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Review

Microplastics removal in wastewater treatment plants: A review of the different approaches to limit their release in the environment

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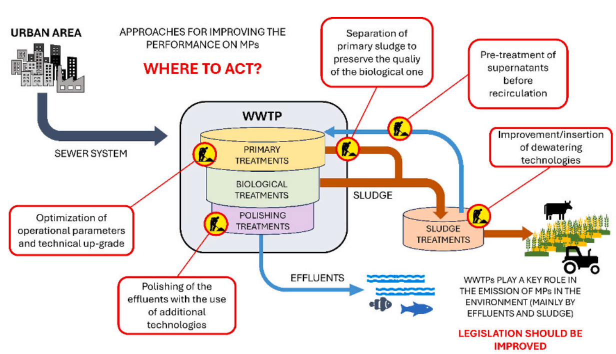
HIGHLIGHTS

- More than 65 % of microplastics (MPs) are accumulated in sewage sludge.
- Actions in water line are not enough to prevent MPs release into the environment.
- A combined approach is the only way for limiting MPs release.
- Agricultural reuse of sludge is a source of spread of MPs into the environment.
- A legislation about the quality of outlets and sludge is needed.

GRAPHICAL ABSTRACT



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ABSTRACT

In last 10 years, the interest about the presence of microplastics (MPs) in the environment has strongly grown. Wastewaters function as a carrier for MPs contamination from source to the aquatic environment, so the knowledge of the fate of this emerging contaminant in wastewater treatment plants (WWTPs) is a priority. This work aims to review the presence of MPs in the influent wastewater (WW) and the effectiveness of the treatments of conventional WWTPs. Moreover, the negative impacts of MPs on the management of the processes have been also discussed. The work also focuses on the possible approaches to tackle MPs contamination enhancing the effectiveness of the WWTPs. Based on literature results, despite WWTPs are not designed for MPs removal from WW, they can effectively remove the MPs (up to 99 % in some references). Nevertheless, they normally act as "hotspots" of MPs contamination considering the remaining concentration of MPs in WWTPs' effluents can be several orders of magnitude higher than receiving waters. Moreover, MPs removed from WW are concentrated in sewage sludge (potentially >65 % of MPs entering the WWTP) posing a concern in case of the potential reuse as a soil improver. This work aims to present a paradigm shift intending WWTPs as key barriers for environmental protection. Approaches for increasing effectiveness against MPs have been discussed in order to define the

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optimal point(s) of the WWTP in which these technologies should be located. The need of a future legislation about MPs in water and sludge is discussed.

1. Introduction

Generally, microplastics (MPs) are defined as the set of plastics with a size <5 mm (Ahmed et al., 2022). Recently, if the dimension is <1 μm, the particles are more specifically defined as nanoplastics (Cai et al., 2021). MPs can be intentionally manufactured in order to exploit their low dimensions (primary MPs), such as the microbeads in some personal care products and in industrial abrasive products and the fibres of synthetic clothes, and then released after usage (Collivignarelli et al., 2021c; Miraj et al., 2021; Thompson, 2015). They can also originate from the fragmentation of bigger plastic items, such as during the friction of the wear of tires on the road. In this case, they are indicated as secondary MPs (De Falco et al., 2019; Kole et al., 2017).

The presence of this emerging contaminant represents a serious issue due to (i) the extent of the problem, and (ii) the negative effect on human health and the environment (Ouyang et al., 2022; Prata et al., 2020). The annual production and release of MPs is strongly influenced by the habits of the population (Galafassi et al., 2019). Although it is almost impossible to estimate the production of secondary MPs, according to Boucher and Friot (2017), the amount of primary MPs that are released in the environment and reach the ocean is comprised from the equivalent of 150 empty grocery plastic bags (GPBs) per capita in North America to 22 GBPs per capita in Africa and Middle East. On average, 212 g per capita of primary MPs were released annually, the equivalent of 43 GPBs (Boucher and Friot, 2017).

The presence of MPs in the environment is also a cause of serious concerns due to the potential bad health effects. Despite the contrasting and only partial results, preliminary data seem to show that the exposure to MPs may bring to heath disruption in humans (Blackburn and Green, 2022; Prata et al., 2020; Vethaak and Legler, 2021). For instance, the studies on animal models showed that the intestines of mice fed with high concentration of polyethylene developed inflammation (Blackburn and Green, 2022). In-vitro studies with human cells and rats indicate that small MPs (< 10 μm) may reach the lymph and circulatory systems, causing exposure and accumulation in liver, kidney, and brain (Vethaak and Legler, 2021). In aquatic wildlife, MPs can enhance the rate of mortality, decreased the mobility, and damage the reproductive organs (Bhuyan, 2022).

Wastewater (WW) function as a "carrier" of both primary and secondary MPs, moving plastics from the source of contamination to the aquatic and soil ecosystems (Österlund et al., 2023; Schernewski et al., 2020). Being able to manage at this level the pollution caused by this emerging contaminant could help to limit the stream of plastic materials discharged in the environment.

In this sense, wastewater treatment plants (WWTPs) can play a key role. Generally, these plants have not been initially designed for the removal of emerging contaminants, including MPs (Sun et al., 2019). Nevertheless, most of the MPs are effectively removed from WW and concentrated in sewage sludge (Hooge et al., 2023), being a matter of concern in case of their reuse as soil improver for agricultural purposes.

This aspect is not of secondary importance given that in the European Union, reuse as a improver in agriculture (directly or as compost) represents the most frequent form of recovery of sludge from urban WWTPs (50.6 % on average) (Eurostat, 2023). Even in the rest of the world, agricultural reuse, for the purposes of nutrient recovery, is among the most frequent forms of use (e.g., 55 % in the U.S.A. and 73 % in Australia) (Marchuk et al., 2023). Therefore, focusing only on the removal from wastewater flux and concentrating them in sewage sludge could simply shift the pathway of entrance of MPs in the environment from water to soil.

In literature, several alternatives of additional treatments (such as separation technologies and chemical oxidation) and optimization of the operational procedures (such as the use of aeration in grit and grease removal units) have been already proposed in order to enhance the quality of the outlets and reduce the pollution of sewage sludge (Hou et al., 2021; Jagadeesh and Sundaram, 2021; Sun et al., 2019). MPs are not only an issue for the environment and human health, but also for the management of the same WWTPs considering that MPs can also negatively impact on the effectiveness of the treatments in terms of organic substance, nutrients, and microorganisms removal (Wu et al., 2021; Zhang and Chen, 2020).

To date several reviews have been already published on this topic. For instance, Iyare et al. (2020), Liu et al. (2021), Lu et al. (2023), Sun et al. (2019), and Z. Xu et al. (2021) already discussed about the effectiveness of primary, biological or polishing treatments in conventional WWTPs on MP. Wu et al. (2021), Zhang and Chen (2020) and Liu et al. (2023) reviewed the negative impact of MPs on the operational activities of WWTPs, while the topic of how to implement the performance of existing systems has been treated in a smaller number of reviews such as in Sol et al. (2020) and Talukdar et al. (2024).

However, despite many technologies have been already proposed in previous studies, the current literature lacks to compare the different approaches in view of limiting the release of MP in the environment. Specifically, one of the main questions that is still unsolved is: "what is/are the optimal point(s) of the WWTP in which the technologies for improving MPs removal should be located?". This review aims to answer this question.

In this work, the effectiveness of the different treatments present in a conventional WWTP and the impact of MPs on the same processes are presented in order to discuss the different approaches that can be adopted to limit the release of MPs in the environment, not only through the outlet but also through sewage sludge considering that its most common reuse option is as improver in soils for agricultural purposes. The aim is to propose the optimal point(s) of the WWTP in which the technologies should be located in order to reduce the content of MPs in WW and sewage sludge. On this topic, to date the literature focuses only on the proposal of possible interventions for tackling the issue of MPs in WWTPs but a clear picture of the possible advantages and disadvantages of each approach to define the optimal solution is lacking. Information about how and where act to reduce the number of MPs in the outlet and improve the quality of sludge is reported and discussed. In this context, a paradigm shift is proposed intending WWTPs not merely as "hotspots" of MPs but as key barriers for environmental protection. The results presented are intended to be useful for both scientific community and technical stakeholders. Moreover, also the key role of the WWTP in the fate of MPs is reviewed and some tips for future studies and for a new legislative scenario are proposed.

2. Methodological approach

This work has two main aims to:

- focus on the open matter about the optimal point(s) of the urban WWTP in which the technologies for improving MPs removal and/or degradation should be located. For this reason, (i) the characteristics of influent urban WW, (ii) the fate of MPs in conventional WWTPs in terms of amount and shape, (iii) the impact of MPs on the operational activities of WWTPs, and (iv) the technologies for improving MPs removal and/or degradation have been discussed;
- discuss the role of urban WWTPs in the fate of MPs and the potential exposure pathways for humans. In this case, the discussion takes into consideration the scenario of a potential reuse of sewage sludge as

soil improver in agriculture considering that, to date, it represents the main option of recovery/reuse in Europe (Eurostat, 2023) and one of their main disposal options in the world (Marchuk et al., 2023).

