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Research article

Microplastic accumulation hotspots in wastewater treatment plants as leverage points for PET valorization and overall emission mitigation

Beatrice Luzi [a], Marco Carnevale Miino [b,*], Elena Cristina Rada [b], Rosa Zullo [a], Vincenzo Torretta [b], Silvia Galafassi [c,a]

[a] Water Research Institute, National Research Council, Largo Tonolli 50, Verbania, 28920, Italy
[b] Department of Theoretical and Applied Sciences, University of Insubria, Via O. Rossi 9 , Varese, 21100, Italy
[c] NBFC, National Biodiversity Future Center, Palermo, 90133, Italy

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ABSTRACT

Wastewater treatment plants (WWTPs) are increasingly recognised as critical control points for mitigating microplastic (MP) emissions, yet their potential role in polymer recovery remains largely unexplored. Among MPs, micro-polyethylene terephthalate (micro-PET), mainly derived from synthetic textile fibers, represents a valuable secondary raw material. This study investigated the fate, removal and recovery potential of MPs and micro-PET along anaerobic digestion, mechanical dewatering and tertiary pile cloth filtration of a full-scale WWTP. Pile cloth filtration proved effective as a refinement step in the water line, achieving an overall MP removal efficiency of 67 ± 12.6%. In the sludge line, anaerobic digestion did not significantly affect MP abundance, whereas mechanical dewatering removed 49.7 ± 32.3 % of MPs via the process water, acting as a barrier to MP release. The water streams identified as potential starting points for the proposed recovery process showed elevated MP concentrations, ranging from 6.86 ± 4.66 MP L^{-1} in filter wash water to 56.5 ± 12.8 MP L^{-1} in dewatering water. Micro-PET was detected in filter wash water, supporting the feasibility of the proposed recovery concept; however, its absence in dewatering water suggests that applicability may depend on the composition of the incoming wastewater and on process-specific factors. The optimized separation protocol showed robust and reproducible performance, enabling micro-PET enrichment from complex wastewater- and sludge-derived matrices despite high biomass loads and biofilm-coated particles. Overall, the results suggest that integrating microplastic mitigation with selective polymer recovery could represent a first step towards more resource-oriented wastewater management.

1. Introduction

Microplastics (MPs) pollution in the environment gained attention due to ecosystem disruption and potential human health implications (Acarer Arat, 2024; Tang et al., 2024). MPs also represent a risk because of the potential release of toxic compounds during their uncontrolled degradation and their role as carriers for pathogens and microbial contaminants (Sathicq et al., 2021). Wastewater (WW) systems represent a major pathway for the spread of MPs given the high number of particles generated in the urban environment (Carnevale Miino et al., 2024). In particular, domestic and industrial activities can contribute substantial loads of MPs to sewerage networks; for example, recent studies highlighted that more than 90 × 10^4 MPs can be produced and released in a single domestic wash cycle (Vragkalis et al., 2025).

In this sense, wastewater treatment plants (WWTPs) play an important role but still fail to fully address the issue, as MPs are released both in the treated water effluent and in the sludge, where they tend to accumulate (Collivignarelli et al., 2021). In the effluent, MPs generally represent 1-10% of the initial concentration in the untreated WW, but their abundance remains several orders of magnitude higher than the receiving water ecosystems (Nava et al., 2023). In the sludge, concentrations can reach 10^3 - 10^4 MPs kg_{DM}^{-1}, depending on the type of treatment to which it is subject, which may pose concerns when sludge is used as soil conditioner for agricultural purposes (Li et al., 2024). It should also be considered that the global amount of MPs already present in soils is 1.5 - 6.6 million tons (Barceló, 2024).

* Corresponding author. marco.carnevalemiino@uninsubria.it (M. Carnevale Miino)
E-mail addresses: beatriceluzi@cnr.it (B. Luzi), marco.carnevalemiino@uninsubria.it (M. Carnevale Miino), elena.rada@uninsubria.it (E.C. Rada), rosa.zullo@irsa.cnr.it (R. Zullo), vincenzo.torretta@uninsubria.it (V. Torretta), silvia.galafassi@cnr.it (S. Galafassi).

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Among the technical solutions adopted within the WWTPs configurations, mechanical filtration is a technology of proven effectiveness for removing MPs from aqueous streams (Hidayaturrahman and Lee, 2019). For instance, Yang et al. (2023) studied the effectiveness of ultrafiltration membranes in four different WWTPs and found 87.8–99.8% retention of MPs. Bayo et al. (2020) proved that rapid sand filtration used as polishing treatment in a WWTP allowed the removal of 75.5% of MPs. Pile cloth filtration could represent a promising alternative thanks to its high compactness and the good cost-effectiveness of the treatment. Despite the good results obtained by Sembiring et al. (2021) in removing MPs from water with pile cloth filters (up to 83.7%), literature is currently very limited.

Regarding the sludge line, studies are generally lacking and most works focus only on the presence of MPs in the final sludge without evaluating the actual effectiveness of individual treatments. To date, only two studies, (Alavian Petroody et al., 2021; Talvitie et al., 2017b), investigated the effectiveness of mechanical dehydration systems.

In urban WW, MPs of polyethylene terephthalate (hereafter referred as micro-PET) are present mainly because of their release during domestic and industrial laundry activities (Tian et al., 2023). In fact, PET is commonly used to produce synthetic textiles due to its properties and economic convenience (Sinha et al., 2010; Stone et al., 2020). However, during washing cycles, synthetic microfibers of PET can be released into the WW system (Luzi et al., 2025). For instance, recent studies quantified that more than 620,000 microfibers per kg of textile can be released in a single washing cycle of garments made with PET and cotton (Periyasamy, 2021). In WWTPs, micro-PET generally tends to accumulate in the sludge given the high density of this polymer (1.37 - 1.45 g cm^{-3}) (Nakao et al., 2021). However, PET has also been detected in WWTPs effluent and released in the environment if proper polishing technologies are not applied (Edo et al., 2020). PET can interact with living organisms, primarily through ingestion. This can potentially lead to endocrine and estrogenic hormone disruption in humans. It has also been shown that PET, when discharged into the aquatic environment, adsorb pollutants such as heavy metals and persistent organic contaminants and provides a refuge for several allochthonous/rare potential pathogens. In this sense, the need to find valuable solutions to extract MPs from WW system has become urgent (Alaraby et al., 2025; Sathicq et al., 2022).

Given the constant release of micro-PET into WW systems and its inefficient removal within WWTPs, identifying effective strategies for their recovery is becoming increasingly relevant. PET is a durable and valuable polymer whose recycling remains limited at the micro-scale, resulting in a continuous loss of resources and additional environmental burdens. Moreover, recent advances in biocatalysis and microbial biotechnology suggest that recovered PET could be converted into higher-value compounds, opening new opportunities for upcycling processes that reduce reliance on virgin raw materials (Rosini et al., 2025a, 2025b). In this context, understanding where micro-PET accumulates within WWTPs and how it can be selectively extracted represents a crucial step toward implementing resource-oriented solutions.

