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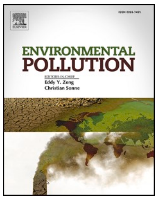

Release of microplastic fibers from synthetic textiles during household washing☆

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ABSTRACT

Textile materials are one of the primary sources of microplastic pollution. The washing procedure is by far the most significant way that textile products release microplastic fibers (MPFs). Therefore, in this study, the effects of various textile raw materials (A acrylic, PA polyamide, PET polyester, RPET recycled polyester and PP polypropylene), fabric construction properties (woven, knitted), thickness and basis weight values on MPFs release at different washing stages (pre-washing, soaping/rinsing) were examined separately. To mimic the most popular home washing procedures, a 10-min pre-wash and a 35-min soaping/rinsing phase at 40 °C were selected for the washing procedure. Utilizing the Image J program on macroscopic images captured by a high-resolution SL. R camera, the microfibers collected by filtering the water have been visually counted. According to the results, knitted fabrics released fewer MPFs than woven fabrics, with the woven acrylic sample (A3-w) exhibiting the highest release (2405 MPFs). The number of MPFs increased along with the thickness and weight of the fabric. Recycled polyester was found to release more MPFs than virgin polyester under the same conditions (1193 MPFs vs. 908 MPFs). This study demonstrates how recycled polyester, although initially an environmentally beneficial solution, can eventually become detrimental to the environment. Furthermore, it is known that the pre-washing procedure—which is optional—releases a lot more MPFs than the soaping and rinsing procedures, and that stopping this procedure will drastically lower the amount of MPFs incorporated into the water.

1. Introduction

The actual overall clothing system creates negative impacts on resources, environment, and society (McNeill & Moore, 2015). Textiles production is a significant source of microplastic fibers (MPFs) (Zhou et al., 2020; Deng et al., 2020; Lim et al., 2022; Palacios-Mateo et al., 2021), the most common form of microplastics (Deng et al., 2020; Mishra et al., 2020; Geyer et al., 2022). MPFs are released from textiles not only during their use in air (Gasperi et al., 2018; Almroth et al., 2018) but also in water due to household washing (Ellen MacArthur Foundation, 2017; (European Environment Agency, 2022)European Environment Agency, 2022; Napper & Thompson, 2016; Gaylarde et al., 2021) and tumble drying (Pirc et al., 2016; O'Brien et al., 2020; Kärkkäinen & Sillanpää, 2021). Microplastics have been linked to potential negative impacts on the aquatic life (Yuan et al., 2022; Nguyen et al., 2019), can be vectors for other pollutants (Gaylarde et al., 2021; Singh et al., 2020; Alimi et al., 2017) and enter the food chain (Gaylarde et al., 2021; Zhang et al., 2020; Periyasamy & Tehrani-Bagha, 2022).

Adopting materials and manufacturing procedures that prevent microfiber shedding (Ellen MacArthur Foundation, 2017; European Environment Agency, 2022; Rathinamoorthy & Balasaraswathi Subramanian, 2020; Liu et al., 2021) will be crucial to reduce the environmental impacts of fashion industry. Synthetic fibers are main sources of primary MPFs released in the oceans (Mishra et al., 2020; IUCN, 2017; De Falco et al., 2019; Suaria et al., 2020; Acharya et al., 2021), and there is urgent need to explore what happens during their

