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The impact of a large textile laundry facility on the overall influx of microplastics and their removal in two wastewater treatment plants in the Netherlands

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Abstract

At present, there is a lack of understanding regarding the extent to which various sources contribute to the total incoming load of microplastics (MPs) into wastewater treatment plants (WWTPs). This study investigated the contribution of an industrial textile laundry facility (ITLF) to the overall influx of MPs and their removal in two WWTPs. MPs were analysed by means of microscopic quantitative analysis in the wash water from a large textile laundry facility, as well as in the influent of the receiving WWTP. Additionally, influent and effluent flows of two WWTPs were analysed. Results demonstrated that a single-point emitter of MPs, i.e. an ITLF, contributed substantially (13%) to the overall influx of MPs in a WWTP. MPs were effectively removed (≥ 99.8% removal, particle size > 50 μm) in two separate WWTPs. As indicated in this study, actions mitigating the emission of MPs from single-point emitters are worthwhile and could be more cost-effective than implementing additional treatment processes in the WWTPs.

Introduction

In the current anthropogenic era, microplastics (MPs) are an omnipresent and persistent part of most environmental matrices [2, 15, 26]. MPs are generally defined as synthetic, water-insoluble polymers with a size ranging from 1 μm to 5 mm [9]. Despite their widespread presence, little is known about the effects of MPs on health and ecology, and there is no consensus on their potential to act as vectors for contaminant transport [10, 13]. Moreover, there is limited understanding of the total discharge of MPs from all potential sources into the environment. This knowledge gap is reflected by the absence of comprehensive regulatory frameworks, as there are currently no overarching policies governing MP emissions. As an initial step toward addressing potential health concerns, MPs have been proposed for inclusion on the Watchlist under Article 13 of the European Drinking Water Directive [9].

Wastewater treatment plant (WWTP) effluent has been recognized as a source of MPs in surface water [18, 23, 30]. Understanding the influx of MPs into these facilities is crucial for mitigating their release into surface water and, subsequently, the environment. MPs enter WWTPs through various pathways and sources, including tire wear (via road run-off), textile washing, cosmetic and personal care products, atmospheric deposition, and fragmentation of plastic

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material (e.g. bottles, bags) [27, 38]. The type and contribution of each source can differ greatly between WWTPs, depending on their design (combined or separate systems). In combined sewer systems, both wastewater and stormwater are collected and treated at the WWTP. In separate systems, only wastewater is treated, while stormwater is discharged directly into surface water without treatment [36]. Currently, the contribution of individual sources, including textile washing, is poorly understood.

The impact of textile washing on the total MP load in the environment is deemed significant, though this is not unambiguously proven [5, 7, 11, 35]. Boucher and Friot [5] concluded that synthetic textile washing and tyre wear are the main sources of plastic in the ocean (defined as plastic particles < 5 mm that directly enter the environment). This is supported by [7], who indicated that washing synthetic clothing could be identified as the largest source of MPs in the ocean. Gaylarde et al. [11] reported that household and commercial washing of synthetic clothing is even thought to be responsible for 90% of primary MPs in the oceans. In contrast, Urbanus et al. [35] concluded that rubber tyres, packaging material and agricultural foil are the largest sources of MP emissions in The Netherlands, with textile washing and wearing ranking fourth and contributing significantly less. Although there is no consensus on the dominant source of MPs, it can be concluded that textile washing is certainly a significant contributor.

Studies have shown that wastewater contains significant levels of MPs and that WWTPs remove a large portion of these from the influent, though not completely [6, 16, 19, 21, 39, 40]. Recently, [16] reviewed MP removal in WWTPs based on 21 global studies and concluded that secondary treatment (e.g., activated sludge) removes approximately 88% of MPs (approximate range 1–5000 µm), while advanced treatment (e.g., (biological) filtration, ultrafiltration/reverse osmosis, disc filters, dissolved air flotation, or membrane bioreactors) can achieve up to 94% removal. Most MPs (approx. 72%) are removed during pre- and primary treatment (screening, removal of coarser particles and grease, sedimentation). Leslie et al. [21] investigated MP removal (10–5000 µm) in seven Dutch WWTPs and reported an average removal efficiency of 72%, with a large standard deviation of approximately 61%. Even with removal percentages between 72 to 94%, discharge of treated wastewater remains a source for MPs in the environment.

To the best of our knowledge, this is the first study that investigates the behaviour of MPs, partly originating from textile washing, across an entire chain: from an industrial laundry facility to removal in the WWTP, and the subsequent discharge of MPs that are not removed into the surface water. The objective of the paper is to assess (1) the contribution of an industrial textile laundry facility (ITLF) to the overall influx of MPs in a WWTP, (2) the removal of MPs in two separate WWTPs (one with and one without advanced treatment) and (3) the number of MPs discharged into receiving surface water. In addition, the removal of different MP shapes (particle versus fibre) and size fractions is considered. Quantifying the contribution of an ITLF to the total MP load entering a WWTP, as well as evaluating the efficiency of MP removal within the WWTP, is essential for understanding the dynamics of MP pollution. Such an assessment can help determine whether targeted mitigation strategies at specific point sources (e.g. an ITLF) are more effective than relying solely on end-of-pipe solutions at the WWTP level. This approach can inform regulatory and technological interventions by highlighting the potential benefits of upstream control measures in reducing the overall environmental discharge of MPs.