However, to date, the literature on the effectiveness of microplastic (and micro-PET) separation systems using pile cloth filtration is extremely limited. Furthermore, due to a limited number of studies, the MP retention fluxes in the water extracted from sludge dewatering, potentially limiting MP release into the environment, are unclear. The present study aims to address these knowledge gaps by evaluating the effectiveness of key WWTP processes in retaining and recovering MPs and micro-PET. Specifically, this work aims to investigate: (i) whether inline pile cloth filtration can serve as an effective technology for removing MPs from WW (ii) whether mechanical dewatering can substantially decrease the microplastic load in the sludge accumulating it in the extracted water, and (iii) whether micro-PET can be selectively extracted from mixed-polymer WW matrices, assessing the technical feasibility of an optimized extraction protocol to support potential valorization or upcycling processes. The impacts of two different approaches (pile cloth filtration and sludge dewatering) in terms of MPs retention been estimated to determine leverage points for MPs and micro-PET valorization.

2. Materials and methods

2.1. Monitored WWTP and sampling activities

Sampling activities were carried out in a WWTP (375,000 population equivalents - P.E.) located in northern Italy, treating urban WW. This plant was selected because (i) the collected water also includes a significant industrial contribution (almost 25% of the total P.E.) coming from micro-PET releasers, i.e. textile and laundry companies, (ii) the WWTP had both filtration and dewatering in its configuration allowing the evaluation of two different MPs retention strategies within the same plant, and (iii) the configuration of the sludge line and the water line (before the pile cloth filtration) reflects that of a conventional WWTP. The WWTP treats almost 100,000 m^3 d^{-1} and presents conventional primary and biological processes with additional polishing treatments (i.e., pile cloth filtration, ozonation and disinfection) (Fig. 1). The plant produces almost 36 t d^{-1} of dewatered sludge after thickening, anaerobic stabilization and centrifugal dehydration.

Pile cloth filtration is performed using twelve disc-filter units (filtering surface: 120 m^2 per unit). Each unit is composed of 24 discs, and the entire plant flow passes through the filter. The filters are used to reduce the concentration of suspended solids below the legislation limits. Backwashing is performed automatically supplying almost 3.4 m^3 of clean water every 2 h per filter per washing cycle (1-3 depending on the concentration of solids in the water), and the extracted wash water is recirculated at the head of the WWTP. The pile cloth filters are made of polyester (PES) and polyamide (PA).

Anaerobic digestion is used to stabilize the sludge, reducing the organic content. In this plant, two digesters operating in parallel are present and are sized to ensure a residence time of the thickened sludge of 30-40 days. The digesters operate in a mesophilic regime (around 35 °C) and heat is supplied via a heat exchanger located in the sludge recirculation system.

Two centrifugal dryers are used for dewatering. The centrifuges can process a maximum hydraulic flow rate of 100 m^3 h^{-1} of thickened and digested sludge or thickened sludge. The dry content of the sludge entering the centrifuges is between 2 and 3% DM, while the dry content at the outlet is on average between 20 and 25%. A polyelectrolyte emulsion solution (usually diluted at 0.5 per thousand) is added to the sludge entering the centrifuge to facilitate its dewaterability. The rotating drum speed can reach 2900 rotations per minute (RPM).

Sampling was strategically carried out between the end of June and the end of July 2024 (13th June 2024, 3rd July 2024, and 17th July 2024). This decision was taken to evaluate the treatment efficiency under stable environmental and operational conditions based on the experience of the WWTP operators. In fact, this period, characterized by minimal meteorological interference, allowed for a focus on the baseline performance of the WWTP. Furthermore, samplings were carried out after at least 48 –h of dry weather to exclude the influence of stormwater runoff on microplastic concentration and distribution. Seven different points were considered: (i) three in the water line (FIL1, FIL2 and FIL3), and (ii) four in the sludge line (SLU1, SLU2, SLU3, and SLU4). The sampling scheme also allowed the performance of the anaerobic stabilization process to be assessed, although this treatment is not specifically designed for particle removal. Sampling points located downstream of treatment stages with multiple parallel units were selected so that the converging flows were already thoroughly and uniformly mixed before collection.

130 L of water were sampled at points FIL1, FIL2, and FIL3 using a membrane pump (BACOENG), and this volume was in situ filtered through a stainless-steel filter (mesh size 100 μm). The retentate was then taken to the laboratory for analysis. At points SLU1, SLU2, and

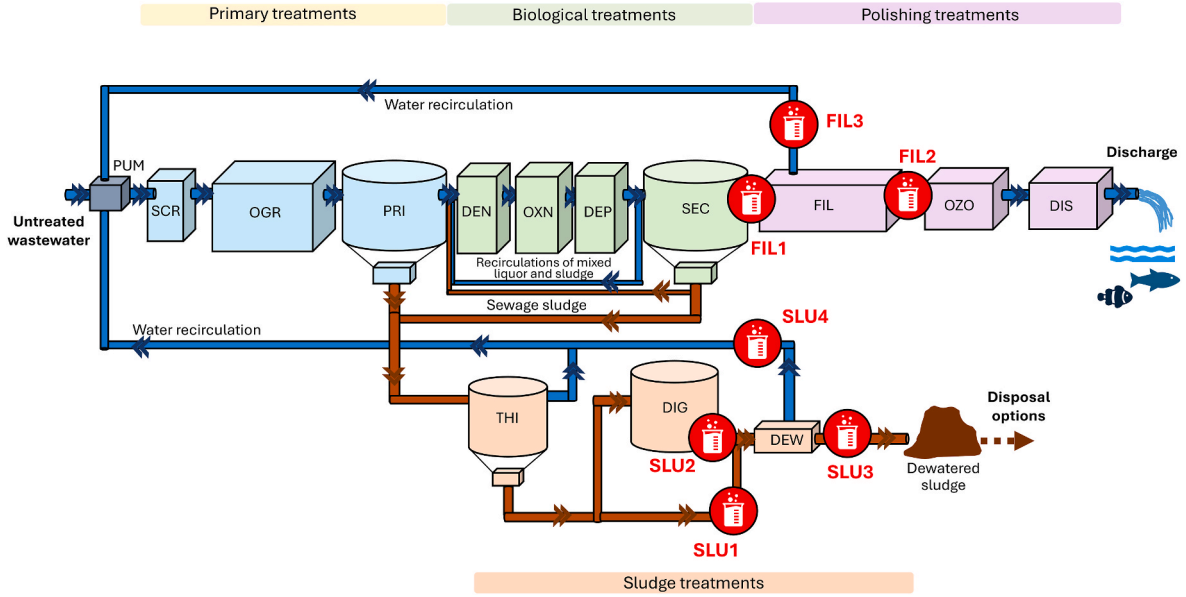

Fig. 1. Scheme of the WWTP and location of sampling activities. PUM: pumping; SCR: screening; OGR: oil and great removal; PRI: primary sedimentation; DEN: denitrification; OXN: oxidation-nitrification; DEP: Dephosphatation; SEC: secondary sedimentation; FIL: filtration; OZO: ozonation; DIS: disinfection; THI: thickening; DIG: anaerobic digestion; DEW: dewatering.