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washing (Salvador Cesa et al., 2017). Previous literature investigated household washing, recording from 6,000,000 (Palacios-Mateo et al., 2021) up to 18, 000, 000 MPFs (Galvão et al., 2020; De Falco et al., 2017) emitted from a 5–6 kg laundry load. The release of microplastic fibers (MPFs) is intricately linked to various factors within the textile life cycle. Textile production and finishing processes play a crucial role in the generation of MPFs (Palacios-Mateo et al., 2021; De Falco et al., 2017; De Falco et al., 2019), on the specific structure of the yarns (Salvador Cesa et al., 2017; Jönsson et al., 2018), the manner in which these yarns are transformed, either through machine knitting or weaving into fabrics, significantly influences MPF release and the age of the textiles is a contributing factor (Carney Almroth et al., 2018; Zambrano et al., 2019). The amount of MPFs released during washing may be lower from tight structures (Yang et al., 2019; Rathinamoorthy and Balasaraswathi Subramanian, 2023; Rathinamoorthy & Balasaraswathi Subramanian, 2023), and from twisted yarns with long fibers (Palacios-Mateo et al., 2021), compared to yarns/fabrics made of short fibers (De Falco et al., 2017). Friction applied to clothes is the main factor (Lim et al., 2022), thus textiles' features as high abrasion resistance (Rathinamoorthy and Balasaraswathi Subramanian, 2023; Rathinamoorthy & Balasaraswathi Subramanian, 2023), low hairiness, and high yarn breaking strength (Yang et al., 2019) reduce MPFs loss during washing, as do softeners (Palacios-Mateo et al., 2021; Zambrano et al., 2019). Hand washing, compared to machine washing, seems to produce less MPFs (Wang et al., 2023). The effect of the type of synthetic fibers has been previously explored. Literature extensively studied polyester (Carney Almroth et al., 2018; Napper & Thompson, 2016; Pirc et al., 2016; O'Brien et al., 2020; De Falco et al., 2017; De Falco et al., 2019a,b; Zambrano et al., 2019; Rathinamoorthy and Balasaraswathi Subramanian, 2023; Rathinamoorthy & Balasaraswathi Subramanian, 2023; Hernandez et al., 2017; Özkan & Gündoğdu, 2020; Vassilenko et al., 2017; Mondal et al., 2022) and polyamide (nylon) (Carney Almroth et al., 2018; De Falco et al., 2017; De Falco et al., 2018; De Falco et al., 2019a,b; Vassilenko et al., 2017; Mondal et al., 2022), the most common synthetic fibers adopted by textile industry (Schöpel & Stamminger, 2019). Few studies involved acetate (Yang et al., 2019), acrylic (Carney Almroth et al., 2018), polypropylene (Palacios-Mateo et al., 2021) and rayon (Zambrano et al., 2019). In overall, literature exploring MPFs release from synthetic fibers during washing provides results that are not often comparable (Salvador Cesa et al., 2017; Galvão et al., 2020) as not obtained in standard conditions, or controversial about the influence of specific features of the washing cycle (load, duration, temperature, detergent, etc.) (Lim et al., 2022; Napper & Thompson, 2016; Pirc et al., 2016; Periyasamy &Tehrani-Bagha, 2022; De Falco et al., 2017; Jönsson et al., 2018; Yang et al., 2019; Wang et al., 2023; Vassilenko et al., 2017; Belzagui et al., 2019). Many studies observed higher release of MPFs in the first phases of the washing cycle (Lim et al., 2022; Napper & Thompson, 2016; Pirc et al., 2016; Periyasamy &Tehrani-Bagha, 2022; De Falco et al., 2019) especially from brushed/bleached (Periyasamy &Tehrani-Bagha, 2022) and aged fabrics (Carney Almroth et al., 2018; Hernandez et al., 2017; Hartline et al., 2016), and using larger volumes of water (Kelly et al., 2019; Lant et al., 2020). Literature results don't agree about the effect of temperature, which enhanced MPFs emissions (Yang et al., 2019; Cotton et al., 2019) or not (Lim et al., 2022; Wang et al., 2023). Also, using a detergent increased MPFs release (O'Brien et al., 2020; Zambrano et al., 2019; Wang et al., 2023) or decreased it (Hernandez et al., 2017), or had no influence (Pirc et al., 2016); the type (powder or liquid) was significant (Xu et al., 2021), while detergent's chemical composition prevailed on the type (Periyasamy &Tehrani-Bagha, 2022) or showed no influence (O'Brien et al., 2020). In the studies conducted, it has been observed that the lengths of microfibers released from textiles are approximately between 100 and 850 μm (Hernandez et al., 2017; Cai et al., 2020). Notably, it is challenging to precisely measure the geometrical dimensions of MPFs below approximately 4 μm using current analytical methods (Xiao et al., 2023). Moreover, literature usually provides results deriving from single replicates of the experiments (Pirc et al., 2016; Salvador Cesa et al., 2017; (Ellen MacArthur Foundation, 2017) Ellen MacArthur Foundation, 2017; Palacios-Mateo et al., 2021; Gaylarde et al., 2021; Volgare et al., 2021; Vassilenko et al., 2021; European Environment Agency, 2022; Rathinamoorthy & Balasaraswathi Subramanian, 2023). Several studies have investigated the connection between the age of garments and the release of microfibers, yielding conflicting results. Some research (Napper and Thompson, 2016; Pirc et al., 2016; Sillanpää and Sainio, 2017; Athey et al., 2020; Cesa et al., 2020) indicates that both new synthetic and natural garments release more microfibers compared to their older counterparts. On the contrary, Hernandez et al. (2017) found no significant influence of garment age on microfiber release. Hartline et al. (2016) reported a contradictory outcome, challenging previous findings that suggested higher mass release from mechanically aged garments using the same washing protocol as new ones. Notably, garments subjected to a 24-h continuous wash showed increased mass release under the same washing conditions as new garments (Hartline et al., 2016). The study by Galvão et al. (2020) conducted research on worn clothes in a real-life environment and found significantly higher numbers of microplastic fibers (MPF) compared to previous studies with new clothes. Another factor considered in microfiber release during laundering is the age of the clothing. Following the first wash, the quantity of microfibers released from laundry reaches a plateau (Zambrano et al., 2019; De Falco et al., 2019a, b; Carney Almroth et al., 2018; Napper & Thompson, 2016; Kelly et al., 2019).