Materials and methods

Sampling campaign

Sampling locations

This study investigated three distinct wastewater chains (WWCs) in the Netherlands. Two of these chains, 'West' and 'Horstermeer', focused on the removal of MPs in a typical wastewater treatment plant (WWTP). The third wastewater chain focused on an industrial laundry facility, examining its wastewater discharge into the 'Kerk en Zanen' WWTP. For this case, only the influent of the WWTP was characterized, without further analysis of treatment performance.

WWC1 (West): WWC1 is a conventional WWTP (Fig. 1). This WWTP consists of a primary sedimentation, followed by an activated sludge process and secondary sedimentation. WWTP West is the largest WWTP of Waternet (the water utility of Amsterdam and surroundings) and was built in 2005. The average flow was 165,937 m^3/d in 2022. The effluent is discharged onto the North Sea Canal.

Fig. 1 Schematic overview of treatment processes at WWTP West (stars mark sampling points)

WWC2 (Horstermeer): WWC2 is an extended WWTP (Fig. 2). This WWTP consists of primary sedimentation followed by an activated sludge process and secondary sedimentation. After the secondary sedimentation, the water is treated with a 1-STEP filter (biologically activated carbon filtration). WWTP Horstermeer is one of the smaller WWTPs of Waternet and was built in 1985. The average flow was 23,676 m^3/d in 2022. The effluent is discharged into the river Vecht.

WWC3 (Industrial Textile Laundry Facility): WWC3 is an ITLF that discharges into a WWTP (Fig. 3). The facility houses three production lines for textile washing, of which only one was investigated in this study. This production line contains a heat exchanger located after the washing machine. To protect the heat exchangers from cotton tangles, a rotating drum filter is installed in front of the heat exchanger. Wastewater from all three production lines is collected in an open-air basin, which is characterized by a discontinuous supply and discharge. The collection basin discharges into the sewage system connected to WWTP Kerk en Zanen. WWTP Kerk en Zanen is managed and owned by the Regional Water Authority Rijnland and was built in 1994. The average flow was 13,382 m^3/d in 2022.

Samples

Blanks Blank samples were included for all sampling events in each WWC. Blank samples were generated by collecting 2 L tap water in a plastic (polypropylene) jerrycan on-site at the day of sampling, thereby simulating filling of sampling bottles and worst-case influence of deposition and/or release of MPs during sampling (e.g. bottle caps, jerry cans, etc.). Previous research demonstrated that tap water is virtually free from larger (> 20 µm) MPs and thereby suitable for the purpose of this blank sample [3]. If MPs are detected in the blank samples, this indicates they originate from the sampling process (e.g., contamination from the air or the laboratory materials). Blank samples were processed in the same manner as the other samples (see Sample pre-treatment) and reported as background contamination levels (not subtracted from the sample counts).

Samples Each sample point in every WWC was sampled on two different dates (April/May 2022 and September/October 2022). Sampling characteristics are provided in Table 1. The first sampling round at WWTP West was conducted during dry weather conditions, both on the day of sampling and during the preceding days. In contrast, the second sampling round at the same location was characterized by rainfall on the sampling day and the preceding day. At WWTP Horstermeer, both sampling rounds were carried out during dry weather conditions, with no rainfall observed on the sampling days or in the days prior.

Sampling methods

Two types of sampling were conducted during the sampling campaign: small volume sampling (SVS) and large volume sampling (LVS). LVS (300–600 L), using a stainless-steel cascade, was applied to relatively clean samples (i.e., WWTP effluent) to improve the recovery and detection limit for MPs. All other sample points had SVS (1–2 L) applied.

Fig. 2 Schematic overview of treatment processes at WWTP Horstermeer (stars mark sampling points)

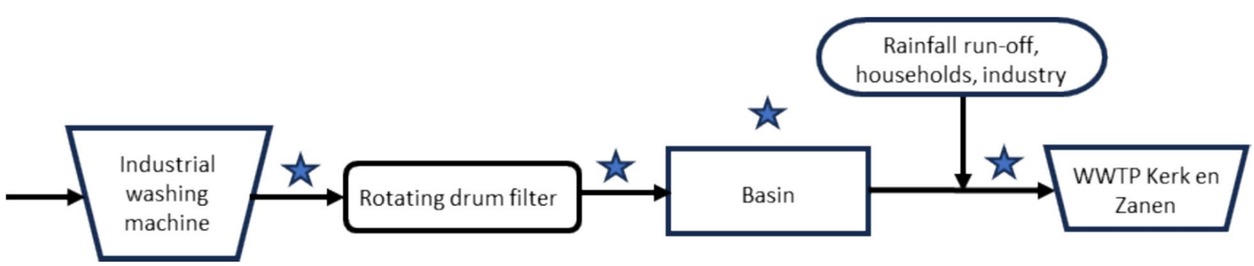

Fig. 3 Schematic overview of wash water flow at the industrial laundry facility (stars mark sampling points)