SLU3, 800–900 g of sludge was sampled, while at point SLU4 (the water extracted during the dewatering phase), 1 L of sample was taken. All samples in the sludge line were collected in glass bottles to avoid the contamination with other MPs and then taken to the laboratory for analysis.

2.2. Microplastic extraction from water samples

Water samples were characterized by low organic content and minimal fine sediment; therefore, their extraction followed a conventional protocol for the analysis of MPs in water. The extraction protocol proceeded as follows: excess water was first removed with a 100 μm stainless-steel mesh sieve, and the retained material was treated with 15% hydrogen peroxide (H_2O_2) at 30 °C for 48 h to oxidize the organic matter. After digestion, the suspension was rinsed on the 100 μm sieve with filtered deionized water to remove residual H_2O_2. When minor sediment was still visible, a saturated NaCl solution (density: 1.20 g cm^{-3}) was applied to separate MPs from remaining mineral particles. The suspension was stirred for 5 min and allowed to settle for 10 min in a homemade cylindrical separation column, as described by (Nakajima et al., 2019). The device consists of a vertical cylinder equipped with a movable upper chamber. After the solution was allowed to settle, the upper section of the column was gently slid laterally across the underlying plate, leaving the pellet beneath while retaining the supernatant in the upper part of the cylinder. This sliding mechanism allowed the supernatant to be mechanically separated from the sedimented fraction without pouring the sample, also preventing resuspension and minimizing particle loss. The floating phase was transferred into a clean glass beaker and filtered under vacuum through 8 μm cellulose filters (Sartorius), which were stored in covered glass Petri dishes until microscopic analysis.

2.3. Microplastic extraction from sludge samples

For sludge samples, which contained larger amounts of organic matter and sediment, the extraction protocol was optimized by treating the material with 30% H_2O_2 and incubating it at 30 °C for 72 h to ensure thorough oxidation. After digestion, the sample was sieved through a 100 μm mesh to remove residual H_2O_2 and collect the treated fraction. Density separation was then performed using saturated KI solution (density: 1.50 g cm^{-3}) by stirring the suspension for 5 min and allowing it to settle for 10 min in the separation column described above. This step was repeated three times to maximize recovery. The floating phase was subsequently filtered through 8 μm cellulose nitrate filter (Sartorius) and stored in glass Petri dishes. Method recovery was previously assessed in our laboratory through spike–recovery experiments using known amounts of visually identifiable plastic particles (both fibers and fragments) added to WWTP matrices. Recovery rates ranged between 95% and 103%, confirming the reliability of the extraction procedure under the tested conditions.

2.4. Visual and chemical analysis

Filters were visually analyzed under a Zeiss stereomicroscope (West Germany, n. 475,052; equipped with 0.8x, 1.2x, 2x, 3.2x, and 5× objectives). Suspected particles were classified according to their shape (i.e. fiber, fragment, film, and bead), color (to the secondary level, following (Lusher et al., 2020)) and size. Both length and width were measured using the stereomicroscope equipped with an AmScope MD500-CK camera (see (Galafassi et al., 2022) for details). A randomly chosen pool of suspected MPs varying from 10 to 40% for each sample, as recommended by the European Commission guidelines (Hanke et al., 2013), was analyzed to assess the synthetic origin with Fourier transformed infrared (FTIR). Measurements were performed using an IRAffinity-1S spectrometer (Shimadzu) equipped with an attenuated total reflectance (ATR) accessory. For each sample, 75 spectra were acquired in the range 600–4000 cm^{-1} with a resolution of 4.0 cm^{-1}. Identification was carried out by comparing the obtained spectra with the reference library provided with the instrument software. Polymer assignment was based on the match of characteristic peaks of the putative material; spectra showing a similarity below 70% with reference materials in the library were not considered.

2.5. Contamination control

Contamination control procedures were implemented throughout all analytical steps to minimize airborne fibers deposition and cross-contamination. Sample handling was always performed inside a

laminar flow hood, which was cleaned with 70% pre-filtered ethanol before and after use. Laboratory blanks were performed by exposing a wet filter in a glass Petri dish near the working area (inside the laminar flow hood) for the entire duration of the sample manipulation. The numbers of MPs in the blank sample were negligible.

All reagents (H_2O_2, NaCl, KI, ethanol, and water) were pre-filter through 8 μm cellulose nitrate filters before use. All laboratory tools and glassware were rinsed with filtered distilled water before use. Operators wore 100% cotton laboratory coats to avoid release of synthetic fibers. The use of gloves was minimized to reduce contamination and, when required, latex gloves were used.

2.6. WWTP data elaboration

The effectiveness of each treatment (RE_i) was calculated as reported in Eq. (1):

$$RE_i\ (\%) = \frac{X_{in,i} - X_{out,i}}{X_{in,i}} * 100 \quad (1)$$

Where $X_{in,i}$ and $X_{out,i}$ represent the load of MPs incoming and outgoing from the i-th process. Considering that flow meters are not available at all sampling points, some assumptions were made. In pile cloth filtration, the loads were calculated assuming that the flow rate entering and exiting the unit (FIL1 and FIL2, respectively) were equal to that exiting the plant. In the sludge line, the flow rates required to quantify the loads at points SLU1, SLU2, and SLU4 were calculated based on the load exiting the dewatering unit (SLU3), the solids concentration (1.7% in SLU1 and SLU2, 23.5% in SLU3 and 0% in SLU4), and the sludge density (1000 kg m^{-3} in SLU1 and SLU2; 1390 kg m^{-3} in SLU3). Given the absence of other flows, the same assumption as for filtration was made in anaerobic digestion, considering SLU1 as representative of the incoming flow characteristic and SLU2 for the outgoing sludge.

2.7. Development of a PET separation protocol

To evaluate the technical feasibility of the selective recovery of PET from WWTP matrices, a PET separation protocol was optimized based on a previously published method (Pongstabodee et al., 2008), using spiked sludge-rich samples. The protocol combined density separation, oxidative surface modification, and hydrophobic flotation. This workflow was tested on both matrices, for a total of four replicates (one water and three sludge samples). For each test, approximately 200 g of WWTP material were collected. To simulate a realistic mixed-polymer environment and allow controlled recovery estimates, each sample was spiked with 100 mg of pink PE, 100 mg of blue PP, 100 mg of white PS, 100 mg of orange PVC and 100 mg of clear PET. MPs were homemade from real plastic items (e.g. plastic cups, clothespins, and water bottles) with an electric grinder; fragments between 300 and 500 μm were isolated using stainless-steel mesh sieves. A procedural blank (200 mL of filtered water processed through the entire protocol) was included to assess external contamination.