The main knowledge gap of state-of-the-art literature is that there aren't studies comparing in the same washing conditions the behavior of multiple synthetic fibers, also accounting different structural features. Compared to existing literature, this study has the following aims and elements of novelty: 1. Analysis of MPFs release from samples of new pure synthetic fibers (acrylic, polyamide, polyester, recycled polyester, and polypropylene) in a single washing cycle simulating household laundry (pre-washing and soaping&rinsing evaluated singularly) carried out in standard conditions (EN/ISO 105-C06:2010/A1M). 2. Analysis of the behavior of 10 fabric samples having different structures (4 knitted and 6 woven), thickness and basis weight, including 5 samples of polyester (4 virgin and 1 recycled), as well as polyamide, and also fibers less explored by literature, as acrylic (3 samples) and polypropylene.

2. Materials and methods

2.1. Methodology

The methodology applied in this study was based on 4 consequent phases (Fig. 1): characterization of the fabric samples, washing tests, MPFs collection and counting, and data analysis.

2.2. Materials

10 fabric samples obtained directly from various companies were included in this study. Following the cutting of the fabrics into standard 160 × 200 mm pieces, the edges of fabrics were intentionally burned to prevent microfibers from escaping the cut areas. These samples were made of different synthetic fibers such as acrylic, polyamide, polyester, recycled polyester, and polypropylene, and they exhibited various constructional parameters and colors, as detailed in Table 1. In details, 4 samples of polyester (PET, 2 knitted and 2 woven), 1 sample of recycled polyester (RPET, woven), 3 samples of acrylic (A, 2 knitted and 1 woven), 1 samples of polyamide (PA, woven) and 1 sample of polypropylene (PP, woven). The fabric structure types of the considered samples were jersey (A1-k, A2-k), interlock (PET1-k), ribana (PET2-k), and plain (PET3-w, RPET-w, PA-w, A3-w, PET4-w, PP-w). While woven fabrics (A3-w, PES3-w, PES4-w, RPET-w, PA-w, PP-w) are structures formed by two different yarn systems interlacing each other at 90° directions (Gowayed, 2013), knitted fabrics (A1-k, A2-k, PES1-k, PES2-k)