Given the aims of the work, the literature was searched on using the keywords "microplastic" AND "wastewater" AND "treatment" AND "plant" in "abstract, title and keywords" fields. Scopus® database has been used to limit the screening on peer-reviewed documents. Original articles, reviews, books, editorials and conference proceedings written in English were considered. In order to focus the work on most recent findings, the documents published before 2014 were excluded. After this first screening 721 documents were selected.

Then, the works were screened in order to avoid papers not completely on the topic. For instance, documents screened with the previous criteria and (i) referring to industrial WW or industrial WWTPs, (ii) only focused on presenting new methodological procedures for MPs detection and quantification, or (iii) only marginally referring to WWTPs were excluded. The documents have been grouped according to their content in three groups useful for the subsequent discussion in the paper: (i) concentration in influent WW, (ii) effectiveness of water and sludge line, (iii) effects of MPs on treatments of WWTPs. In total, 89 articles were reviewed and inserted in the discussion of the paper.

The number of the cited references of this work is higher because the documents related with aspects such as, for instance, (i) data about MPs production and sludge reuse options, (ii) the legislation about the presence MPs in water and sludge, (iii) studies on the health issues given by MPs exposure, and (iv) possible pathways from WWTPs to humans have been found using more specific keywords and/or referring to grey literature (e.g., for the legislative background).

3. Microplastics in the untreated WW

Despite the relevant number of studies dealing with the MPs in untreated urban WW, define a single range of concentration about the MPs is not simple. The amount and the type of MPs in urban sewage can be strongly influenced by several factors.

Firstly, the type of WW collected by the urban wastewater system can affect the number and the type of MPs (Table 1). For instance, strong industrial contribution from textile factories or laundries can enhance the load of MPs, influent to WWTPs, especially fibres (Grillo et al., 2023; Ramasamy et al., 2022). A separate collection of sewage and stormwater can help to avoid the entering of MPs due to the abrasion of tyre and road wear particles, atmospheric debris, and exterior paints (Landeros Gonzalez et al., 2022).

Secondly, the types and sources of MPS seems to be influenced by the lifestyle of population and the income of the different countries (Boucher and Friot, 2017; Galafassi et al., 2019). However, it should be noted that most studies available in literature are referred to high-income countries while only a few of them investigate the concentration of MPs in urban WW of low- middle-income countries representing a serious gap (Orona-Návar et al., 2022).

Nevertheless, the composition of raw urban WW in terms of MPs concentration can be also influenced by the absence of a standardize protocol for MPs sampling and detection, despite in many studies some guidelines are provided (Dey et al., 2021; Sol et al., 2023). Therefore, the type of sampling (simple or composite), the duration and the volume filtered, the size of the mesh used to filter WW, the type of extraction technique and the reagents used, and the identification techniques can vary across studies (Khan et al., 2020).

In untreated urban WW, >30 MPs polymers have been detected but, generally, polyester (PES), polyethylene (PE), polyethylene terephthalate (PET), polyamide (PA), and polypropylene (PP) are the most widely detected. PES, PET, and PA mainly originate from the washing of synthetic clothes, while PE and PP mainly derive from the fragmentation of plastic waste, and the use of personal care products (Liu et al., 2021;

Table 1
Results about influent concentration of MPs in urban WWTPs. It should be note that other studies are available in literature but are not reported here. The aim of this table is to show the heterogeneity of results about the MPs in urban wastewater and the techniques used for their detection and quantification. WW: wastewater; D: domestic contribution; M: industrial and domestic contributions; S/C: simple or composite. FTIR: Fourier transform infrared; SEM: scanning electron microscopy; n.a.: not available; *: stormwater is collected separately; **: assumption based on the description made by the authors.

Country	Type of WW contribution [D/M]	Range considered [μm]	Volume filtered [L]	Type of sampling [S/C]	Analytical quantification and characterization	Influent concentration [unit of MPs L^{-1}]	Classification by shape	References
Italy	n.a.	10–5000	30	S**	Visual and μ-FTIR	2.4	6 % lines, 21 % fragments, 73 % films	Magni et al. (2019)
France	n.a.	3–5000	1	S**	μ-FTIR coupled with freeware for the quantification	15,148 - 41,497	n.a.	Yang et al. (2023)
Finland	M*	250–5000	4–30	S**	Visual, FTIR microscopy and/or Raman spectroscopy	57.6 ± 12.4	More than 90 % of MPs are composed by fibres	Lares et al. (2018)
Spain	M	100–5000	5–10	S**	Visual and FTIR microscopy	275–586	21 % flakes, 30 % fragments, 34 % fibres, 14 % films, 1 % spheres	Franco et al. (2020)
United Kingdom	n.a.	38–100	0.5	S**	μ-FTIR coupled with freeware for the quantification	2102	n.a.	Cunsolo et al. (2021)
Canada	M	>1	1	S**	Visual and FTIR microscopy	31.1 ± 6.70	70 % fibres, 27 % fragments	Gies et al. (2018)
USA	M	20–4750	1–2	S**	Visual	133 ± 35.6	62 % fibres, 22.9 % fragments, 11.1 % microbeads	Michielssen et al. (2016)
USA	M*	20–4750	1–2	S**	Visual	92 ± 12	54.5 % fibres, 25.9 % fragments, 15.8 % microbeads	Michielssen et al. (2016)
China	M	> 75	30	S**	Visual and FTIR microscopy	288.5	More than 60 % of fibres, almost 15 % of fragments and almost 15 % of films	Z. Yang et al. (2021)
China	M	> 38	20	S	Visual and Raman spectroscopy	126.0 ± 14.0	More than 40 % of fibres, almost 35 % of fragments and <10 % of pellets	Jiang et al. (2020)
Australia	M	> 25	1	S**	Visual and μ-FTIR microscopy	55–98	49–84 % of fibres and 15–51 % of fragments	Ziajahromi et al. (2021)

Sun et al., 2019). PES, PE and PP can also derive from the wear of tires and textile factories (Liu et al., 2021). Nevertheless, the range provided by literature per each polymer is quite wide (Table 2), suggesting a huge variability depending on the sources of MPs release in the specific case study.

MPs can be also classified according to their shape. In the untreated WW, generally fibres are the most abundant (50–80 %) (Alavian Petroody et al., 2021; Hamidian et al., 2021; Sun et al., 2019). They are mainly secondary MPs, released during the washing of synthetic clothes, with an elongated shape (Herzke et al., 2021; Šaravanja et al., 2022). For instance, (Napper and Thompson, 2016) estimated that a typical washing of acrylic clothes (6 kg) can release >700,000 fibres. Fragments represent the second fraction (25–30 %) and are primary MPs related with the use of cosmetic and personal care products or secondary MPs produced by the erosion of plastic materials (Dronjak et al., 2023; Sun et al., 2019). Also, films can be detected in untreated WW (10–15 %) due to the shredding of plastic bags and packaging (Dronjak et al., 2023; Ren et al., 2020). Other shapes such as beads and foams generally are a minority group. These proportion can be different depending by several regional factor such as the lifestyle of population and the contribution of industrial WW. For instance, (Bayo et al., 2020b) but also (Galafassi et al., 2022) detected fragments as the most abundant type of shape (almost 47 % and up to 98 %, respectively) in untreated WW convoyed to urban WWTPs. Industrial activities such as laundries and textile factories can have a huge impact on the number of fibres convoyed to the WWTP (Lares et al., 2018).

Despite some uncertainties remain, in terms of size, smaller MPs (< 1 mm) are the majority (>60 %) This aspect can have an influence on the subsequent treatments considering that smaller particles generally tend to float while larger ones can be settled more easily (Azizi et al., 2022; Reddy and Nair, 2022). Moreover, the size also affects the interaction with other substances. High surface-to-volume ratio of small MPs stimulates their reactivity with other pollutants (e.g., heavy metals), and this can induce adverse impacts on WWTPs' biota and, if not properly treated, the human health and the environment (Azizi et al., 2022; Gao et al., 2023).