The optimized protocol consisted of three main steps:

(i) Density separation of low-density polymer: each sample was sieved using a 100 μm stainless-steel mesh to concentrate the solid fraction. The retained material was transferred into the cylindrical column described in section 2.2 and suspended in saturated NaCl solution. The suspension was stirred manually for 5 min and then allowed to settle for 20 min. The floating supernatant was collected as the low-density fraction (LD).

(ii) Oxidative treatment of the residual high-density fraction: the material remaining after the NaCl separation step was transferred to a clean beaker and treated with 1.25 mM $KMnO_4$ solution. The mixture was stirred at 60 °C, 300 rpm for 50 min. Based on previous studies reporting that $KMnO_4$ can modify polymer surface properties and affect their behavior in aqueous systems (Chen et al., 2022; Pongstabodee et al., 2008), this oxidative treatment was applied to promote differential behaviour among polymers during the subsequent separation. After oxidation, the sample was rinsed thoroughly on the 100 μm sieve with filtered tap water to remove residual $KMnO_4$. The washed material was kept in clean filtered tap water for 5 min before the next step.

(iii) Pine oil flotation for PET and PVC separation: the oxidized material was transferred into a vertical cylindrical glass column, placed inside a larger beaker to collect the overflow. Pine oil (17.5 g L^{-1}) was added directly into the column and air was introduced from the bottom for 1 min, to promote the formation of oil bubbles and the flotation of hydrophobic particles. During aeration, the floating phase overflowed from the top of the column over the surrounding beaker and was collected as the hydrophobic fraction (HF) and then vacuum-filtered. The material that remained at the bottom of the column after flotation, consisting of the residual high-density fraction (HD), was also recovered and filtered.

All the fractions generated by the PET separation workflow (LD, HF, HD) were filtered onto 8 μm cellulose nitrate filters and then examined under a stereomicroscope for particle counting and classification. Particles that could not be reliably discriminated visually (e.g., by color) were analyzed using ATR-FTIR spectroscopy for polymer confirmation. Polymer counts were used to evaluate the distribution of microplastic across the three fractions generated. Since the initial number of particles in the spiked sludge was not determined, a true recovery efficiency could not be calculated. Therefore, data analysis was based on the total number of particles recovered across all fractions, and results are expressed as the relative distribution of polymers among the different fractions rather than absolute recovery. For each fraction, particle counts from the four experimental replicates were pooled prior to percentage calculation. Polymer composition was expressed as the relative contribution (%) of each polymer to the total number of particles recovered in that fraction (weighted proportion). Polymer percentages were calculated according to Equation (2):

$$P_{p,f} = \frac{n_{p,f}}{N_f}\ x\ 100 \quad (2)$$

Where $P_{p,f}$ is the number of particles of polymer p recovered in fraction f and N_f is the total number of particles recovered in that fraction. Results are reported as mean relative abundances (%) ± standard deviation (SD), calculated from the four independent experimental replicates per fraction.

3. Results

3.1. Microplastic extraction from the tertiary treatments

The pile cloth filtration reduced the MP concentration in tertiary water: incoming water contained 1.11 ± 0.29 MP L^{-1}, which decreased to 0.39 ± 0.25 MP L^{-1} after filtration (Fig. 2a), with a removal efficiency of 67 ± 12.6% (Fig. 3). MPs retained by the filters were released during the washing step, producing wash water highly enriched in MPs (6.86 ± 4.66 MP L^{-1}). Micro-PET was found exclusively in fibrous form (Table S1) in the effluent of filtration unit (<0.1 MP L^{-1}), while it was not detected in the incoming water, perhaps due to its very low concentration. In the wash water, the concentration reached 0.17 ± 0.01 micro-PET L^{-1}, accounting for 3.6% of the total MPs detected.

Analysis of MP shapes revealed that the filtration unit was more effective at removing fragments and beads than fibers and films (Fig. 4a). Prior to filtration, fragments accounted for 57.6 ± 0.2% of MPs; this proportion decreased to 45.3 ± 0.2% in the filtered effluent, with spheres being entirely absent. Conversely, the proportion of fibers