Table 1 Sampling characteristics (WWTP, sampling points and sample volumes)

WWTP West	Sample volume [L] Round 1	Sample volume [L] Round 2
Influent	2	1
Effluent	588	329
Blank	2	1
WWTP Horstermeer	Sample volume [L] Round 1	Sample volume [L] Round 2
Influent	2	1
After the activated sludge tank (prior to the 1-STEP filter)	540	497
Effluent	562	497
Blank	2	1
WWTP Kerk en Zanen	Sample volume [L] Round 1	Sample volume [L] Round 2
Influent	2	1
Industrial Textile Laundry Facility	Sample volume [L] Round 1	Sample volume [L] Round 2
Wash water prior to rotating drum filter	1	1
After rotating drum filter	1	1
Open-air basin	1	1
Blank	2	2

Small Volume Sampling (SVS)

With SVS, 1 L or 2 L glass bottles were filled with water from the sampling location. A stainless-steel bucket was filled with water and subsequently poured into glass bottles. Bottles were tightly sealed and transported to the laboratory. Samples were refrigerated at 4°C. Samples were processed by following the particle isolation step (see Particle isolation) and then prepared immediately.

Large Volume Sampling (LVS)

With LVS, a large volume of water from the sample location was filtered on-site to isolate solid particles. Here, the particle isolation step (see: Particle isolation) occurred on-site. Water was drawn from the sampling point using a peristaltic liquid pump and subsequently filtered through several sieves with different mesh sizes (see: Particle isolation). Sampling flow rate was set between 2 and 10 L per minute. Volumes ranging between 300 and 600 L were filtered to ensure that sufficient particles would be collected. The effluent from the sampling process was discharged either into the sewer or back into the source downstream of the abstraction point.

Particle isolation

MPs were isolated from water through sieve cascade filtering. Small volume samples were drained through a filter cascade at the laboratory. The LV-samples were filtered on-site over a cascade, after which the cascade was transported to the laboratory. In this campaign, isolation of particles was achieved by using a sieve cascade containing from top to bottom mesh sizes of 5 mm, 1 mm, 250 µm, 125 µm and 50 µm (Retsch®, Serial No: 19111524, ID: 25 cm, stainless steel). After isolation, each sieve was individually back flushed by tap or deionized (DI) water, with use of a funnel (ID: 25 cm, plastic) into 5 glass bottles (50 mL). Each sieve fraction was collected separately into a bottle and stored as a suspension for subsequent pretreatment, resulting in five classes ranging from < 5 mm to < 50 µm. All sieves were cleaned in an ultrasonic bath (Branson 5200, 40 kHz) for 5 min, then covered with aluminium foil and stored for future use.

Analytical method

Sample pre-treatment

Samples were pre-treated according to the procedure described by Bäuerlein et al. [3]. In short, each fraction was further concentrated using a nylon mesh filter (30 µm mesh, D = 2.5 cm). The residues, with MPs and organic matter on the 30 µm sieve, were rinsed off with a minimal amount of pre-filtered MilliQ water into five separate glass beakers (200 mL). To remove organic material, 10 mL aliquots of 30% hydrogen peroxide (H_2O_2, Emprove®, CASnr: 7722–84-1) were added to the samples to destroy organic material. All fractions were then placed on a hot plate and heated to 75 °C. Beakers were covered with a glass plate to prevent evaporation and re-inspected every hour. Aliquots H_2O_2 were added based on the turbidity for a maximum of 24 h. If samples stopped simmering, the heating process was stopped. The fractions were subsequently filtered, and concentrated over 30 µm nylon mesh. The solid residues were rinsed off the nylon mesh filter with pre-filtered MilliQ water towards the final collection step. Finally, the solid residues of each fraction were vacuum filtered over a separate 0.45 µm cellulose nitrate (CN) filter (Sartorius Stedim®, ID: 50 mm) which were held in place by a stainless-steel setup with directly below a depressurized funnel to accelerate the filtration process. The wetted CN filters with captured MPs were moved into plastic petri dishes, sealed with parafilm, and stored at 3 °C until analysis. To prevent mold formation storage was limited to a maximum of 5 days.

Analysis

Microscopic quantitative analysis was performed as described by Bäuerlein et al. [3]. An Olympus stereomicroscope SZX10, magnification 6.3-63x, assisted by a light source (Photonische Optische Geräter, LED LichtquelleF3000) was used. Particles were classified as MP if solid (tested by moving) and not breaking down when applying force by tweezers. Particles from all fractions were counted and categorized based on morphology (particle or fibre) and color. A fibre is characterized by a length-to-diameter ratio ≥ 3:1 in line with Na et al. [25]. If interfering material (e.g., sand, or organic matter) was overabundant, a minimum of 10% of the CN filter was counted and findings were extrapolated to the total filter. In some cases, aliquots of the sample filter were necessary as samples could contain up to 400 manually detected particles in just 6% of the filter. The cases where only an aliquot of the sample was analysed, rather than the entire sample, are shown in SI1.1. For these samples, there is an inherent uncertainty associated with the extrapolation of results to estimate total microplastic loads. Although expertise-based efforts were made to ensure representative subsampling, error due to subsampling could still occur and should be considered when evaluating the reported microplastic counts.