4. Influence of the WWTP on the amount of microplastics

4.1. Microplastics in wastewater line

WW acts as a carrier for MPs, bringing to the WWTPs a huge amount of material every day, depending on the quality of the influent WW (Section 2). Despite in the past WWTPs were known as ineffective on MPs, their treatments have a high impact on the quality of WW (Prata, 2018). Several authors investigated the effectiveness of MPs removal in conventional WWTPs. In Fig. 1, the estimation of MPs particle flows in a conventional WWTP is reported. In wastewater line, primary treatments, conventional active sludge system (CAS) with nutrients removal and additional polishing treatments have been considered. Sludge line was assumed composed by both dewatering technologies and stabilization processes. The mass flows have been calculated based on the effectiveness of the treatments found in literature (Alavian Petroody et al., 2021; Dronjak et al., 2023; Gies et al., 2018; Hidayaturrahman and Lee, 2019; Kwon et al., 2022; Magni et al., 2019; Murphy et al., 2016; Ren et al., 2020; Tadsuwan and Babel, 2021; Talvitie et al., 2017b).

Table 2
MPs polymers most widely detected in untreated urban WW. PES: polyester; PE: polyethylene; PET: polyethylene terephthalate; PA: polyamide; PP: polypropylene.

Polymers	Percentage composition (%)	References
PES	28–89	Sun et al. (2019)
PE	4–64	Sun et al. (2019), Liu et al. (2021)
PET	4–35	Sun et al. (2019)
PA	3–30	Sun et al. (2019)
PP	5–33	Sun et al. (2019), Liu et al. (2021)

Based on the analysis of the mass flows (Fig. 1), almost 1–10 % of MPs entering the WWTP are discharged in the effluents, while potentially >65 % of the MPs can be accumulated in the sewage sludge. The remaining MPs are removed from the water flux with the other residues (grease, oils, …). This is a significant problem for two main reasons. First, the remaining amount of MPs in the effluent of WWTPs is higher in term of concentration with respect to the receiving waters (Nava et al., 2023) and high in term of load given the large flowrate of outlets (Bretas Alvim et al., 2020). This represents a serious issue for the aquatic organisms (Ziajahromi et al., 2016). Second, the accumulation of MPs in sludge is a serious risk for the ecosystem in case of sludge reuse as soil improver. Despite the data are quite limited, it is already proved that the presence of MPs in soils is directly influenced by the amount of sludge spread as soil improver (van den Berg et al., 2020; J. Yang et al., 2021). A detailed discussion is presented in Section 7.

4.1.1. Primary treatments

Primary treatments can remove up to 70–80 % of MPs in the water flux (Prata, 2018; Sun et al., 2019). Treatments like screening, grit and grease removal and primary sedimentation can be effective on plastic particles in three different types of physical separation.

The first way is the removal of MPs by flotation (such as in technologies for grease removal) exploiting the light density of some particles which tend to remain in the superficial layer of the WW (Priya et al., 2023; Sun et al., 2019).

The removal by sedimentation is the second type of physical separation and generally occurs in the grit removal tank and in the primary settler (Liu et al., 2021). In this case, MPs can settle spontaneously (heavy-density MPs) or can be entrapped in the flocs and forced to settle (Z. Xu et al., 2021). Larger MPs (1–5 mm) can be potentially removed up to 96 % by decantation (Lofty et al., 2022).

Finally, MPs can be removed from WW in primary treatments also by separation by fine- and micro-screens (<6 mm and <0.5 mm, respectively) (Reddy and Nair, 2022). Although MPs are smaller than the opening size of raw (<20 mm) and fine screen, they can be entrapped in larger materials and separated from the water flux (Rasmussen et al., 2021).

4.1.2. Biological treatments

MPs cannot be easily degraded by biological treatments, especially considering the relatively low-retention time (hours) in a WWTP (Acarer, 2023). For this reason, conventional active sludge systems are not effective for MPs degradation (Liu et al., 2021). However, thanks to their hydrophobicity properties, MPs can be adsorbed on the surface of biomass flocs, being removed from water flux in the secondary settler (Collivignarelli et al., 2021c; Hatinoğlu and Sanin, 2021; Mahon et al., 2017). Almost 10–15 % of MPs entering the WWTP are removed in this way (Hu et al., 2019; Prata, 2018).

Primary and biological treatments still have an impact on the presence of fibres in WW (Fig. 2), probably due to the entrapment of these in flocculating particles and their subsequent removal in the settlers (Liu et al., 2021; Sun et al., 2019; Talvitie et al., 2017b). This would explain why in sewage sludge generally >50 % of MPs are constituted by fibres, as confirmed by many studies (Mahon et al., 2017; Rolsky et al., 2020). However, due to their characteristics, the effectiveness of conventional WWTP against fibres is not enough considering that fibres can represent almost the two thirds of the total MPs released by the WWTP (Conley et al., 2019; Dronjak et al., 2023). Fragments and films, accounting for 10–15 % of the total MPs of the effluent, are generally removed by a conventional wastewater line (Blair et al., 2019; Dronjak et al., 2023). Light weight fragments and films tend to float and are generally removed with oil in preliminary treatments (Reddy and Nair, 2022). In this case, the injection of air can increase the buoyancy of plastic particles adhering to them and stimulating their separation (Esfandiari and

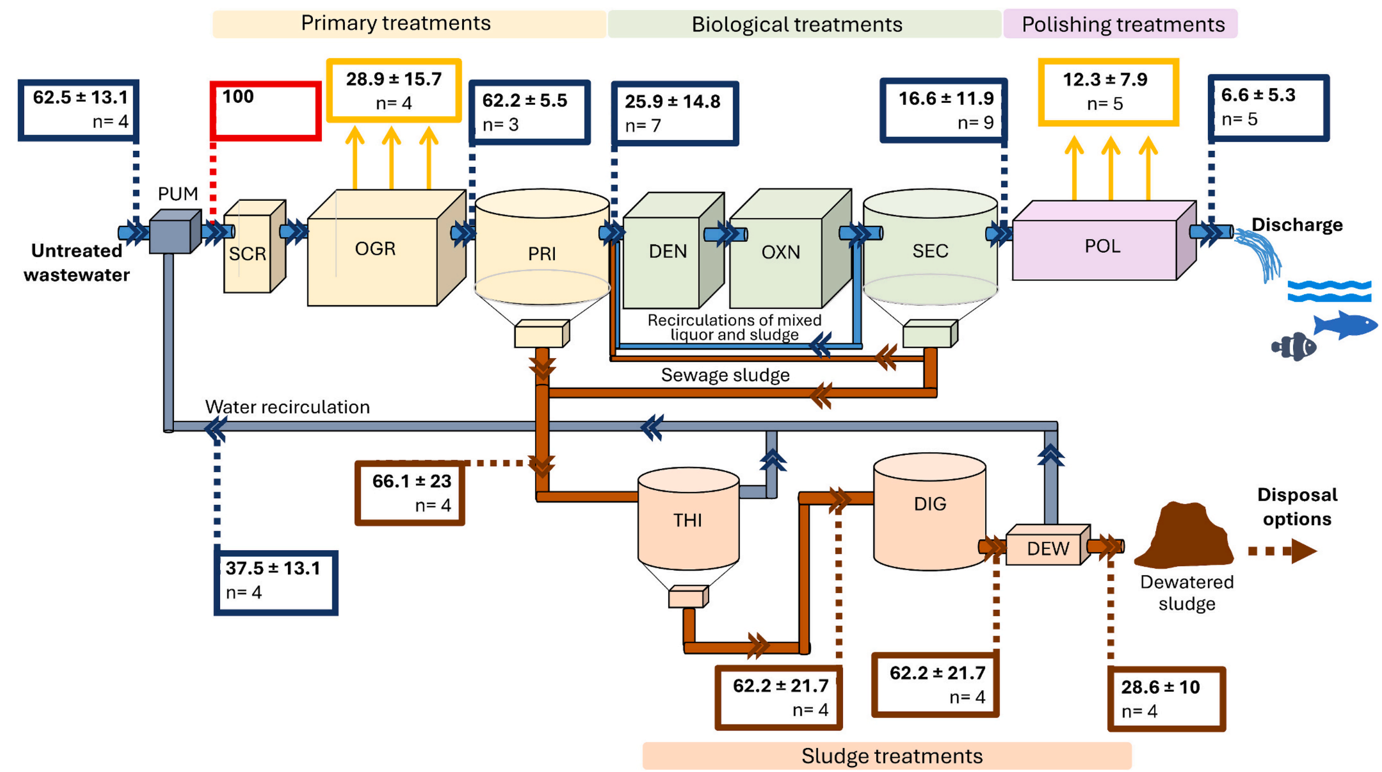

Fig. 1. Mass flows in a conventional WWTP. Data represented the number of MPs in water and sludge lines given 100 MPs entering the WWTP. Data about the effectiveness of processes in wastewater line were taken from Dronjak et al. (2023), Gies et al. (2018), Hidayaturrahman and Lee (2019), Kwon et al. (2022), Magni et al. (2019), Murphy et al. (2016), Ren et al. (2020), Tadsuwan and Babel (2021), Talvitie et al. (2017b). Data about the sludge line were based on the results of Alavian Petroody et al. (2021). PUM: pumping; SCR: screening; OGR: oil and great removal; PRI: primary sedimentation; DEN: denitrification; OXN: oxidation-nitrification; SEC: secondary sedimentation; POL: polishing; THI: thickening; DIG: anaerobic digestion; DEW: dewatering.