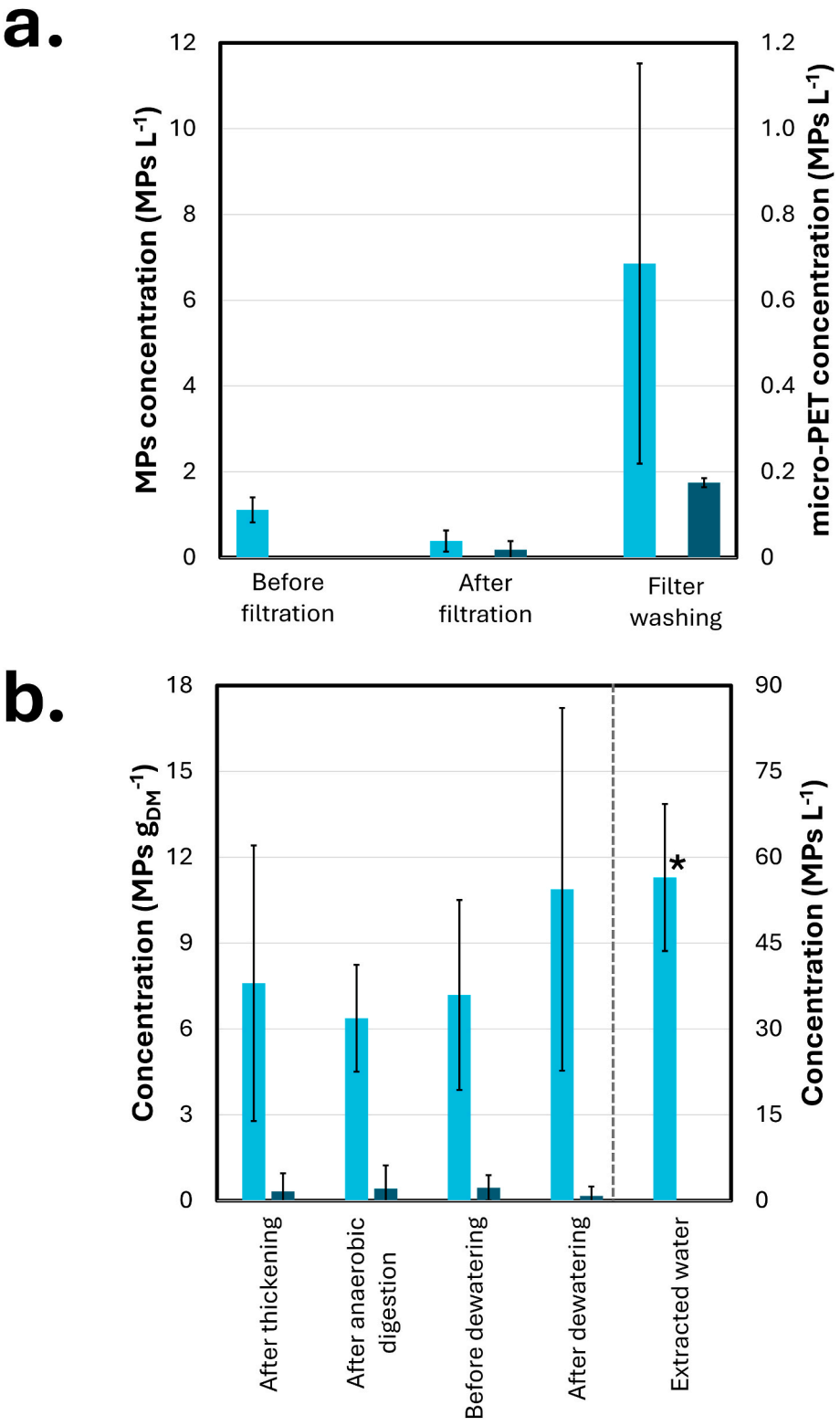

Fig. 2. Concentration of MPs (light blue) and micro-PET (green) in the (a) filtration unit and (b) sludge line. *: data about extracted water are reported in MPs L^{-1} (right y-axis). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

and films increased from 40.7 ± 0.1% in the inlet to more than 54.7 ± 0.2% in the outlet, indicating lower retention efficiency for this kind of particle shape.

3.2. Microplastic recovery from the sludge line

Only dewatering appeared to have a significant impact on the concentration of MPs in the sludge. After thickening, sludge contained on average 7.6 ± 4.81 MPs g_{DM}^{-1}, with values up to 12 MPs g_{DM}^{-1} (Fig. 2b; Table S2). Micro-PET accounted for 4-7% of the total, reaching

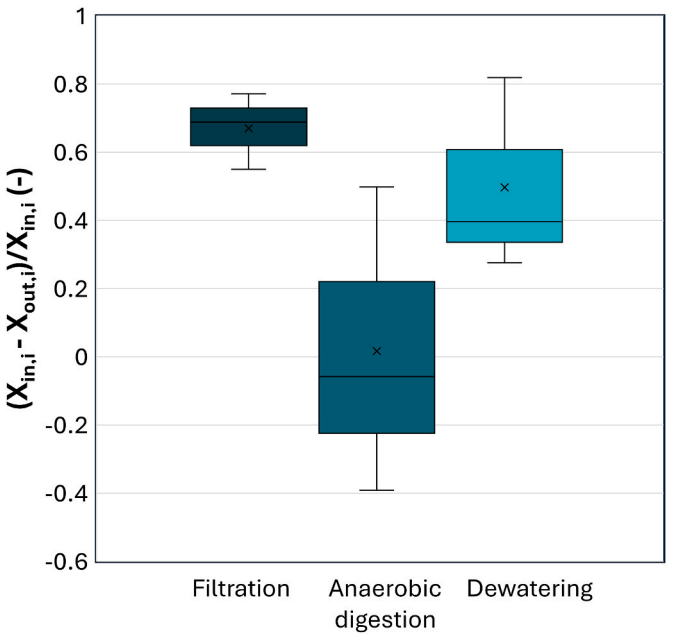

Fig. 3. Removal of MPs in the filtration unit and in the sludge line. Boxplots represent the distance between the first and third quartiles while whiskers are set as the most extreme (lower and upper) data point not exceeding 1.5 times the quartile range from the median. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

0.32 ± 0.63 micro-PET g_{DM}^{-1}, and was detected exclusively as fibers.

Anaerobic digestion did not significantly alter either the concentration or the composition of MPs. MP loads remained comparable to those in thickened sludge, and micro-PET levels were also unaffected. Despite the variability of the data, the average removal was negligible (2%) (Fig. 3). The micro-PET concentration in the digested sludge also remained relatively unchanged at 0.42 ± 0.82 micro-PET g_{DM}^{-1} (6.7% of the total).

Mechanical dewatering partially redistributed MPs from the solid to the liquid phase. On average, 49.7 ± 32.3% of the MPs present in the incoming sludge (which was a mixture of thickened and digested sludge) were released into the extracted water, reducing the concentration in the sludge from over 7 MPs g_{DM}^{-1} to below 4 MPs g_{DM}^{-1}. The MPs accumulated in the extracted water where they were found with an average concentration of 56.5 ± 12.8 MP L^{-1}, likely transferred during centrifugation. Although the process influenced the total MPs concentration, dewatering did not have a significant impact on micro-PET which maintained a concentration in the dehydrated sludge of 0.49 micro-PET g_{DM}^{-1}, very similar to the incoming concentration. Consistently, no micro-PET was detected in the water extracted from the centrifugal dewatering.

MP shape distribution changed after dewatering (Fig. 4b). Thickened sludge showed a prevalence of fragments (48.3 ± 0.1%), followed by fibers (43 ± 0.2%) and, to a lesser extent, films (8.4 ± 0.1%) and spheres (0.3 ± 0.1%) (Fig. 4b). This composition roughly mirrors that found in WW, with a higher presence of fibers. These proportions remained stable after digestion. However, dewatered sludge composition shifted dramatically: fragments increased to 87.6 ± 0.2%, while fibers decreased to 9.3 ± 0.1% and films to 3.1 ± 0.1%. In the extracted water, 44.4 ± 0.4% of the MPs were fibers, while the remaining 55.6 ± 0.4% were fragments. In the dewatered sludge, micro-PET appeared predominantly as fragments, while it was initially present only as fibers. This result could be due to the shear stress during the mechanical dewatering phase, which could have reduced the length of the fibers to the point that they assumed a configuration classified by the operator as fragments. However, this hypothesis remains speculative at present. Although a reduction in MP size following the application of mechanical dewatering processes has already been observed (Yang et al., 2024), data on the possible effect of this process on the shape of MPs contained in the sludge are still lacking, and further studies are therefore necessary.

3.3. Micro-PET separation protocol

The polymeric composition of the tertiary filter wash water and dewatering water showed a dominance of low-density materials, mainly PP, PE and their copolymers, which are among the most widely used polymers in the plastics industry (Plastics Europe, 2023). Minor proportions of denser polymers, such as PET, PA and ABS, were detected, while other high-density materials were absent. Given the low occurrence of PET and the lack of other polymers with comparable densities, a spiking procedure was applied to increase the overall particle concentration and to introduce additional polymers with densities similar to PET (i.e., PS and PVC). This approach enabled a robust assessment of the polymer portioning of the protocol.

Polymer distribution across the three fractions obtained by the optimization of the protocol (LD, HF, HD) showed a clear and highly reproducible pattern over the four spiking experiments performed on both water and sludge matrices (Fig. 5). Low-density polymers (PE, PP, PS) were almost exclusively recovered in the LD fraction, which contained 32.3% ± 15.0% PE, 55.9 ± 10.5% PP and 8.7 ± 3.5% PS, together accounting for more than 96% of the LD composition. A minor contribution of PVC (2.4 ± 2.0%) and PET (0.8 ± 0.5%) were also detected in this fraction.