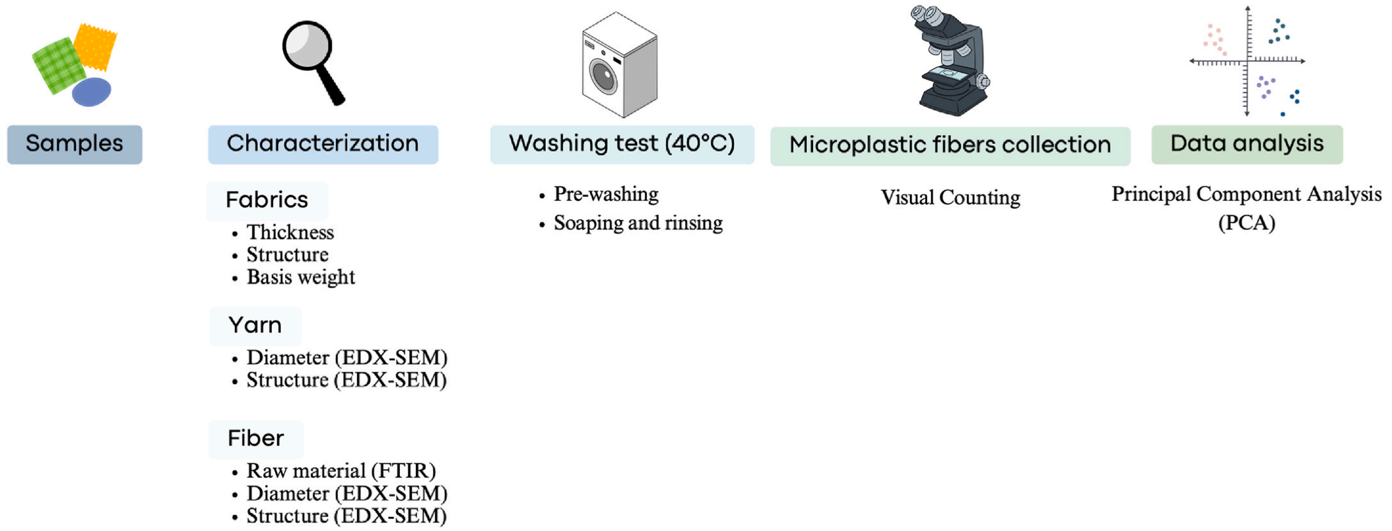


Fig. 1. Outline of the applied methodology.

are structures in which the fabric is produced by creating loops with a single yarn system (Fangueiro & Soutinho, 2011).

2.3. Physical characterization

The samples' images were obtained with a high-resolution SL. R camera (Sony ILCE-7RM3 v 1.01). The characterization was as follows (Appendix, Figs. S1 and S2): (i) about the fabrics, the raw materials were identified through microscopy coupled with Fourier-transform infrared spectroscopy (micro-FTIR) (Shimadzu, AIM-9000). Thickness, expressed in mm, was measured using a digital thickness gage (Mitutoyo 0.01–150 mm); basis weight, expressed in g/m^2, was calculated by dividing the fabric weight by the area of the fabric through an analytical balance (KERN ABJ220-4NM); (ii) about the yarn, diameter and structure were analyzed through energy dispersive X-ray scanning electron microscopy (EDX/SEM) (FEI Inspect S).

2.4. Standardized washing tests

The washing tests were carried out according to EN/ISO 105-C06:2010/A1M standard though a micro-Deval apparatus (4.40 L volume), instead of in a Launder-Ometer (0.55 L volume) as requested by the standard, adapting the washing conditions (Appendix, Table S1). The washing cycle was performed on 160 × 200 mm fabric samples (weight was between 2.4 and 13.76 g depending on the basis weight) at 40 °C involving two phases, e.g., 10 min pre-washing and 35 min soaping&rinsing. Liquid detergent (Marseille soap) was used in the soaping&rinsing phase. 40 °C temperature, less than 1 h duration, and liquid detergent are the conditions recommended by literature for sustainable household laundry (Dewaele et al., 2006; Eberle et al., 2007; Schages et al., 2020; Tomšič et al., 2023). The wastewater (1.2 L) was collected separately after each phase.