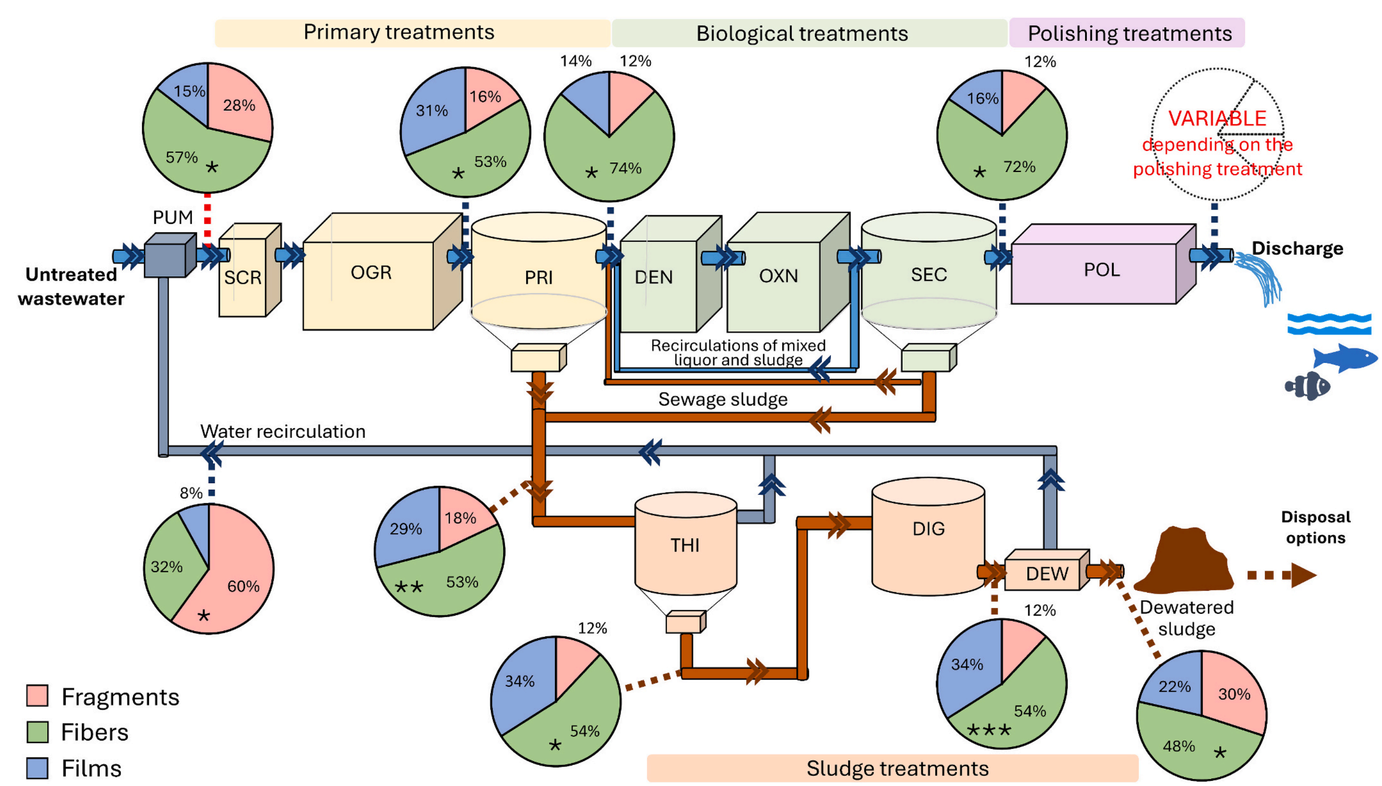

Fig. 2. Shape of MPs in a conventional WWTP. *: Dronjak et al. (2023); **: Tadsuwan and Babel (2021); *** data were assumed equal to undigested sludge, as reported in Alavian Petroody et al. (2021). PUM: pumping; SCR: screening; OGR: oil and great removal; PRI: primary sedimentation; DEN: denitrification; OXN: oxidation-nitrification; SEC: secondary sedimentation; POL: polishing; THI: thickening; DIG: anaerobic digestion; DEW: dewatering.

Mowla, 2021). The other fragments are well removed in settlers, especially in secondary sedimentation due to the agglomeration in biological sludge (Liu et al., 2021).

4.1.3. Polishing treatments

If present, polishing treatments can play a polishing effect on the quality of the WWTPs' effluents. The effectiveness against MPs' pollution strongly depends by the type of treatments. For instance, rapid sand filtration proved to physically remove 70–97 % of MPs (Bayo et al., 2020a; Hidayaturrahman and Lee, 2019; Ngo et al., 2019). Among filtration techniques, membrane disc filters allow to remove up to 80 % of treated MPs. In this case, particular attention must be paid to the choice of the diameter of the pores which if too large (mm) risk being ineffective for the MPs, while if too small (μm) they limit the release of MPs but risk having to require backwash frequencies very high (Hidayaturrahman and Lee, 2019). The effectiveness of disinfection is strongly related with the type of oxidant and the contact time. Chlorination proved to be useful for removing 20–68 % of the remaining MPs, due to the direct degradation of their polymeric structure or further sedimentation of the particulate in the baffled path where the disinfection takes place (Galafassi et al., 2022; Liu et al., 2019; Ngo et al., 2019). Ozone has a similar effect changing the physical properties of MPs and granting almost 90 % of their degradation (in case of 12.6 mg_{O3} L^{-1} in 1 min of contact time) (Hidayaturrahman and Lee, 2019). Also, UV can affect and break the structure of MPs, but generally with a lower effectiveness (up to 10 %) (Galafassi et al., 2022).

In terms of shape, the effect of polishing treatments is still under discussion. For instance, rapid sand filtration proved to better remove fibres and films (76 % and 73 %, with respect to fragments (56 %) (Hidayaturrahman and Lee, 2019). These results are in conflict with those found, for instance, by (Bayo et al., 2020a) who highlighted better particle removal (95.5 %) compared to fibres removal (53.8 %). Differences can be related to the operational condition of the process and the size of the MPs. If the dimensions of MPs are lower than the diameter of sands, the effectiveness of rapid sand filtration can be hindered (Hidayaturrahman and Lee, 2019). Membrane systems proved to be effective on all types of shapes (>80 %). However, higher effectiveness has been reported for particles due to (i) the possible release of fibres in the effluent caused by the damage of polymeric membranes (Talvitie et al., 2017a), and (ii) the ability of fibres to pass the membranes longitudinally (Hidayaturrahman and Lee, 2019). Considering that the ratio fibres/particles could vary in the different plants, this aspect could explain why the effectiveness of membranes could be variable and why some studies highlighted higher performances (also up to 99 %) (Poerio et al., 2019). Regarding disinfection, a clear pattern between the type of oxidant and the removal of a specific type of shape has not been found (Galafassi et al., 2022).

4.2. Microplastics in sludge line

The treatments in the sludge line can be considered only partially effective on the separation of MPs from sewage sludge. Limited studies on the effectiveness of sludge treatments on MPs are currently available in literature. However, thickening and dewatering seem to be able to remove up to 6 % and 54 % of MPs from sludge flux, respectively (Alavian Petroody et al., 2021).

In the case of thickening, the separation could be attributed to the flotation of the light-weight MPs that are removed with the supernatant (Alavian Petroody et al., 2021). The aerobic or anaerobic digestion can stimulate the solubilization of flocs and the consequent release of MPs in the liquid fraction, despite being ineffective in their biological degradation (Alavian Petroody et al., 2021; Cydzik-Kwiatkowska et al., 2022; Hatinoğlu and Sanin, 2021). However, this help to promote the removal of MPs from sewage sludge and the accumulation in the supernatant during the mechanical dewatering (Alavian Petroody et al., 2021).

In terms of shape, the treatments in the sludge line does not impact substantially the composition of MPs, mainly fibres and fragments (Collivignarelli et al., 2021c; Mahon et al., 2017; Rolsky et al., 2020). For this reason, the detection of fibres as an indicator for studying the land application of sewage sludge has been proposed (Sun et al., 2019). The difference in prevalence of fibres or fragments can be mainly related to (i) the initial characteristics of the WW, and (ii) the types of treatments in the wastewater line that generate sludge (Collivignarelli et al., 2021c).

Based on the analysis of the mass flows (Fig. 1), 20–40 % of the initial MPs remain in the sludge after treatments while the 25–50 % of MPs are recirculated in the wastewater line after the extraction from sludge. When the sludge line is simplified, it can result in reduced efficiency in capturing MPs and an increased accumulation of MPs in the sludge compared to a scenario with a complete sludge line.