After $KMnO_4$ oxidation, PVC exhibited a strong affinity for the hydrophobic fraction, representing 55.6 ± 9.8% of the HF composition, whereas PET accounted for only 9.7 ± 4.8%. Conversely, PET was predominantly recovered in the HD fraction, where it represented 73.8 ± 11.4%% of all particles, with PVC contributing 22.3 ± 11.3%, and negligible amounts of PE, PP and PS (<2% combined).

Fractional patterns were highly reproducible across the replicates: tests performed on water and sludge matrices showed comparable partitioning behavior, indicating that the protocol performed consistently even when sediment load and organic matter content differ.

4. Discussion

4.1. Discussion of the results

The aim of this study was to evaluate the removal performance of MPs, and in particular of micro-PET, through (i) pile cloth filtration as a refinement of WWTP effluents, and (ii) the dewatering and anaerobic digestion processes present in the sludge line. A further objective was to determine whether pile cloth filter wash water and the water extracted from dewatering could be considered suitable points for micro-PET extraction in light of its potential biotechnological valorization (Rosini et al., 2025b).

Pile cloth filtration provided excellent results in reducing MPs (67 ± 12.6%), demonstrating high retention efficiency. Previous studies have already confirmed the effectiveness of polymeric membrane systems in retaining up to 80% of MPs (Hidayaturrahman and Lee, 2019). In one of the few studies on the effectiveness of cloth filtration on MPs, Sembiring et al. obtained results fully comparable to those observed in the present work. They reported that up to 85% of plastic particles could be removed using a filter with pore sizes of 57.5 μm (Sembiring et al., 2021), consistent with the performance of the cloth filter tested in this study (5-10 μm). Removal efficiencies observed across studies are influenced by multiple interacting factors beyond nominal pore size, including particle shape and deformability, hydrodynamic conditions, filter loading, and the formation of a dynamic filter cake. These aspects likely explain the variability in MPs retention reported in the literature

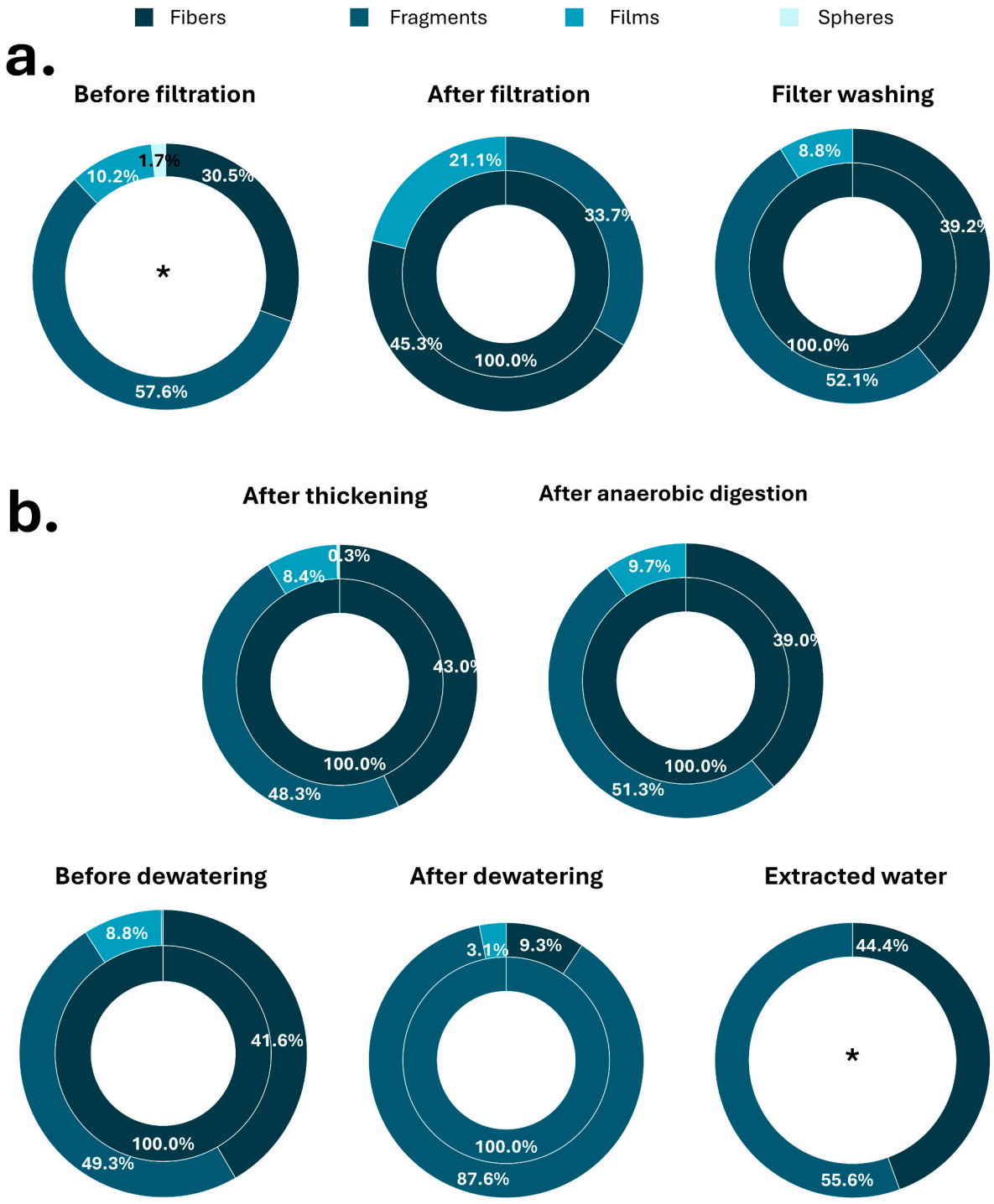

Fig. 4. Average percentages of shape of MPs (outer circles) and micro-PET (inner circles) in the (a) filtration unit, and (b) sludge line. * indicates that micro-PET has not been found in these samples. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

and indicate that filtration processes should be interpreted as dynamic systems rather than purely size-based barriers. The main concern associated with membrane filtration is the potential release of MPs due to wear of the polymeric surface (Talvitie et al., 2017a). Although a previous study (Cavazzoli et al., 2025) suggested this, in our work such release appears negligible, as indicated by the similarity between the percentage composition of the influent, the filtrate, and the wash water fraction. In the wash water, PES, of which the pile filter cloths are made of, represented 3% of the total MPs, very similar to the 1.4% found in the feed water and the 3.7% in the filtered water. The other main polymer of pile cloth filters, PA, was detected in a very low percentage in the wash water (2.3%). This difference in membrane behavior could be due to a different frequency of backwashing or a different age of the membranes studied in the plants examined in the two studies.