Calculation of the contribution of an industrial textile laundry facility (ITLF) on the overall influx of MPs in a WWTP (WWC 3)

The ITLF collects all wash water in a large basin outside on the premises. The wash water is pumped from this basin discontinuously (average flow 8 $m^3/h = 192\ m^3/d$) into the sewer system and transported to WWTP Kerk en Zanen. To determine the contribution of an ITLF to the incoming flux of MPs at the WWTP, the number of MP fibres and particles was analysed in the basin and multiplied by the flow. This value was divided by the number of MPs (particles and fibres) detected in the influent of WWTP Kerk en Zanen and multiplied by the average flow of the WWTP according to Eq. 1.

$$ContributionITLF[\%] = \frac{Q_{ITLF} \bullet C_{basin}}{Q_{KerkenZanen} \bullet C_{influentKerkenZanen}} \bullet 100\% \quad (1)$$

in which:

Q_{ITLF} = Flow of basin water discharged to sewer (= 8 m^3/h) [m^3/h].

C_{basin} = Concentration of MPs in basin of ITLF [n/m^3].

$Q_{Kerk\ en\ Zanen}$ = Influent flow WWTP Kerk en Zanen [m^3/h].

$C_{influent\ Kerk\ en\ Zanen}$ = Concentration of MPs in influent WWTP Kerk en Zanen [n/m^3].

Table 2 Experimental blanks

Blank	Fibres per sample	Particles per sample	Total
ITLF sampling round 1	268	3	271
Horstermeer sampling round 1	195	9	204
West sampling round 1	191	33	224
ITLF sampling round 2	161	68	229
Horstermeer sampling round 2	138	17	155
West sampling round 2	128	23	151
Average	180	26	206
Standard deviation	51	23	74

Results and Discussion

Method validation (background contamination)

The in-house validated sampling and analytical method, along with its performance characteristics, is presented in the Supplementary Information (S1.2 to S1.8). Minimum reporting limits (MRLs) were 506 fibres per m^3 and 161 particles per m^3 (pump) and 254 fibres per m^3 and 20 particles per m^3 (tap). The spread in results attributable to uncertainty in the analytical method is 13%. If the difference in number of MPs between the two sampling rounds exceeds 13% it is attributed to differences in the samples rather than to uncertainties in the analytical method.

Experimental blanks provide insight into the extent of sample contamination resulting from filling the sample bottles, atmospheric deposition and/or release of MPs during sampling (e.g. bottle caps, jerrycans, etc.). Experimental blanks (tap water collected at the sampling location on the sampling day) were included in both sampling rounds. The results are presented in Table 2.

