samsun, Trabzon and Rize cities of Türkiye (Akdemir & Gedik 2023). It was determined that a total of 6.18×10^{10} MP from 15 WWTPs was discharged into the marine environment per day, of which 1.24×10^{10} MP was discharged to the Black Sea and 4.94×10^{10} MP was discharged to the Marmara Sea (Akdemir & Gedik 2023). Although the MP removal efficiency of Antakya, Serinyol, and Narlıca WWTPs in Hatay is over 90%, it has been reported that the MP load given to the Asi River in one day is 37,440,000, 2,122,450, and 6,014,367 MP/day, respectively (Kılıç *et al.* 2023). In other words, an average of 45 million MP is discharged into the Asi River from three WWTPs per day (Kılıç *et al.* 2023). As a result of multiplying the MP concentration in the effluent (8.45 MP/L) of a WWTP in Bursa with an average flow rate of 61,800 m^3/day, it was determined that an average of 525 million MP per day was discharged into the Nilüfer Stream, which is used for irrigation purposes throughout the basin and reaches the Marmara Sea (Üstün *et al.* 2022). Although the concentration of MPs in the effluent of the WWTP in Bursa is low (4.1 MP/L), it is reported that 7.5×10^7 MPs per day are released into the Marmara Sea due to the outlet flow rate of the WWTP being 1.8×10^4 m_3/day (Can *et al.* 2023). Sari Erkan *et al.* (2021) compared the water samples collected from the coastline of Istanbul in the Marmara Sea, 7 different deep-sea discharge locations and 10 different sea discharge locations, and they found that the average amount of MP at the deep-sea discharge locations was higher than that at the sea discharge points. This result in the study is attributed to the application of simple treatments such as pre-treatment and primary treatment in deep-sea discharge, while advanced wastewater treatment processes are applied in sea discharge. The study showed that MPs in the form of fragments, fiber films, foams, and pellets were dominant in the water samples collected from the sea discharge and deep-sea discharge points, respectively (Sari Erkan *et al.* 2021).

Table 3 shows the results of the abundance and dominant characteristics of MPs in aquatic environments in Türkiye. A limited number of studies have shown that fibers and fragments are particularly dominant in aquatic environments in Türkiye. In addition to the discharge from WWTPs to receiving environments, the factors that cause an increase in MP pollution in surface waters can be listed as follows: (1) population, (2) maritime traffic, (3) tourism, (4) social activities in surface waters, (5) industrial activities around the receiving environment, (6) fishing activities, paint on ship surfaces and ship maintenance activities, (7) atmospheric deposition, (8) surface runoff, (9) poor waste management strategies including plastic waste recycling, and (10) poor environmental awareness of the public. Therefore, it is worth underlining that MP pollution in the results in Table 3 includes all land-based and aquatic environment-based sources. However, it is worth noting that there is no comprehensive research study investigating the abundance and characteristics of MP at the points where WWTPs are discharged into the aquatic environment in Türkiye and in locations close to the points, and this issue needs to be investigated further.

Taking measures to reduce MPs released from WWTPs into aquatic environments would be beneficial to minimize the negative effects of MPs on the aquatic environment and aquatic biota. The first step in reducing the amount of MP released from WWTPs into the aquatic environment is to comply with the 3R principle (reduce, reuse, recycle) for plastics. Providing education to the public about the sources of MPs, MP pollution, the environmental effects of MPs, and effective methods to reduce MP pollution can contribute to increasing environmental awareness and reducing MP pollution. Since the majority of the fibers in the influent of WWTPs originate from the washing of synthetic clothes and textiles, filters to retain the fibers in domestic and industrial washing machines can be developed and the fibers can be prevented from reaching WWTPs. Using products containing environmentally friendly, natural, and biodegradable additives instead of products containing plastic particles contributes to the reduction of MPs in the influent of WWTPs.