The removal was higher for fragments and spheres (59.3 ± 0.2% of the total MPs before filtration, 45.3 ± 0.2% after filtration) than for fibers (30.5 ± 0.1% vs. 33.7 ± 0.1%, before and after the pile cloth filter, respectively). This difference can be mechanistically explained by the interplay between particle shape, flexibility and hydrodynamic behavior. Fibers, due to their elongated morphology and flexibility, tend to align with flow streamlines and can more easily pass through filter pores or re-enter the water phase after temporary entrapment. In

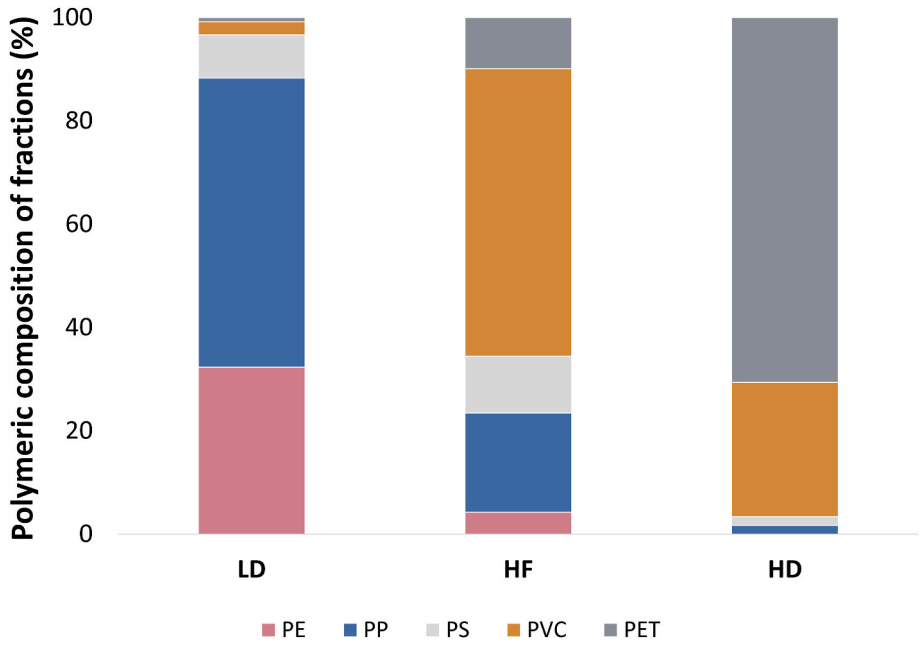

Fig. 5. Polymeric composition of the fraction obtained by the optimized separation protocol. LD: low-density fraction obtained by the first flotation in saturated NaCl solution; HF: hydrophobic fraction, and HD: high-density fraction obtained by the pine oil flotation. PE: polyethylene; PP: polypropylene; PS: polystyrene; PVC: polyvinyl chloride; PET: polyethylene terephthalate. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

contrast, more compact particles such as fragments and spheres are more effectively retained due to their larger effective cross-sectional area and lower deformability. This has been also confirmed in previous studies involving other types of membrane (Hidayaturrahman and Lee, 2019). This result, together with the low concentration in the unfiltered water, helps to explain the low concentration of micro-PET (totally present in the form of fibers) found in the filter wash water. However, the large flow rate of the plant suggests that the amount of micro-PET saved daily from the release in the environment is approximately 2.59×10^6 particles (7.26×10^7 the total amount of MPs saved) (Table 1). Converting these particle counts into a meaningful mass of MPs and micro-PET is not simple because it depends on the particle size distribution and the type of polymers. If the dimension of the particles is assumed to be on average 0.3 mm and considering the micro-PET density is 1.455 g cm^{-3}, approximately 53.3 g of this polymer can be saved daily from the release. Although this quantity is limited in mass, several aspects must be considered. The first is that this value refers to a single medium-sized plant, so the overall extraction and recovery potential would be greater if this approach were applied to multiple large plants. The second aspect is related to the objective; in this case, it is not to extract micro-PET for use as a recycled polymer, but to potentially feed new supply chains for its valorization into high-value compounds (e.g. (Rosini et al., 2025a, 2025b),), where even smaller quantities could justify any necessary functional upgrades in the plant. However, prior to large-scale application, economic assessments would be necessary, which are beyond the scope of this work. The third aspect concerns the impacts on the environment and human health. While the latter are still to be clearly defined, the negative impact of micro-PET (and MPs in general) on ecosystem health is certain (Acarer Arat, 2024; Tang et al., 2024), so even the removal of a limited mass quantity of MPs (but significant in terms of particle number) could have a positive effect on the biotic component of the ecosystem.

Table 1
Estimation of the load of MPs and micro-PET released and saved from the environment thanks to pile cloth filtration and dewatering.

	Total MPs [MPs d^{-1}]	micro-PET [MPs d^{-1}]
Approach 1 - Pile cloth filtration as quaternary treatment		
Without pile cloth filtration	1.11×10^8	4.42×10^6
With pile cloth filtration	3.86×10^7	1.82×10^6
Saved from environment	7.26×10^7	2.59×10^6
Recirculated	6.86×10^6	2.45×10^5
Trapped in filters	6.58×10^7	2.35×10^6
Approach 2 - Sludge dewatering		
Without dewatering	4.40×10^6	2.76×10^5
With dewatering	2.21×10^6	2.76×10^5
Saved from environment	2.19×10^6	0[a]

[a] Micro-PET has not been found in the extract water.

The results seem to suggest that a substantial amount of MPs that remain trapped in the free-fibers filters, however, are not removed during backwashing (almost 89.6%), thus limiting the MPs and micro-PET recirculation in the preliminary treatments. This interpretation, however, should be treated with caution. The quantification obtained in this study may also reflect limitations in the sampling approach, as backwash release is unlikely to occur at a constant concentration over time. It is therefore possible that sampling was performed during a phase in which the filters had already undergone partial cleaning, resulting in an underestimation of the actual release. For these reasons, future studies should address both the behavior and retention–release dynamics of MPs within free-fiber filtration systems, and the development of dedicated sampling methodologies capable of accurately characterising the temporal variability of MP discharges during filter washing. The occurrence of micro-PET in WW, exclusively in fibrous form, therefore of textile and laundry origin, further highlights the importance of assessing the effectiveness of in-situ separation solutions at the source, which will be the subject of further evaluations.

In the sludge line, after thickening, MP concentrations are high, reaching values above 12 MPs g_{DM}^{-1}, of which 7.1% correspond to micro-PET. The high density of this polymer causes it to spontaneously settle in aqueous solution, explaining the accumulation in the sludge and the significant concentration present even after thickening. This behavior is consistent with the role of gravity-driven separation processes in WWTPs. Units such as thickening and sedimentation act as accumulation points because particles with densities higher than water, or incorporated into flocs, progressively partition towards the solid phase.