2.5. Collection and analysis of microplastic fibers

The wastewater samples have been vacuum filtered on 0.7 μm pore-size glass fiber filters (Whatman, Ø 47 mm), then dried at 40 °C for 12 h. MPFs have been identified as fibers having diameter below 50 μm, length in the range 1 μm–5 mm and length-to-diameter ratio above 3 ((Carney Almroth et al., 2018)Almroth et al., 2018; Salvador Cesa et al., 2017; Zambrano et al., 2019; Hernandez et al., 2017; Liu et al., 2019). The details on the pre-treatment of the filters and on MPFs' counting are in the Appendix (Figs. S3 and S4). MPFs collected from light-coloured samples A1-k, PET2-k, PET3-w, PA-w were dyed with few drops of Nile red (72,485-100 MG Sigma Aldrich, 1000 μg/mL in acetone) (Shruti et al., 2021; Maes et al., 2017) and dried for 2 h. MPFs have been visually counted (Ivleva, 2021) through ImageJ software applied to macroscopic images obtained with a high-resolution SL. R camera (Sony ILCE-7RM3 v 1.01) under normal and UV light.

To prevent contamination, all the experimental work was done while wearing nitrile gloves and cotton lab coats. A glass beaker was used to collect wastewater. Running an empty washing cycle at 40 °C for 30 min following the conclusion of each washing test helped to reduce cross-contamination of microfibers between washes. For every washing cycle, distilled water was utilized to avoid contamination. During the washing sequence, samples of different colors were selected consecutively to prevent mixing samples of the same color and to avoid affecting subsequent washes. Only the counting, insertion into the filter holder, separation from the filter holder, and storage in a Petri dish exposed the filter to potential air contamination during the filtering process.

2.6. Data analysis

The performances of the washing tests have been assessed through the following metrics: total MPFs released (Number of fibers), release of MPFs per weight of fabric (MPFs/g), release of MPFs per weight of fabric and minute of washing (MPFs/g.min) to account the different samples, and release of MPFs pre-washing and soaping&rinsing to account the different phases of washing cycle. The experimental results have been statistically analyzed to identify potential correlations by applying Pearson's bivariate correlation test on Excel (Microsoft Office) and Principal Component Analysis (PCA) via MATLAB PCA toolbox.

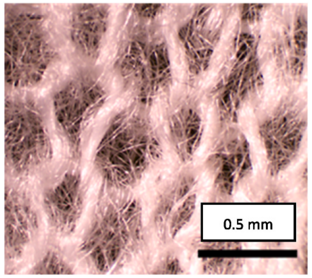
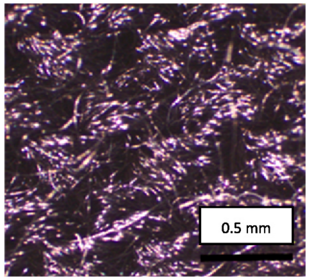
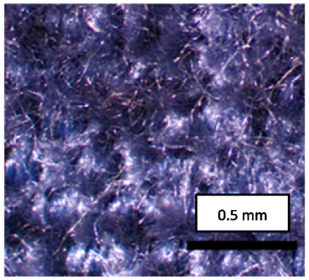
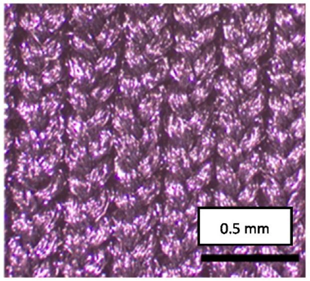
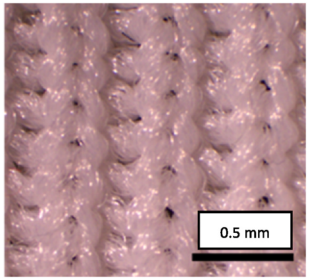
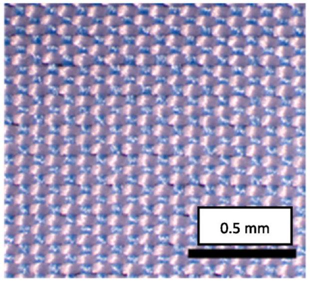
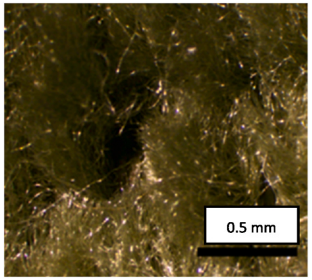
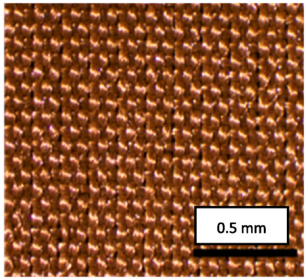
3. Results and discussion