However, even when considering the better scenario, two aspects are matter of concern. The remaining MPs in sewage sludge are concentrated in a low amount of material if compared to the effluent stream of wastewater line. This poses a significant concern, particularly when considering the potential reuse of this sludge as a soil improver, as employing a highly concentrated residue with an abundance of MPs could potentially endanger the ecosystem. Moreover, the MPs removed in the sludge line are not effectively degraded but only moved from a matrix, the sludge, to another one, the water. For this reason, attention should be paid to the recirculation of supernatant rich in MPs that can count for the 25–50 % of the total load of MPs entering the WWTP.

5. Influence of the microplastics on the operation of the WWTP

5.1. Wastewater line

The presence of MPs can potentially affect both water and sludge lines (Table 3). In preliminary treatments, for instance, MPs can determine blockage of fine grilles (3–10 mm) due to the high amount of material in the untreated WW (Zhang and Chen, 2020). MPs can act as a carrier of other pollutants such as pesticides, pharmaceuticals, heavy metals, and polycyclic aromatic hydrocarbons (Godoy et al., 2019; Martinho et al., 2022). Therefore, the presence of high quantity of MPs and their removal by sedimentation in primary settler can affect the quality of the primary sludge carrying also other unwanted substances (Wu et al., 2021).

MPs proved also to affect biological processes, inhibiting autotrophic bacteria responsible of nitrification and, at the same time, promoting the denitrification rate (Li et al., 2020), despite this last aspect remains unclear with contrasting results on the effect of MPs on denitrifying biota (Wu et al., 2021; Zhang and Chen, 2020). Some studies highlighted that phosphorus removal can be negatively affected by MPs, especially nanoplastics, due to the inhibition of the responsible microorganisms (Zhang and Chen, 2020). What is certain is the ability of MPs to change the structure of the microbial community in the biological systems, altering some enzymes and metabolic intermediates (Wu et al., 2021). Nanoplastics are also proven to be the cause of acute inhibition of activated sludge biota, due to their surface charge, with a consequent lower efficiency in terms of COD removal (Zhang and Chen, 2020). As in primary settler, the presence of pollutants attached on MPs affects the quality of secondary sludge extracted from the clarifier, bringing also to potential inhibitory effects during its stabilization (X. Zhang et al., 2020). The presence of MPs in the WW can change EPS structure released by aerobic biomass reducing the settling properties of both granular biomass and conventional activated sludge (Jachimowicz et al., 2022; J. Xu et al., 2021). Some authors also relate the MPs with a higher consumption of energy to generate air bubbles given the presence of a greater concentration of suspended solids (Wu et al., 2021).

MPs can also affect the operation of polishing treatments. They can reduce the effect of disinfection in two ways: (i) acting as scavenger and consuming part of chlorine or ozone, and (ii) being an "umbrella" for bacteria and other microorganism, thus hindering the effectiveness of

Table 3
Effects of MPs on different treatment stages in conventional WWTPs.

Treatment stages	Adverse effects	References
Wastewater line		
Primary treatments	• Blockage of fine grilles	Zhang and Chen (2020)
	• Low quality of the sludge for the presence of MPs and other unwanted pollutants	Wu et al. (2021)
Biological treatments	• Inhibition of nitrification, organic substance, and phosphorous removal	Zhang and Chen (2020)
	• Potential inhibition of denitrification	Wu et al. (2021), Zhang and Chen (2020)
	• Change of the structure of microbial community	Wu et al. (2021)
	• Higher energy consumption for aeration	Wu et al. (2021)
	• Low quality of the sludge for the presence of MPs and other unwanted pollutants	X. Zhang et al. (2020)
	• Low settleability of the sludge	Jachimowicz et al. (2022), J. Xu et al. (2021)
Polishing treatments	• Increase fouling a damage of membrane systems	Wu et al. (2021), Zhang and Chen (2020)
	• Increase energy consumption in membrane systems	Acarer (2023), Zhang and Chen (2020)
	• Hinder activity of chemical reagents and UV	Shen et al. (2021), Wu et al. (2021), Zhang and Chen (2020)
	• In case of the use of oxidants, possible formation of disinfection by-products	Ghanadi et al. (2023)
Sludge line		
Digestion	• Inhibition of the biological activity of biota	Mohammad Mirsoleimani Azizi et al. (2021), Wei et al. (2021)
	• Inhibition of methane and hydrogen production (anaerobic conditions)	Wei et al. (2019), J. Zhang et al. (2020)
Dewatering	• Reduction of the dewaterability of the sludge	J. Xu et al. (2021)

chemical reagents and UV (Shen et al., 2021; Wu et al., 2021; Zhang and Chen, 2020). The production of disinfection by-products (DBPs) due to the use of reactive reagents in WW rich in MPs has been also highlighted (Ghanadi et al., 2023). MPs can also wear membranes in filtration systems, like ultrafiltration and microfiltration, and enhance the fouling (Wu et al., 2021; Zhang and Chen, 2020). The cake layer can increase the effectiveness of the process, acting as a second membrane, but at the same time it can increase the transmembrane pressure and therefore the energy consumption (Acarer, 2023; Zhang and Chen, 2020).

5.2. Sludge line

In sludge line, MPs can affect biological aerobic or anaerobic degradation of sludge. In anaerobic digestion, MPs can reduce the production of methane (J. Zhang et al., 2020), and production of hydrogen during the alkaline anaerobic fermentation of secondary sludge due to the inhibition of hydrolysis, acidogenesis and acetogenesis (Wei et al., 2019). Several inhibition mechanisms of MPs against anaerobic processes have been highlighted such as (i) the release of toxic chemicals, (ii) the alteration of enzymes' activities and protein structures, (iii) the production of reactive oxidative species, and (iv) the damage of microbial cells (Mohammad Mirsoleimani Azizi et al., 2021). Despite the number of studies is still quite limited, also aerobic digestion of activated sludge seems to be sensible to MPs, some polymers such as PET. In this case, the presence of PET can inhibit aerobic digestion by up to 11 % due to induced oxidative stress (Wei et al., 2021).

Studies have shown that the chronic exposure to MPs reduces the dewaterability of sludge. J. Xu et al. (2021) have shown that even more than the type of polymer, it is the size of the particle that influence the dewaterability of the sludge. The larger MPs (mm) can reduce dewaterability by up to 47 % due to the physical crushing of MPs on sludge flocs. The smaller ones (nm) inhibit the activity of the biomass causing a state of stress which leads to alter the composition and the distribution of the extracellular polymeric substances (EPS) which reduce dehydration performance (J. Xu et al., 2021).

6. How to improve the performance of WWTPs against microplastics

Several works focused on the approaches to enhance the effectiveness of WWTPs against the presence of MPs in WW (Freeman et al., 2020; Sun et al., 2019). Differences in outcomes can be highlighted depending on the choice of act in primary, biological or polishing treatments' stage (Table 4).

6.1. Primary treatments

One of the most economical approaches is to optimize the operational parameters of grit and grease removal units and the primary settlers (e.g., hydraulic retention time) or made simple structural upgrades to enhance the removal of MPs (Sun et al., 2019). These treatments already proved to be able to remove a significant portion of MPs

Table 4
Effects of different approaches to improve the effectiveness of WWTPs against the presence of MPs in WW. ✓: advantage; X: drawback.

Approaches	Advantages	Disadvantages
Primary treatments	✓ Reduce the MPs released in the effluent	**X** Greater amount of residues produced (e.g., sand, oil, reside from screening, …) that should be disposed of.
	✓ Enhance the quality of sludge (if flux of primary sludge is separated from the secondary one)	**X** Production of chemical sludge (if coagulants are added)
	✓ No need of new reactors	**X** Use of chemical reagents (if coagulants are added)
	✓ Reduce problems caused by MPs in sludge line	**X** Less organic substance for the subsequent denitrification
	✓ Reduce the request of oxygen in biological processes	
Biological treatments	✓ Reduce the MPs released in the effluent	**X** Addition of chemical substances (if flocculants are added)
	✓ No need of new reactors	**X** Additional costs in case of the addition of reagents
	✓ Enhance the effectiveness of disinfection in polishing treatments	**X** Low quality of biological sewage sludge
	✓ If in polishing treatments membrane filtration is present, fouling problems is reduced	
Polishing treatments	✓ Reduce the MPs released in the effluent	**X** No changes in the quality of biological sewage sludge and no "protection" to the biological treatments
	✓ In some cases are compact systems (e.g., membranes)	**X** Need of new reactors
		X Production of residue that should be disposed of (e.g., in adsorption, electrocoagulation, …)
		X Need of chemical reagents (e.g., some AOPs)
		X Examples of full-scale applications of some technologies (e.g., bioremediation) are still limited

(Kurt et al., 2022), and their efficiency can be further enhanced with additional measures. For instance, the use of aerated grit chamber, instead of rotary grit tank, helps to prevent the release of MPs due to the fragmentation of bigger particles. In this way, an increase in MPs of up to 50 % can be avoided (Khan et al., 2022). In this case, the presence of a greater number of MPs in residues (sand and oil) should be considered.