The most effective process in retaining MPs in a wide size range, different shapes, and different polymer types is the membrane filtration process (Acarer 2023c). MPs are retained on the membrane surface and pores and are effectively separated

Table 3 | Results of some studies investigating MP pollution in surface waters in Türkiye

MP Sampling Point	Number of Stations	Average MP Amount	DominantMP Shape	Dominant MP Size (mm)	Reference
Munzur river	9	0.16–1.51	Fiber	–	Gündoğdu *et al.* (2023)
Pülümür river	10	0.01–28.21	Fiber		
Tributaries that fall into Uzunçayır Dam Lake Water	4	0.04–0.98 (items/m^3)	Fiber		
Black Sea	23	18.68 ± 3.01 (items/m^3)	Fiber	2.07 ± 0.04	Terzi *et al.* (2022)
İstanbul Strait	1	15.49	Fiber	1 ± 0.63	Gürkan & Yüksek (2022)
Çanakkale Strait	1	6.67	Fiber	1.17 ± 0.6	
İzmit Bay	3	5.88–20.39	Fiber	1.1 ± 0.7–1.37 ± 1.02	
Bandırma Bay	3	10.78–34.9	Fiber	1.18 ± 0.71–1.37 ± 0.88	
Gemlik Bay	2	4.12–9.02	Fiber	0.93 ± 0.73–1.21–0.85	
Erdek Bay	3	6.86–15.88 (items/m^3)	Fiber	0.81 ± 0.66–1.41 ± 1.15	
Arpaçbahşiş river	–	613	Fiber	~ 1.35	Özgüler *et al.* (2022)
Göksu river	–	344	Fiber	0.79	
Lamas river	–	95 (items/m^3)	Fiber	~ 1.38	
Marine	9	276.1857	Fragment	1–5	Sari Erkan *et al.* (2021)
Piers	8	3,497.02	Fragment	0.3–1	
Streams	9	1,487.52	Fragment	1–5	
Sea decharge points	10	349.23	Fragment	1–5	
Deep sea decharge points (Marmara Sea)	7	813.75 (items/km^2)		1–5	
Dalyan İztuzu (Eastern Mediterranean) Coastline	14	0.148 ± 0.07 (items/m^2)	Fragment	1–5	Zilifli & Tunçer (2021)
Marmara Sea	14	1.26 ± 130.5 (items/m^2)	Fragment	2–4	Tunçer *et al.* (2018)
İskenderun Bay	14	1,067,120 (items/km^2)	Fragment	0.1–0.3	Gündoğdu (2017)
Mediterranean coast of Türkiye	18	16,339–520,213 (items/km^2)	–	–	Güven *et al.* (2017)
Southeastern coast of the Black Sea	12	$1.2 \pm 1.1 \times 10^3$ (items/m^3) (november) $0.6 \pm 0.55 \times 10^3$ (items/m^3) (february)	Fiber	0.2–5	Aytan *et al.* (2016)

from wastewater. When the studies reporting MP removal in WWTPs in Türkiye were evaluated, it was determined that there was no study reporting the effect of membrane filtration application on MP removal in WWTPs. Application of MBRs for biological treatment of wastewater or membrane filtration processes for further treatment of the effluent of WWTPs can significantly contribute to reducing the MP concentration in the effluent. For instance, a study conducted in China reported that MPs were removed with a 62.6% efficiency in a WWTP where primary sedimentation followed by a conventional activated sludge process was applied (Cai *et al.* 2022). The same study showed that the MP removal efficiency after the MBR and RO processes was 93.2 and 98%, respectively, in the WWTP where preliminary sedimentation, biological treatment, MBR and RO processes were applied, respectively (Cai *et al.* 2022). Therefore, there is a need to improve existing treatment processes in WWTPs in Türkiye and include membrane filtration processes in WWTPs to minimize MPs released into the aquatic environment.