3.1. Physical characterization of the samples

The thickness and the basis weight values of the samples (Fig. 2) ranged between 0.05 and 0.8 mm and 75–430 g/m^2, respectively.

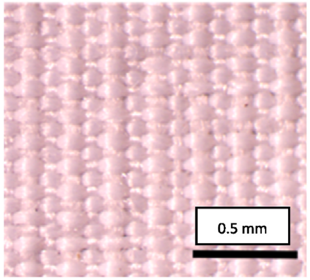
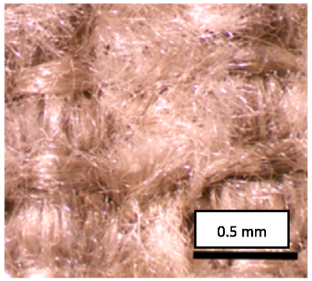
Micro-FTIR analysis results showed that each fabric composed of 100% pure polymers (Appendix, Fig. S1). The results of SEM/IMAGE J analyses (Table 2) indicated that the fibers' diameter ranged 10–20 μm for knitted fabrics and 10–22.5 μm for woven fabrics, independently of thickness and basis weight. Fiber and yarn diameters were measured from 10 different regions and the average values were given with their standard deviations.

Table 1
List and main features of the fabric samples.

		Fabric type			
		Knitted (k)		Woven (w)	
Synthetic fiber	Acrylic (A)	 0.5 mm Sample ID: A1-k Fabric structure: Jersey	 0.5 mm Sample ID: A2-K Fabric structure: Jersey	 0.5 mm Sample ID: A3-w Fabric structure: Plain	
	Polyester (PET)	 0.5 mm Sample ID: PET1-k Fabric structure: Interlock	 0.5 mm Sample ID: PET2-k Fabric structure: Ribana	 0.5 mm Sample ID: PET3-w Fabric structure: Plain	 0.5 mm Sample ID: PET4-w Fabric structure: Plain
	Recycled polyester (RPET)			 0.5 mm Sample ID: RPET-w Fabric structure: Plain	

(*continued on next page*)

Table 1 (*continued*)

	Fabric type	
	Knitted (k)	Woven (w)
Polyamide (PA)		 0.5 mm Sample ID: PA-w Fabric structure: Plain
Polypropylene (PP)		 0.5 mm Sample ID: PP-w Fabric structure: Plain