Also, the addition of coagulant and flocculants before the primary settler can promote the formation and the settling of flocs, with the consequent increase of MPs separation (Tang and Hadibarata, 2021; Zhang and Chen, 2020). In this scenario, the formation of a high amount of chemical sludge that should be properly disposed of should be considered. In case of separation of the flux of primary sludge from the biological one, the quality of the sewage sludge exiting the plant could be higher (Mininni et al., 2004), especially in terms of a lower concentration of MPs.

The use of additional fine screening devices (< 5-6 mm) before grease removal section can enhance the effectiveness of primary treatments against MPs contamination blocking larger particles (Iyare et al., 2020; Liu et al., 2019). However, the production of residues during the operational phases of the devices, that should be disposed of, must be considered.

Intervene in primary treatments is expected to also reduce the inhibitory effects of MPs on biota of subsequent treatments. However, being these approaches not specific for MPs, the enhancement of primary treatments by chemical additives can also reduce the content of organic substance in WW (a critical aspect for denitrification (Tas et al., 2009)) and limit the use of oxygen in conventional activated sludge systems (Bachis et al., 2015).

6.2. Biological treatments

MPs removal in biological treatments can be enhanced by the addition of flocculants in conventional active sludge system. Flocculants increase the dimension of biological flocs stimulating the aggregation of suspended solids including MPs (Murphy et al., 2016; Wu et al., 2021). At the same time, the addition of an external reagent means an extra-cost in the management of the WWTP. For the separation of solids and MPs from the water flux, the use of dissolved air flotation coupled with skimming instead of conventional clarifiers can help to reach the 95 % of MPs' removal (Sol et al., 2020).

Membrane biological reactors (MBRs) are a valid alternative to conventional active sludge (CAS) system in terms of MPs removal. Studies demonstrated that, thanks to the integration of micro- or ultrafiltration membranes to biological systems, MPs removal can be improved up to 99 % (Sol et al., 2020; Tang and Hadibarata, 2021). Despite some authors highlighted the high maintenance costs, others pointed out that membrane bioreactor is a more cost-effective option with respect to CAS systems (Bui et al., 2020; Sol et al., 2020; Vuori and Ollikainen, 2022). Sequencing batch reactors (SBR) and anaerobic anoxic-oxic process (A^2O) gave better performance with respect to cyclic activated sludge technology (47.5 % and 37.3 % vs. 13.8 %, respectively). In this case, the higher effectiveness should be attributed to the different type of sedimentation (gravitational in case of SBR and A^2O while in cyclic activated sludge technology the intermittent aeration determines a limited static settlement process) (Zhang et al., 2023).

However, all these approaches limit the discharge of MPs into the aquatic environment, but none of these determine a reduction of the pollution of sewage sludge exiting the WWTP.

6.3. Polishing treatments

Polishing treatments allow removing from the water flux organic and inorganic substances not affected by the previous treatments. Beyond technologies that are already applied especially in large-size WWTPs such as disinfection, filtration on sand or membrane disks, other possible approaches are under investigation. These technologies, as the others, are not targeted for MPs removal but can have an impact also on this pollutant (Cheng et al., 2021; Dos Santos et al., 2023; Ge et al., 2022; Shen et al., 2022).

For instance, advanced oxidation processes (AOPs) are currently under investigation for their use in WWTPs mainly against emerging contaminants such as pharmaceutical and perfluoroalkyl compounds (Sbardella et al., 2020; Taoufik et al., 2021; Uwayezu et al., 2023). The production of sulphate or hydroxyl radicals stimulates the unselective oxidation of a wide range of chemical compounds (Collivignarelli et al., 2023, 2021b, 2021a). They have also an impact on the presence of MPs in the effluents, up to 90 % depending by the process, the operational conditions, and the types of MPs (Dos Santos et al., 2023).

Heterogeneous photocatalysis with titanium dioxide proved to be able to degrade MPs in a very promising way (Ge et al., 2022). However, attention should be paid to the shape of MPs. The presence of a high concentration of films can hinder the activation of photocatalyst by the UV radiation limiting the performance of the system (Llorente-García et al., 2020). No requirement of external chemical reagents is one of the main advantages of this approach. On the contrary lack of selectivity, fouling of the catalyst and high energy consumption (mainly due to UV lamps) are main drawbacks of the process (Sharma et al., 2021).

Electrocoagulation represents another alternative in which the production of metal hydroxide coagulants leads to destabilization of the surface charges of the pollutants and disintegration of the colloids (Sharma et al., 2021). Aluminium anode gave better performance than iron anode (almost 99 % in the optimal conditions). Higher effectiveness has been found for fibres with respect to particles (Shen et al., 2022). The need of replacing sacrificial anodes, the production of chemical sludge and the high operational costs are the main disadvantages of the technology (Sharma et al., 2021; Shen et al., 2022).

UV/H_2O_2 degrades polyester microfibres up to 52.7 % after 48 h of reaction time forming shallow holes, and cracks across fibres' surface and changing the relative abundance of oxygen containing functional groups (Easton et al., 2023). It requires the addition of chemicals but, in terms of carbon footprint, this AOP remain more sustainable with respect to ozonation with almost 85 % less of CO_2eq emitted per m^3 of WW treated (Dos Santos et al., 2023).

Adsorption as polishing treatment has been investigated for MPs removal and has been found effective especially for MPs < 5 μm (up to 98.5 %) and in general non-polar MPs. Pellets and fragments are well removed (up to 86 % and 69 %, respectively) (Cheng et al., 2021). However, two main drawbacks remain: (i) the high cost of virgin material (that could be overcome by the use of alternative adsorbents like biochar and activated agricultural residues) (Abuwatfa et al., 2021; Siipola et al., 2020; Wang et al., 2020), and (ii) the production of a high amount of spent material due to the high flowrate that should be treated (Zhao et al., 2022).

About membranes, a recent approach is to adopt dynamic membranes instead of common micro- or ultrafiltration. In this case, an adequate support (with enough permeability and robustness) is used to generate a cake deposit acting as second barrier and useful to increase the retainment of MPs (Krishnan et al., 2023). Dynamic membranes allow to separate also low-density/poorly settling particles and generally require less energy operating under gravity mode, use of less expensive materials, and more compact sizes of the system with respect to conventional filtration (Poerio et al., 2019).

Among other approaches, bioremediation is seen as a promising technology for non-chemical MPs degradation. Bacteria, fungi, algae, and eukaryotic species were tested for MPs accumulation and eventually degradation of several types of MPs (Krishnan et al., 2023; Masiá et al., 2020). For instance, studies showed the possibility to degrade polyethylene and polyurethane with *Pseudomonas* species (Krishnan et al., 2023). The main drawbacks of this bio-approach include (i) the difficulties of containing these organisms in the WWTP preventing the unwanted release, and (ii) the relatively lower number of studies and applications (mainly at laboratory scale) with respect to other techniques (Masiá et al., 2020).

7. Wastewater treatment plants and the release of MPs

7.1. Why wastewater treatment plants act as "hotspot" for MPs

Despite not being designed for MPs removal, treatments in the wastewater line of conventional WWTPs have a huge impact on the concentration of MPs (up to 99 % in some references). However, the remaining MPs in water are still a problem considering (i) the high flow rate discharged by WWTPs, and (ii) the remaining concentration of MPs can be several orders of magnitude higher than that of receiving waters. A recent survey on 38 lakes in different parts of the world highlighted a concentration of 0.1–10 MPs m^3 vs. 1–100 MPs L^{-1} in the outlets (Nava et al., 2023). In addition, to date, WWTPs act as hotspots of MPs contamination considering that potentially >65 % of MPs influent to the WWTP are accumulated in the sewage sludge. When properly treated in a structured sludge line, as in the scenario assumed in this study, 25–50 % of MPs are recirculated from sludge line to wastewater line as supernatant and almost 20–40 % (mainly fragments and fibres) remain in the dewatered sludge.

This represent a matter of concern considering that the most frequent option of sewage sludge reuse from urban WWTPs is as soil improver in agriculture for nutrients recovery, directly or after composting. In Europe, on average >50 % of the entire amount of sewage sludge from urban WWTPs is reused in agriculture. In countries like France, Spain, and United Kingdom the percentage is higher than 75 % (Eurostat, 2023). In other countries like U.S.A. and Australia are respective 55 % and 73 % (Marchuk et al., 2023). Therefore, also in the case of proper treatment in the sludge line, the remaining MPs can pose a severe risk to the ecosystem. In fact, many studies confirmed a pathway of pollution and highlighted the accumulation of MPs in soils after the spreading of contaminated sewage sludge (Collivignarelli et al., 2021c; Corradini et al., 2019; L. Zhang et al., 2020) (Fig. 3).