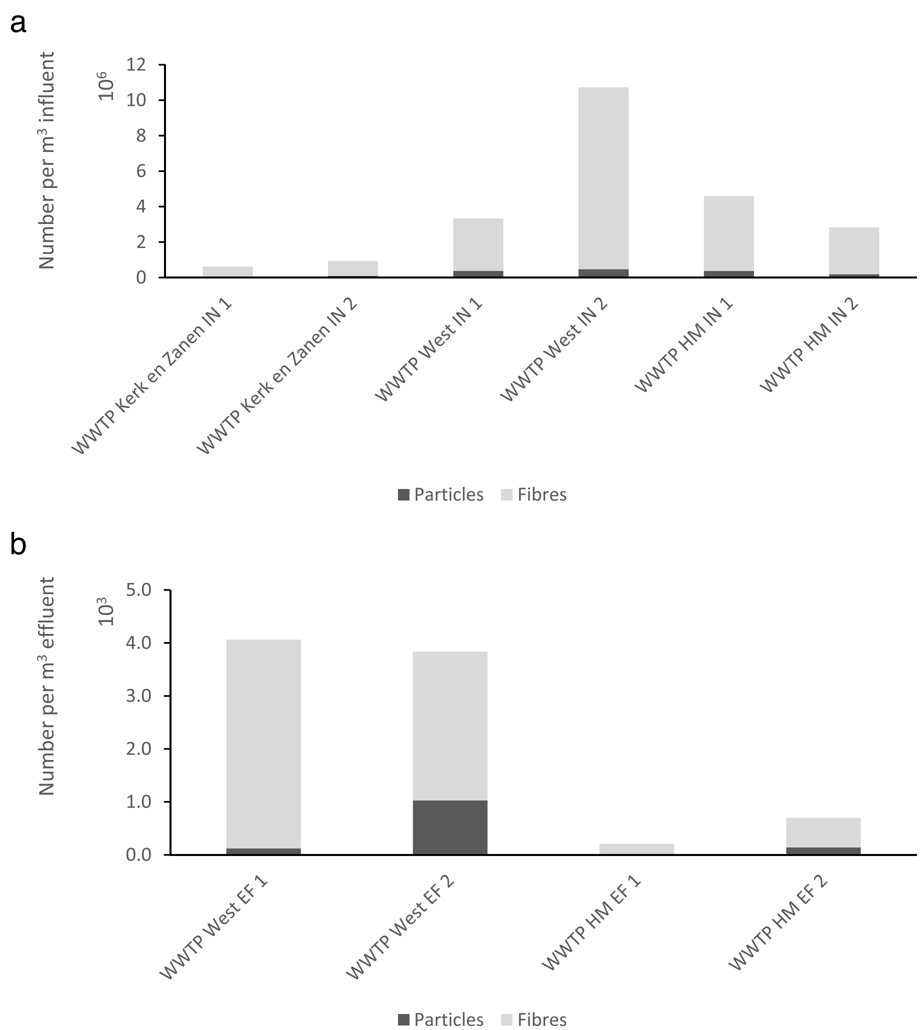

Fig. 4 **A** Number of microplastic particles and fibres per m^3 influent of WWTP Kerk en Zanen, WWTP West and WWTP Horstermeer (HM). **B** Number of microplastic particles and fibres per m^3 effluent of WWTP West and WWTP HM

Table 2 shows that the experimental blanks were close to the MRL (254 fibres per m^3, 20 particles per m^3). This suggests that some contamination may have occurred due to sampling or atmospheric deposition, but this contamination was minor compared to the number of particles and fibres found in the WWTPs and ITLF samples. Additionally, it indicates that contamination in the blanks is more affected by contact with sampling and laboratory materials or air than by the sample volume.

MP particles and fibres in WWTP influent and effluent

Figure 4A demonstrates the total number of MP particles and fibres (all size fractions together) detected in the influent samples of WWC1, WWC2, and WWC3 (in number of particles or fibres per m^3 water). Figure 4B presents the corresponding data for the effluent samples of WWC1 and WWC2.

The influents of WWTP West and Horstermeer contained in the order of 190 $\cdot 10^3$ to 500 $\cdot 10^3$ particles per m^3. Additionally, the influent contained 2.5 $\cdot 10^6$ to 10 $\cdot 10^6$ fibres per m^3. The number of fibres analysed in the influent of WWTP Kerk en Zanen was lower, ranging from 600 $\cdot$ 10^3 to 850 $\cdot$ 10^3 fibres per m^3. These values are in line with other studies that reported MP concentrations in WWTP influent ranging from 1,000 to 18 $\cdot$ 10^6 per m^3 [31], size range: 0.7 µm – 300 µm; [29],size range: 10–500 µm), but higher than reported by [21] (510 $\cdot$ 10^3 – 910 $\cdot$ 10^3 MPs/m^3; size range: 10–5000 µm) and Do et al. [8] (183 $\cdot$ 10^3 – 443 $\cdot$ 10^3, size range: 1.6–5000 µm). This discrepancy could be explained by the larger size investigated in the latter two studies, as well as differences in analytical techniques, weather conditions, geography, or sewage system design.

The number of particles and fibres detected in the influent of Kerk en Zanen is an order of magnitude lower than in the influents of WWTP West and Horstermeer. This could be explained by differences in weather conditions, geographical factors (e.g. discharges from households, industry, and agricultural land), and/or differences in the sewage system (e.g. residence time).

The effluents of WWTP West and Horstermeer contained about < 161–1,000 particles per m^3. Additionally, the effluents of both WWTPs contained approximately <506–4,000 fibres per m^3.

Mintenig et al. (2017) quantified MP concentrations in the effluent of 12 WWTPs in Lower Saxony, Germany. They reported concentrations ranging from 0 to 50 particles per m^3 for MPs larger than 500 µm, and from 10 to 9,000 particles per m^3 for MPs smaller than 500 µm. This discrepancy may be attributed to the lower detection limit (20 µm) used by Mintenig et al. (2017), which likely enabled the detection of a greater number of smaller particles. In a subsequent study, Mintenig et al. [23] reported MP concentrations ranging from 941 to 1,741 particles/m^3 in the effluent of three Dutch WWTPs. The MP levels observed in the effluents of WWTP West and Horstermeer in the current study are of the same order of magnitude as those reported by Mintenig et al. [23].

The average flow at WWTP West was 165,937 m^3/d in 2022. This means that WWTP West discharged between 9.8 and 62.4 billion particles and between 170 and 239 billion fibres per year. The average flow at WWTP Horstermeer was 23,676 m^3/d in 2022, implying that it discharged between <1.4 billion particles and between 4.4–4.8 billion fibres per year.

The number of MP fibres entering the WWTP is much higher than the number of MP particles (Table S4). A similar pattern is observed in the effluents. These results are consistent with findings from other studies Conley et al. [6], Lares et al. [19], which reported that fibres accounted for a significant portion of the total number of MPs in both influent and effluent. Moreover, numerous studies have demonstrated that fibres are the most abundant MP fraction in various environmental compartments (e.g. ice, snow, surface water, sediment, lakes, seas, beaches) [17, 1, 4, 34].