In addition, biological and physicochemical aggregation processes occurring in activated sludge systems favour the incorporation of MPs into sludge flocs, enhancing their retention and transfer along the sludge line. Polymer-specific behaviour is primarily governed by intrinsic properties such as density, surface characteristics and susceptibility to biofilm formation. PET, having a density higher than water, shows a strong tendency to settle and accumulate in sludge, whereas lower-density polymers (e.g., PE and PP) are more likely to remain suspended unless incorporated into flocs. Furthermore, biofilm development can modify particle density and surface properties, promoting the transfer of initially buoyant particles towards the solid phase and altering their transport within the treatment line. The values found in this study are compatible with those reported by Magnusson and Norén who analyzed sludge from several Swedish plants with characteristics comparable to the thickened sludge (average dry matter 4.5%) and found an average MPs concentration of approximately 16.7 MPs g_{DM}^{-1} (Magnusson and Norén, 2014). However, other studies such as that of Dronjak et al. detected MPs concentration equal to over 4300 MP L^{-1} (therefore 143 MPs g_{DM}^{-1}, assuming a sludge with a 3% dry matter content), well above the concentration measured in the present study (Dronjak et al., 2023). This difference can be attributed to the different characteristics of the WW being treated and to the different operating conditions of the plant. However, the same study confirmed a micro-PET concentration of around 1% of the total (Dronjak et al., 2023).

The subsequent anaerobic digestion phase had no effect on the presence of MPs and micro-PET, as previously observed (Cydzik-Kwiatkowska et al., 2022). Some studies have shown that the presence of MPs can be a determining factor in decreasing digester efficiency (Zhang et al., 2020). However, this aspect was not evaluated as it was not one of the study's objectives. Dewatering, however, demonstrated marked effectiveness, ensuring the extraction of 49.7 ± 32.3 % of the MPs from the sludge via the process water and acting as a "barrier" to reduce the amount of plastic released into the environment. These yields are similar to those identified by (Alavian Petroody et al., 2021) (46%) but higher than those shown by (Talvitie et al., 2017b) (20%). The difference in this case could be due to the different layout of the WWTP and the diverse characteristics of the fed sludge.

Although the approach is functional for the separation of MPs from the sludge flow, the technology did not allow for the separation of micro-PET, which is still found in the dehydrated sludge (Table 1). This result is in contrast with what was reported by (Nakao et al., 2021), who instead highlighted an accumulation of fibrous PET in the extracted effluent of the centrifuge. The difference could be related to the different operating parameters of the centrifuge and the different characteristics of the initial sludge.

When compared with previously published fractionation approaches, the performance of the optimized protocol demonstrates a solid capacity to selectively recover micro-PET, although with slightly lower recoveries than those reported in controlled laboratory studies. Pongstabodee et al. achieved PET recovery efficiencies close to 90% using density-based separation applied to clean plastic mixtures (Pongstabodee et al., 2008). In contrast, the micro-PET analyzed in the present work had been incubated in real WW and sludge environments, and this exposure likely altered their characteristics through biofilm formation, which can modify surface properties and affect density. Moreover, the sludge-derived samples processed here contained high biomass loads and substantial organic and inorganic matter, which likely alter particle aggregation and hinder complete recovery during separation. These differences in matrix complexity and particle conditioning plausibly explain the lower recovery observed relative to idealised laboratory conditions, while reinforcing the relevance of validating separation protocols directly on WWTP-derived samples rather than on artificial mixtures.

4.2. Limitations of the study

The first possible limitation is given by the selection of the WWTP. Although the present study was carried out on a WWTP with a conventional configuration upstream of the treatments under study, in the case of a full-scale application of approaches related to the recovery and valorization of MPs and micro-PET, the results require validation in the specific case study. Another possible limitation can be related to the relatively short duration of the sampling. This decision was made to base the study on data obtained during a period of stable plant operating conditions, thus avoiding periods of almost complete industrial shutdown, such as August, or periods of excessive rainfall, such as spring and autumn. In any case, before possible full-scale implementations of the approach, future studies should consider multi-seasonal sampling to account for variations in influential characteristics. A further limitation is related to the size range of MPs considered in this study. Particles smaller than 100 μm were not included due to analytical constraints associated with FTIR detection limits. This choice was made to ensure robust and reliable identification and quantification of MPs. However, it should be noted that smaller particles may exhibit different transport, filtration, and sedimentation behaviors. Therefore, the results and conclusions of this study are limited to MPs >100 μm, and further investigations are needed to assess the fate of smaller size fractions within WWTPs.

5. Conclusions

This study shows that WWTPs can contribute to the mitigation of MPs emissions (>100 μm) and may also offer initial opportunities for polymer recovery within a circular economy framework. The evaluation of key treatment steps showed that pile cloth filtration represents an efficient refinement process for reducing MP loads in the water line (67 ± 12.6%), while mechanical dewatering significantly decreases the MP content of the sludge (49.7 ± 32.3%) by transferring a substantial fraction of particles to the process water.

Although micro-PET was largely retained in the solid phase after dewatering, its detection in filter wash water indicates that this stream may represent a potential target for recovery-oriented strategies. Conversely, micro-PET was not detected in dewatering water, suggesting that its release into this stream is limited under the investigated operational conditions. The absence of micro-PET in dewatering water may be related to the characteristics of the treated WW and to process-specific factors, including the configuration and operating parameters of the dewatering unit; however, this aspect remains speculative and warrants further investigation. Overall, these treatment steps, together with the WW treatment line as a whole, play a key role in retaining MPs, substantially limiting their release into the environment. These results highlight the need for site-specific assessments when evaluating the feasibility of micro-PET recovery within different WWTP configurations.

The optimization of a selective separation protocol enabled effective micro-PET enrichment from complex WW- and sludge-derived matrices, even in the presence of high biomass loads and biofilm-coated particles. These findings underscore the importance of validating separation approaches under realistic operational conditions rather than relying solely on laboratory-based systems.

Overall, integrating targeted MP removal processes with selective polymer recovery strategies may support the transition of WWTPs from end-of-pipe treatment facilities to resource-oriented infrastructures. Such an approach offers promising opportunities to reduce environmental emissions, recover secondary raw materials and contribute to cleaner production and more sustainable WW management systems. In this sense, the recovered MPs could serve as a starting point for new valorization chains currently being explored by the scientific community, aimed at their bioconversion into high-value molecules. From a technological point of view, the separation of MPs from water and sludge exploits already widely known processes. However, before a

large-scale upgrade of the approaches evaluated in this study to micro-PET extraction and separation, an economic analysis will be necessary to determine the system's feasibility and the most sustainable solution.

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CRediT authorship contribution statement

Beatrice Luzi: Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft. **Marco Carnevale Miino:** Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft. **Elena Cristina Rada:** Supervision, Writing – review & editing. **Rosa Zullo:** Supervision, Writing – review & editing. **Vincenzo Torretta:** Funding acquisition, Project administration, Supervision, Writing – review & editing. **Silvia Galafassi:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2026.129980.

Data availability

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

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