Moreover, the use of water from polluted sources for agricultural purposes can enhance the content of MPs in soils. On the contrary, preliminary studies suggest that the water runoff is able to mobilize only <1 % of MPs (Pérez-Reverón et al., 2022; Schell et al., 2022). While the ingestion of polluted crops (fruit, vegetables, cereals), meat, fish, and drinking water is the main route of human exposure to MPs (Domenech and Marcos, 2021). Specifically, in case of agricultural products, studies proved that nanoplastics can directly enter into the plant tissue due to their small size (Azeem et al., 2021).

Also, the other residues produced by the WWTPs (e.g., sands and oil) can be presumably sources for the release of MPs accumulated during WW treatment. For instance, sands recovered in the plants can be reused in construction sector after screening and cleaning procedures with water. Otherwise, they are disposed of in landfills (Borges et al., 2015). In any case, the presence of MPs represents a potential source of spread in the environment that, to date, has not been properly investigated.

Moreover, during WW treatments and the disposal of residues, MPs can be released in the atmosphere. The unwanted fragmentation of MPs in smaller particles and the injection of air, in aerated processes, could stimulate this phenomenon (Gangula et al., 2023; Zhang et al., 2022). The consequent inhalation of the released aerosol is another source of human exposure to MPs (Chen et al., 2020; Domenech and Marcos, 2021; Koutnik et al., 2021).

In this context, the WWTP could act as a key barrier to protect the environment from the release of MPs and therefore reduce human exposure to this emerging contaminant.

7.2. A paradigm shifts of WWTPs from "hotspot" to barrier for environmental protection

Many published works deal with this topic presenting a wide range of techniques and processes that can help reduce MPs pollution in WW (Poerio et al., 2019; Priyanka and Saravanakumar, 2022; Rajala et al., 2020; Sampaio et al., 2023). However, the main question that could be raised is: "what is/are the optimal point(s) of the WWTP in which the technologies for improving MPs removal should be located to limit the

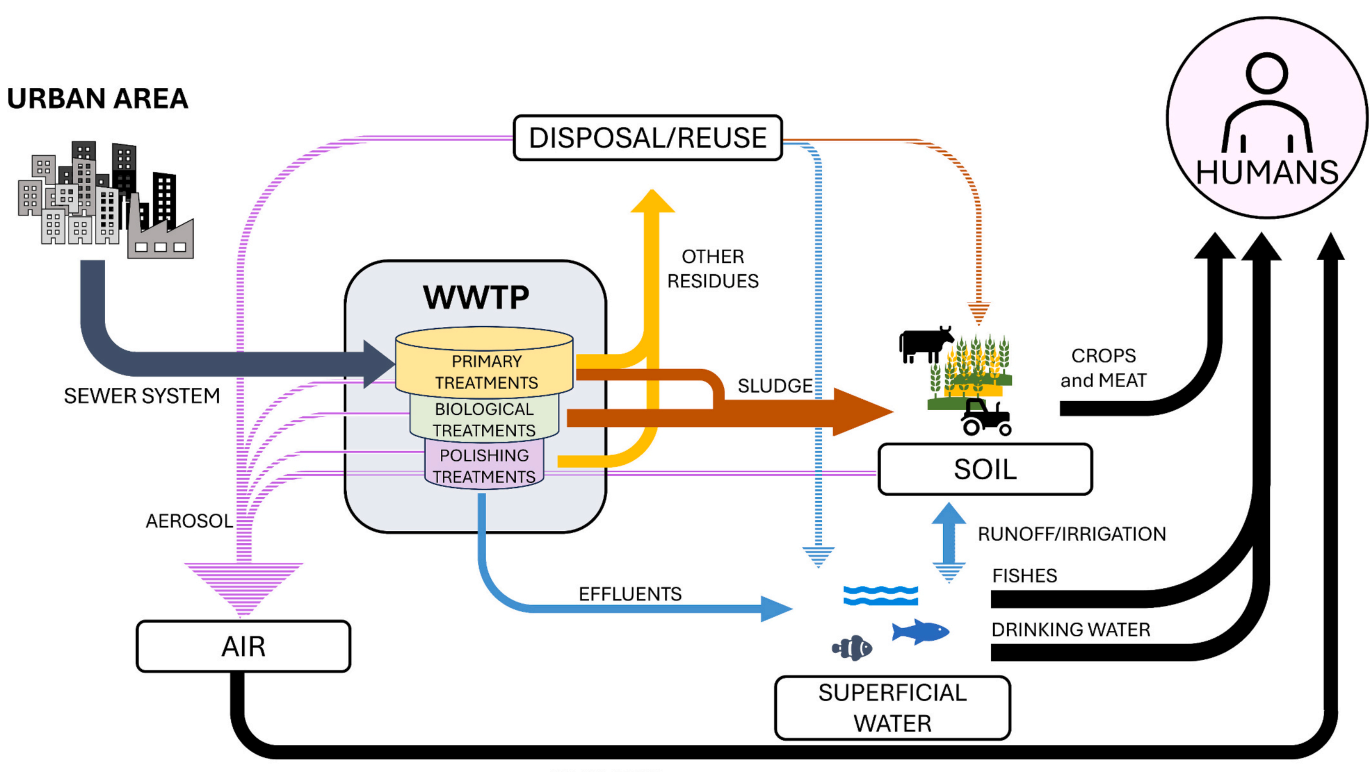

Fig. 3. Ascertained and potential pathways (solid and dashed lines, respectively) of pollution by MPs from urban areas and key role of WWTPs.

spread of MPs in the environment?".

To answer this question, it should be taken into account that the spread of polluted sludge in soils for agricultural purposes is a major pathway of environmental contamination. Therefore, solutions that only enhanced the removal or degradation of MPs in WW tackle the problem only partially. A combined approach for limiting the release of MPs in the outlets and enhance the quality of sludge is needed:

1. Optimize the operational parameters of primary treatments and separating the flux of primary sludge from the biological ones can enhance the removal of MPs from WW without affecting the quality of the sewage sludge. In this way, the impact of MPs on the activity and characteristics of WWTP's biota (e.g., inhibition, change in the structure of the community) can be reduced.
2. Polishing treatments can be helpful in limiting the residual MPs contamination of effluents, but considering their presence does not affect the quality of biological sludge, they cannot be intended as resolutive if not coupled with interventions in primary treatments (Fig. 4). It should be also taken into account that polishing treatments are not currently present in all WWTPs. For instance, in North and Central Europe the majority of WWTPs do not have a final disinfection phase while in the South-East almost 25 % of WW are discharged without proper treatment (van Dijk et al., 2023).
3. At the same time, a structured sludge line can help to limit the content of MPs, with dewatering technologies evaluated as more effective than biological ones. Coupling different approaches and interventions is the only way to reduce the release of MPs and intend the WWTPs as an effective barrier to environmental protection, especially in case of sludge reuse in agriculture.
4. Finally, if dewatering technologies are applied in sludge line, additional treatments for enhance the quality of supernatants and reduce MPs recirculation in wastewater line could represent an option. Up to 50 % of MPs entering the wastewater line are carry out in this water. Supernatants are generally characterized by a huge concentration of suspended solids (> 1000 mg L^{-1}) and dissolved contaminants like organic substance (COD>300 mg L^{-1}) and nutrients (N > 100 mg L^{-1}; P also up to 35 mg L^{-1}) (Hu et al., 2017) while water extracted from a centrifugation units can have >400 MPs L^{-1} according to (Dronjak et al., 2023). However, to date no examples about this type of approach have been developed and therefore no results are available.

Although further strategies may be implemented to strengthen environmental protection, it must be kept in mind that:

(i) to date no technology allows the complete removal or degradation of MPs from water and sludge. To date, studies that focus on the complete degradation of polymers through polishing treatments (e.g., AOPs) are still few, just as the diffusion of these treatments in WWTPs is low;
(ii) the remaining MP sin the outlets can pose a severe impact to ecosystems given the high flow rates and the concentration of MPs several order of magnitude higher than the receiving waters;
(iii) enhancing the preliminary removal of MPs negatively affects the quality of other WWTP residues (e.g. sand and oil) posing a potential source of environmental risk when they need to be disposed. In this sense, to date, there is a strong literature gap about the quantity and quality of MPs in sands and oils from WWTPs.