The predominance of microplastic fibres may be partially explained by the broad range of anthropogenic activities that release fibre-shaped MPs. These include: textile laundering, discharge from wastewater treatment plants, the use of synthetic fishing equipment (nets, ropes), landfill leakage, cigarettes, and sanitary products [17, 34]. In addition, fibres are characterized by lower settling velocities in the water phase which may further contribute to their environmental persistence [28]. To gain a better understanding of the relative impact of different sources, future research should focus on quantifying their individual contributions.

Contribution of an industrial textile laundry facility

Table 3 presents the number of MPs particles and fibres analysed in samples from the ITLF and in the influent of WWTP Kerk en Zanen.

The MPs in the wash water of the ITLF, which is collected in the basin, consisted of 85 to > 99.9% fibres and < MRL to 15% particles. This ratio is approximately similar to that of the influent at the receiving WWTP (Kerk en Zanen), which consisted of 90 to 94% fibres and 6 to 10% particles.

Based on the number of particles and fibres detected in the open-air basin (particles: < MRL to $980 \cdot 10^3$ per m^3 and fibres: $5{,}5 \cdot 10^6 – 7{,}8 \cdot 10^6$ per m^3) and the influent of WWTP Kerk en Zanen (particles: $35 \cdot 10^3 – 98 \cdot 10^3$ per m^3 and fibres: $583 \cdot 10^3 – 845 \cdot 10^3$ per m^3), the contribution of the ITLF to the overall incoming flux of MPs can be calculated according to Eq. 1. The average flow at WWTP Kerk en Zanen was 13,382 m^3/d in 2022, and therefore the contribution of the ITLF to the total incoming flux of MPs at WWTP Kerk en Zanen equals 13%.

Table 3 shows that the rotating drum filter effectively removed 75% of the particles and 45% of the fibres during the first measuring campaign. However, during the second campaign, only 31% of the particles were removed, and an increase in the number of fibres was observed. This can be explained by clogging of the filter, which resulted in an untreated stream bypassing the rotating drum filter. Since the rotating drum filters were specifically implemented to protect the heat exchangers from cotton tangles, and not for MPs removal, this result is not surprising. The removal of MPs can therefore be considered an added benefit of the rotating drum filter, which is only effective when the filter is not clogged.

Removal in WWTPs

Both WWTPs are characterized by very high MP particles and fibre removal ($\geq$ 99.8%, Table 3). This is higher than the previously reported average removal of 72% in seven Dutch WWTPs (Leslie et al. 2018). Since the investigated size range was similar, the lower removal percentage is most likely due to differences in WWTP configurations. However, numerous international studies have also reported high removal efficiencies ranging from 89–99%, consistent with the findings of the present study [12, 19, 20, 24, 29, 32, 22, 37].

The removal efficiency of the 1-STEP filter could not be determined due to very low counts of particles and fibres in the influent, which were close to the numbers detected in the blank.

Table 3 MP particles and fibres detected (in number of particles/fibres per m^3 water) for WWC1, WWC2, and WWC3 for sampling round 1 and 2