Currently, there is no legal regulation that limits the MP concentration in the effluent of WWTPs in Türkiye. First, the development of a standard method for MP analysis in wastewater at an international level is mandatory to make research studies carried out both in Türkiye and other countries comparable. Then, the limit value for MP concentration in the effluent of WWTPs needs to be introduced at the national or international level. Additionally, the implementation of regulations requiring the monitoring of MP concentration in the effluent of WWTPs may contribute to reducing the amount of MP released from WWTPs into the aquatic environment.

Since the Marmara Sea is semi-enclosed, the limited water circulation in the sea makes the Marmara Sea more sensitive in terms of MP pollution. It is worth noting that approximately 19% of the population in Türkiye lives only in İstanbul, which is located in the Marmara region, and most of the industry in Türkiye is located in the Marmara region. Cities in the Marmara region, such as İstanbul, Kocaeli, and Bursa, where industrial activities are intense, cause the Marmara Sea to become more polluted day by day. Terzi *et al.* (2022) reported that, as a result of the MP analysis conducted at 23 stations on the southern coast of the Black Sea, the lowest, highest and average MP abundance were 4.42 ± 1.34, 55.67 ± 9.72, and 18.68 ± 3.01 particles/m^3, respectively. In the study, MP pollution was found to be higher on the west coast of the examined area (Marmara region) (Terzi *et al.* 2022).

MPs in the aquatic environment have the ability to adsorb various pollutants and MPs also act as vectors in the transportation of pollutants to different regions in the aquatic environment (Acarer 2023a). MPs released from WWTPs into aquatic environments are swallowed as food by aquatic organisms and MPs are transferred to other organisms through the food chain (Yan *et al.* 2022). Moreover, in the aquatic environment, MPs form nanoplastics through physical, chemical, and biological effects. Nanoplastics exhibit a different distribution in aquatic environments compared to MPs composed of the same polymer. Buoyant force is effective in the distribution of MPs, which are larger in size than nanoplastics, in the water column, depending on their density and shape. However, the distribution of nanoplastics is not governed by buoyancy force (Issac & Kandasubramanian 2021). The collision of nanoplastics with water molecules and Brownian motion control their distribution, and therefore nanoplastics negatively affect all areas in the aquatic environment (Issac & Kandasubramanian 2021).

6. STRATEGIES FOR MICROPLASTIC POLLUTION REDUCTION

Due to increasing population, urbanization, and plastic consumption, MP pollution in aquatic environments continues to increase and becomes a more serious problem day by day. MPs, especially fiber-shaped and <1 mm in size, especially <0.5 mm, are discharged into the receiving environment from WWTPs in Türkiye. In Türkiye, although WWTPs remove MPs from wastewater with high efficiency, considering the capacity of WWTPs, millions of MPs are discharged into the receiving environment every day. Considering the increasing abundance of MP in domestic wastewater and the increase in the number of WWTPs due to the ever-increasing population, the frightening aspect of MP pollution caused by WWTPs emerges. When the research studies in the literature are evaluated, it has been seen that fragment and fiber-shaped MPs are mostly dominant in surface waters in Türkiye.

Recommendations for reducing MP released into aquatic environments from WWTPs in Türkiye and other parts of the world are listed below:

(1) Reducing plastic consumption is the main factor that prevents the release of plastic waste into the environment. Therefore, education should be provided in schools and educational advertisements should be broadcast on television to reduce plastic consumption and increase public awareness of MP pollution in the environment. In addition, educational activities should be organized by institutions and organizations to raise awareness against MP pollution.
(2) The government should provide funds to facilities/workplaces where plastic recycling is carried out and alternative solutions to plastic are sought. Additionally, research projects investigating biodegradable polymers and alternatives to plastics should be financially supported.
(3) 3Rs (reduce, reuse, and recycle) waste management should be adopted for plastic waste. To ensure the recycling of plastic waste, plastic waste collection points should be established in public areas, and/or their number should be increased. A reward-based system should be developed by the government to encourage people to bring plastic waste to waste collection points.
(4) There should be restrictions on the use of microbeads and plastic glitters in personal care products and cosmetic products. Environmentally friendly and natural additives should be used instead of plastic additives in cosmetics and personal care products.