7.3. The need of a proper legislation

In terms of legislation, the policy of the European Union is oriented to prevent the release of MPs, especially from industrial sectors (e.g., textile, tyres, paints) and at the same time focused on the reduction of the environmental pollution (EU, 2023). However, to date, a proper

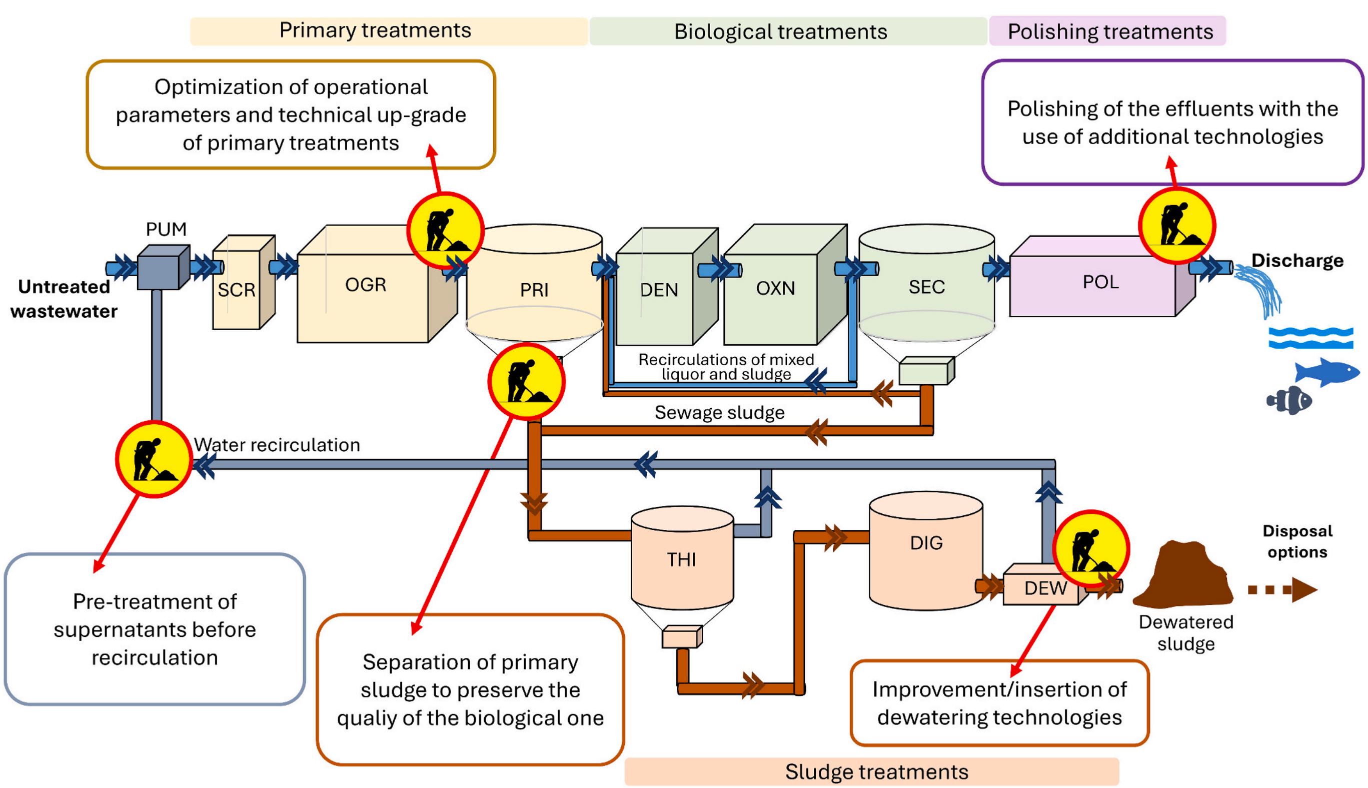

Fig. 4. Suggested approaches and actions to limit the release of MPs into the environment in urban WWTPs. PUM: pumping; SCR: screening; OGR: oil and great removal; PRI: primary sedimentation; DEN: denitrification; OXN: oxidation-nitrification; SEC: secondary sedimentation; POL: polishing; THI: thickening; DIG: anaerobic digestion; DEW: dewatering.

legislation on the release of MPs into environments through the WWTPs' outlets and sewage sludge is not available. The revision of the Urban Wastewater Treatment will include the monitoring of MPs in WWTPs' effluents and sludge in order to collect enough data for a subsequent specific legislation (EU, 2023, 2022).

Even other countries do not currently have specific legislation regarding the limit concentration of MPs that can be present in wastewater from WWTPs and in outgoing sewage sludge (Osuna-Laveaga et al., 2023). Therefore, a legislation that also considers this emerging contaminant must be developed as soon as possible. Please take into account that:

(i) in the case of reuse of WWTPs' effluents, agricultural reuse is one of the primary destinations (e.g., 44 % Europe; 37 % USA; 60 % South Africa; 87 % India) (Kesari et al., 2021)
(ii) to date, the main destination of sewage sludge from urban WWTPs is agriculture (Eurostat, 2023; Marchuk et al., 2023; Collivignarelli et al., 2019). In this sense, it would be useful to increase knowledge especially regarding possible additional/alternative treatments for improving the quality of the sludge in view of its subsequent valorisation. In this sense, for instance, thermal treatments (e.g., pyrolysis) seem to provide promising results with effectiveness on MPs degradation higher than 90 % (Hooge et al., 2023).

8. Conclusions

MPs in untreated urban WW can vary according to the geographical region but are generally mainly composed by fibres and/or fragments. Treatments in conventional WWTPs proved to be effective (up to 99 % in some references) in removing MPs from WW, especially due to physical separation in primary treatments and secondary settlers. However, MPs are not effectively degraded but only moved in treatments' residues, mainly in sewage sludge (potentially >65 %) posing a serious risk in case of sludge reuse as soil improver.

Biological stabilization is not effective for the degradation of MPs and dewatering seems the only site-approach that can be useful to reduce MPs content in sewage sludge. Nevertheless, in this case MPs are recirculated in wastewater line without an effective degradation. Therefore, WWTPs are currently acting as "hotspot" for the spread of MPs in the environment and, at the same time, all stages of treatment in the plant are affected by the presence of MPs.

Despite several technologies to tackle MPs contamination enhancing the effectiveness of the WWTPs have been presented in literature, a combined approach in wastewater line (primary and polishing treatments) and sludge line (separate primary and secondary sludge, improve or insertion of dewatering technologies, treatment of extracted water) seems the only way to reduce the content of MPs in WW without affect the quality of sludge. The results of this work are therefore useful for the managers of water utilities to define the best approaches and actions to limit the release of MPs into the environment.

However, several research gaps should be solved:

(i) literature lacks information about the fate and release of MPs in other WWTP's residues (e.g., sands and oil). Further studies focused on the concentration of MPs in these residues, the amount of MPs that can be possibly released depending on the form of reuse/disposal and the pathways of spread in the environment are simulated;
(ii) there are few data about the impact of treatments in sludge line on MPs concentration and type. More detailed studies on the effectiveness of this treatments on MPs content, the influence of MPs on biological processes are required. The authors also suggest evaluating the techno-economic feasibility of treating for MPs removal the extracted water (from thickening and dewatering) before its recirculation in wastewater line;
(iii) literature lacks data about the effectiveness of additional treatments (e.g., thermal treatments) on the degradation of MPs and the possible pathways of release in the environment (e.g., in air). It is a very serious point considering that these treatments could be an alternative to the reuse in agriculture for high contaminated sludge, in terms of MPs.

Despite some efforts have been made proposing the monitoring of MPs in WWTPs in the draft of the new Urban Wastewater Treatment Directive, to date the legislation lack to impose limit on the content of MPs in WWTPs' discharge and sewage sludge, especially for possible reuse in agriculture. In this sense, the authors think that imposing a minimum efficiency limit on the MPs content during WW treatment could be useful to stimulate actions for enhancing the performance of WWTPs. Moreover, new legislation about sludge reuse in agriculture should take into account also this emerging contaminant in order to stimulate alternative solution of disposal/reuse for highly contaminated sludge.

The results of this study showed that WWTPs are currently not yet able to provide complete protection from the release of MPs into the environment. For this reason, in parallel with the research activities on improving the efficiency of WWTPs, it is suggested to develop approaches that allow limiting the release of MPs at the source.

Ethical approval

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Consent to participate

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Consent to publish

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CRediT authorship contribution statement

Marco Carnevale Miino: Writing – original draft, Visualization, Methodology, Conceptualization. **Silvia Galafassi:** Writing – review & editing, Visualization, Funding acquisition. **Rosa Zullo:** Writing – review & editing, Visualization, Funding acquisition. **Vincenzo Torretta:** Writing – review & editing, Validation, Project administration, Funding acquisition. **Elena Cristina Rada:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data generated or analysed during this study are included in this published article.

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