WWC1 = WWTP West	**Particle distribution (n/m^3)**						**Fibre distribution (n/m^3)**					
Sampling round 1	> 5mm	1—5 mm	250 µm – 1 mm	125 µm – 250 µm	> 50 µm – 125 µm	TOTAL	> 5mm	1—5 mm	250 µm – 1 mm	125 µm – 250 µm	> 50 µm – 125 µm	TOTAL
Influent (IN)	3,000	4,000	156,993	60,771	156,993	381,757	8,500	80,000	1,134,400	379,821	1,347,100	2,949,821
Effluent (EFF)	< MRL[1]	< MRL	113	10	< MRL	< MRL	31	3,329	466	112	0	3,938
Removal (IN – EFF) (%)	100.0	100.0	99.9	> 99.9	100.0	> 99.9	99.6	95.8	> 99.9	> 99.9	100.0	99.9
Sampling round 2	> 5mm	1—5 mm	250 µm – 1 mm	125 µm – 250 µm	> 50 µm – 125 µm	TOTAL	> 5mm	1—5 mm	250 µm – 1 mm	125 µm – 250 µm	> 50 µm – 125 µm	TOTAL
Influent (IN)	7,000	8,000	27,667	256,545	176,375	475,587	69,000	114,000	2,600,667	3,433,182	4,035,875	10,252,724
Effluent (EFF)	7	51	234	233	505	1,030	99	81	184	629	1,816	2,809
Removal (IN – EFF) (%)	99.9	99.4	99.2	99.9	99.7	99.8	99.9	99.9	> 99.9	> 99.9	> 99.9	> 99.9
	Particle distribution (n/m^3)						Fibre distribution (n/m^3)					
WWC2 = WWTP Horstermeer												
Sampling round 1	> 5mm	1—5 mm	250 µm – 1 mm	125 µm – 250 µm	> 50 µm – 125 µm	TOTAL	> 5mm	1—5 mm	250 µm – 1 mm	125 µm – 250 µm	> 50 µm – 125 µm	TOTAL
Influent (IN)	2,500	14,000	202,571	60,771	96,221	376,063	11,500	51,500	1,813,014	941,957	1,392,679	4,210,650
Before 1STEP (B1STEP)	< MRL	13	72	2	< MRL	< MRL	46	26	131	183	143	529
Effluent (EF)	< MRL	2	5	< MRL	< MRL	< MRL	30	14	66	68	23	< MRL
Removal 1STEP (IN – B1STEP) (%)	100.0	99.9	> 99.9	100.0	100.0	> 99.9	99.6	99.9	> 99.9	> 99.9	> 99.9	> 99.9
Removal (IN – EFF) (%)	100.0	> 99.9	> 99.9	100.0	100.0	> 99.9	99.7	> 99.9	> 99.9	> 99.9	> 99.9	> 99.9
Sampling round 2	> 5mm	1—5 mm	250 µm – 1 mm	125 µm – 250 µm	> 50 µm – 125 µm	TOTAL	> 5mm	1—5 mm	250 µm – 1 mm	125 µm – 250 µm	> 50 µm – 125 µm	TOTAL
Influent (IN)	< MRL	24,000	99,600	4,150	62,250	190,000	24,000	39,000	1,983,700	170,150	423,300	2,640,150
Before 1STEP (B1STEP)	18	30	121	101	72	342	72	62	91	211	434	870
Effluent (EF)	8	26	26	22	60	< MRL	76	109	107	99	167	558
Removal 1STEP (IN – B1STEP) (%)	-	99.9	> 99.9	99.5	99.9	99.9	99.7	99.8	> 99.9	99.9	99.9	> 99.9
Removal (IN – EFF) (%)	-	99.9	> 99.9	99.5	99.9	99.9	99.7	99.7	> 99.9	99.9	> 99.9	> 99.9
	Particle distribution (n/m^3)						Fibre distribution (n/m^3)					
WWC3: Industrial Textile Laundry Facility												
Sampling round 1	> 5mm	1—5 mm	250 µm – 1 mm	125 µm – 250 µm	> 50 µm – 125 µm	TOTAL	> 5mm	1—5 mm	250 µm – 1 mm	125 µm – 250 µm	> 50 µm – 125 µm	TOTAL

Table 3 (continued)

WWC1 = WWTP West	**Particle distribution (n/m³)**						**Fibre distribution (n/m³)**					
Prior to rotating drum filter	< MRL	1,000	3,000	< MRL	< MRL	4,000	20,000	19,000	276,000	1,236,496	2,309,314	3,860,810
After rotating drum filter	< MRL	< MRL	< MRL	< MRL	1,000	1,000	< MRL	< MRL	158,000	1,497,408	453,330	2,108,738
Basin	< MRL	< MRL	< MRL	< MRL	< MRL	< MRL	< MRL	< MRL	2,077,915	3,786,060	1,942,660	7,806,635
Sampling round 2	> 5mm	1—5 mm	250 µm – 1 mm	125 µm – 250 µm	> 50 µm – 125 µm	TOTAL	> 5mm	1—5 mm	250 µm – 1 mm	125 µm – 250 µm	> 50 µm – 125 µm	TOTAL
Prior to rotating drum filter	3,000	5,929	42,000	45,273	63,250	159,451	79,000	44,464	446,000	1,037,500	2,130,333	3,737,298
After rotating drum filter	3,000	8,000	16,000	23,000	60,364	110,364	440,000	43,000	348,000	856,000	2,293,818	3,980,818
Basin	18,000	28,000	98,000	105,636	730,400	980,036	109,000	265,000	531,000	1,682,636	2,929,900	5,517,536
	Particle distribution (n/m³)						Fibre distribution (n/m³)					
WWC3: WWTP Kerk en Zanen												
Sampling round 1	> 5mm	1—5 mm	250 µm – 1 mm	125 µm – 250 µm	> 50 µm – 125 µm	TOTAL	> 5mm	1—5 mm	250 µm – 1 mm	125 µm – 250 µm	> 50 µm – 125 µm	TOTAL
Influent	0	0	6,951	7,090	21,270	35,311	5,000	3,500	170,994	`148,890	255,240	583,624
Sampling round 2	> 5mm	1—5 mm	250 µm – 1 mm	125 µm – 250 µm	> 50 µm – 125 µm	TOTAL	> 5mm	1—5 mm	250 µm – 1 mm	125 µm – 250 µm	> 50 µm – 125 µm	TOTAL
Influent	2,000	11,000	48,000	23,000	14,000	98,000	14,000	32,000	296,000	169,000	334,000	845,000

[1] MRL = Minimum Reporting Limit, provided in the SI

Removal of different particle and fibre sizes

Both WWTP West and WWTP Horstermeer showed high and comparable removal efficiencies for all particle and fibre size classes, ranging from 96 to > 99.9%. This is in line with the study by Conley et al. [6], who demonstrated that removal efficiencies for different size fractions (> 418 µm, 178–418 µm, 60–178 µm) varied between 96 to 99% at WWTP Plum Island, 80 to 97% at Rifle Range Road, and 79 to 96% at Center Street (all located in the USA). However, Menéndez-Majón et al. (2022) reported that overall removal of MPs > 500 µm was slightly higher compared to the other size fractions. This aligns with the findings of Talvitie et al. [33], who reported that pre-treatment effectively removed larger size fractions (> 300 µm and 100–300 µm), resulting in a higher abundance of smaller fractions (20–100 µm). Additionally, advanced treatment processes such as membrane bioreactor, rapid sand filter, dissolved air flotation and microsieve filtration with disc filters were effective in removing all investigated size classes (20–100 µm, 100–300 µm and > 300 µm).