(5) Since fiber-shaped MPs, which generally constitute the majority of the influent and effluent of WWTPs, originate from the laundry process, a unit that retains the fibers should be designed and placed in washing machines in households and in industries where washing is applied, such as the textile industry.
(6) The lack of a standard method for MP analysis makes comparing the results of research studies complex. Therefore, a globally accepted standard method for sampling and analysis of MPs in water/wastewater should be adopted. Then, the government should introduce a legal regulation in the country that provides a limit value for MP concentration in the effluent of WWTPs according to the accepted reference method.
(7) The application of membrane processes such as MF, UF, NF, RO and MBR in WWTPs provides superior benefit in minimizing the MP concentration in the effluent of the WWTPs. Therefore, membrane technologies should be used more widely in WWTPs.
(8) Studies that develop treatment systems that remove MPs from the influents of WWTPs completely or with much higher efficiency should be financially supported by the government. In addition, studies to improve the MP removal efficiency of existing treatment methods should also be supported.

7. CONCLUSION AND FUTURE PERSPECTIVE

Currently, there are a limited number of studies in Türkiye examining the abundance and characteristics of MPs in the influent and effluent of WWTPs. Studies investigating the MP removal efficiency of WWTPs in Türkiye are also limited. Unfortunately, there is no comprehensive study in Türkiye investigating the contribution of each treatment unit of WWTPs to MP removal and the characteristics of MPs (polymer type, shape, size, and color) found in the treated water after each treatment unit. This may be because there is no standard method for MP analysis in wastewater and there are a limited number of scientists specialized in MP identification/characterization in Türkiye. First of all, the development of a standard MP analysis procedure is urgently needed worldwide to be able to compare the results of national and international studies. The government should contribute to preventing this research gap by establishing state-of-the-art laboratories to perform MP identification and characterization in samples collected from WWTPs. In addition, the government should financially support research on the development of technologies for MP removal in wastewater and the improvement of existing processes. I recommend that future studies focus on MP pollution in WWTPs, especially in the Marmara Region, which is the most densely populated and industrially developed region in Türkiye. The following topics should be investigated in Türkiye's WWTPs, especially in the WWTPs in the Marmara Region: (1) MP concentration and MP characteristics in the influent/effluent of WWTPs, (2) effects of WWTPs on the aquatic environment and (3) distribution of MPs in WWTP effluent in aquatic environments. The dominant MP characteristics (polymer type, shape, and size) in the effluent of WWTPs should be taken into account, and filtration techniques should be improved for greater removal of MPs from the effluents. Studies should be focused on developing membranes that remove MPs from wastewater with high efficiency. Studies in different parts of the world focus on MP removal by membrane filtration, modeling the distribution of MPs in the aquatic environment, and the conversion of MPs separated in WWTPs into value-added products.

As a result, there is still a need to investigate the following topics in WWTPs in Türkiye to eliminate the lack of data: (1) abundance and characteristics of MPs (polymer type, shape, size, and color) in WWTPs, (2) MP removal efficiency of WWTPs, (3) environmental impacts of MPs released from WWTPs, (4) developing strategies and methods for the disposal and recycling of MPs separated from WWTPs, (5) modeling of the distribution of MPs in the aquatic environment and (6) removal techniques for increased retention of MPs in the effluent of WWTPs.

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AUTHOR CONTRIBUTIONS

Seren Acarer Arat, the sole author of this review article, contributed 100% to the concept and design of this article. Conceptualization, investigation, writing Draft, writing-review & editing and visualization were carried out by Seren Acarer Arat.

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CONSENT TO PARTICIPATE

Not applicable.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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