Results regarding colour distribution were beyond the scope of this study but are detailed in the Supplementary Information (S3 – Colour distribution of particles and fibres).

Implications for practice

Although the removal efficiency of MP particles and fibres was very high in both WWTPs, the absolute number of MPs released into the environment remains substantial. This high discharge is due to the vast volumes of wastewater treated annually, amounting to millions of cubic metres. To minimise the release of MPs into surface water (or their presence in water recycling processes when reuse is considered), two strategies can be applied: (1) reducing the inflow of MPs into the WWTP (*prevention*), or (2) enhancing MP removal within the WWTP through additional treatment processes (*end-of-pipe treatment*).

For the first strategy, sources of MPs entering the WWTP must be identified and quantified. This study showed that the ITLF contributed substantially (13%) to the total incoming MP load. However, the sources responsible for the remaining 87% remain unclear. Future research should focus on identifying and quantifying these (point) sources, such as other ITLFs, plastic recycling companies, and household laundry water. Contributions from various sources may differ significantly between WWTPs, depending on their design (combined or separate systems), and mitigation measures should be tailored to site-specific conditions. Naturally, prioritising the reduction of major contributors will be more effective than targeting minor ones. A first step in identifying industries that discharge MPs into the sewer system-and subsequently into the WWTP – could involve reviewing permits issued by water authorities. Another source that should be identified and quantified is MPs from household laundry water, particularly in comparison to the MP load from industrial facilities.

Based on the findings of this study, the first strategy (*prevention*) appears more viable than the second *(end-of-pipe treatment).* Improving WWTP performance by implementing additional treatment processes would require significant investments and operational costs, while the potential increase in removal efficiency is expected to be marginal (≤ 0.2%) given the already high levels of removal. Additionally, MP removal in WWTPs typically results in their accumulation in sludge [14, 16, 40], a challenge that persists under strategy 2. In contrast, strategy 1 would also reduce the amount of MPs ending up in sludge. Advanced treatment technologies such as nanofiltration or reverse osmosis can effectively remove MPs and produce water of very high quality-nearly reaching potable standards. However, these methods are only cost-effective when the treated water is reused for drinking purposes, rather than being discharged into surface water, as is currently the case in the Netherlands.

Although this study clearly demonstrates that an ITLF can contribute substantially to the MP load entering a WWTP, sampling was limited. The method proved adequate for samples from a laundry facility, but future research should include a more extensive sampling campaign over a longer period, incorporating seasonal variations. This is important, as results from sampling rounds 1 and 2 showed large differences at some sampling points (Table 3, especially for particle sampling in the ITLF basin).

Conclusions

This study investigated the behaviour of MPs along an entire chain: from an industrial textile laundry facility, through removal in the WWTP, to the eventual discharge of MPs that were not removed into surface water.

The number of MP particles in the influent of the three WWTPs varied from $35 \cdot 10^3$ to $476 \cdot 10^3$ per m^3, while fibres ranged from $584 \cdot 10^3$ to $10.3 \cdot 10^6$ per m^3. The number of particles in the effluent of WWTP West and Horstermeer ranged from <161 to 1,000 per m^3, and fibres ranged from <506 to 4,000 per m^3. Fibres made up the predominant fraction of MPs both entering and exiting the WWTPs, compared to particles.

The number of particles and fibres detected in the influent of WWTP Kerk en Zanen was an order of magnitude lower than in the influent of WWTP West and Horstermeer. This difference could be explained by varying weather conditions, geographical factors (e.g. differences in discharges from households/industry and agricultural land), and/or differences in the sewage system (e.g. residence time).

An ITLF in the Netherlands contributed 13% of the total MP load entering a WWTP. This underpins the importance of mitigating MP discharges at single point sources rather than implementing additional treatment processes in WWTPs. Both WWTP West and Horstermeer demonstrated very high removal efficiencies for MP particles and fibres (≥ 99.8%). They also showed high removal efficiencies across all particle and fibre size classes (50 µm – 125 µm, 125 µm – 250 µm, 250 µm – 1 mm, 1—5 mm and > 5 mm), varying between 96 and > 99.9%.

Despite this effective removal, significant quantities of MPs are still discharged into surface water. WWTP West discharged 9.8–62.4 billion particles and 170–239 billion fibres per year. WWTP Horstermeer discharged <1.4 billion particles and 4.4–4.8 billion fibres per year.

Supplementary Information

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Supplementary Material 1.

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Data availability
No datasets were generated or analysed during the current study.

Declarations

Competing interests
The authors declare no competing interests.

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