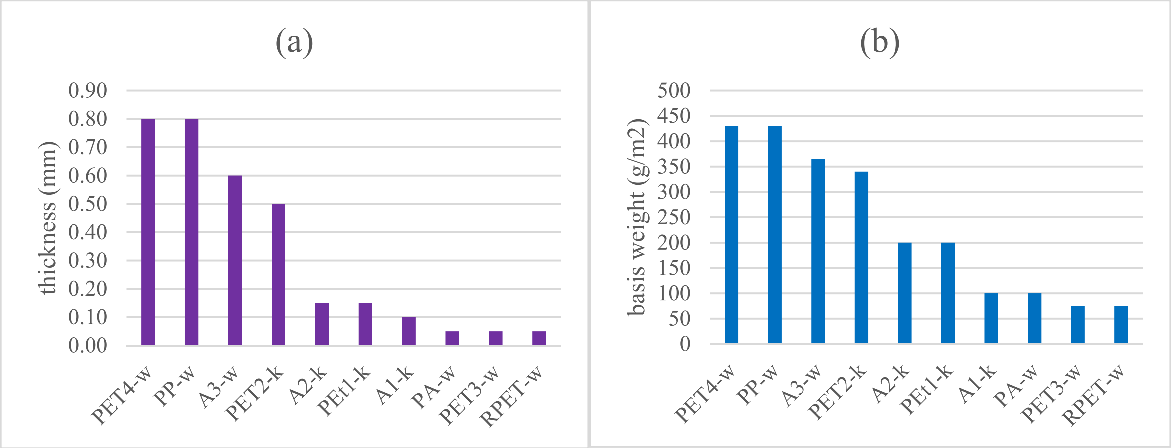


Fig. 2. Results of the physical characterization of the samples: (a) thickness and (b) basis weight of the fabrics.

Table 2
Average fiber and yarn diameter values of samples.

ID	Fiber diameter (μm)	Yarn diameter (mm)
A1-K	20.0 ± 0.67	0.50 ± 0.04
A2-K	20.0 ± 1.96	1.00 ± 0.22
A3-W	10.0 ± 1.33	2.50 ± 0.12
PA-W	15.0 ± 2.16	0.25 ± 0.70
PET1-K	10.0 ± 0.69	0.35 ± 0.93
PET2-K	20.0 ± 1.16	1.50 ± 0.18
PET3-W	10.0 ± 0.24	0.13 ± 0.98
PET4-W	15.0 ± 0.54	5.00 ± 0.17
PP-W	22.5 ± 1.12	3.00 ± 0.57
RPET-W	10.0 ± 0.29	0.13 ± 0.87

3.2. *Washing tests*

In Table 3, the total number of MPFs released from the pre-washing and soaping&rinsing stages is presented, along with the release of MPFs per weight of fabric (MPFs/g) and per weight of fabric and minute of washing (MPFs/g.min) to accommodate the various samples. Pearson correlation tests had been performed to measure linear correlation among the data sets. The release of MPFs per weight of fabric and minute (MPFs/g min^{-1}) during pre-washing is higher than during soaping and rinsing for all the samples, see Table 3. However, strong positive correlations are present between the following metrics: release of MPFs (MPFs/min) during pre-washing and during soaping and rinsing (Pearson correlation coefficient = 90.0%), release of MPFs per weight of fabric (MPFs/g) during pre-washing and during soaping and rinsing (Pearson correlation coefficient = 86.8%) and release of MPFs per weight of fabric and minute of washing (MPFs/g.min^{-1}) during pre-washing and during soaping and rinsing (Pearson correlation coefficient = 95.1%). These results indicate that the samples with the highest release of MPFs during the first stage of pre-washing, displayed the highest release of MPFs during soaping and rinsing. Therefore, the specific characteristics of the fabrics significantly determine the behavior of the fabric samples during washing.

3.2.1. *The influence of raw material*

Samples A3-w, PET4-w, and PP-w have plain weave structures and have the same or similar thickness and basis weight values. Therefore, when these three samples are evaluated, it is noteworthy that although A3-w has lower thickness (0.60 mm) and basis weight (365 g/m^2) values, it releases more MPFs both in pre-washing (1119) and soaping and rinsing (1286) stages compared to the other two samples (PP-w 698, 1063; PET-w 585, 890). In a study conducted by Napper and Thompson (2016), it was estimated that 23 MF/g were released from polyester-cotton blend fabric, 83 MF/g from polyester fabric and 122 MF/g microfibers from acrylic fabric. Therefore, it was concluded that polyester and acrylic fabrics, which are frequently preferred in the clothing industry based on their low cost and durability, may cause less

Table 3
Results of the washing tests: MPFs released during pre-washing and soaping&rinsing, and total specific release of MPFs per weight unit (MPFs/g) and per weight of fabric and minute of washing (MPFs/g min^{-1}).

ID	pre-washing (MPFs)	pre-washing (MPFs/g)	pre-washing (MPFs/g min^{-1})	soaping& rinsing (MPFs)	soaping &rinsing (MPFs/g)	soaping &rinsing [MPFs/(g min^{-1})]	total MPFs released	Total MPFs/g	pre-washing (MPFs/g min^{-1})	soaping &rinsing [MPFs/(g min^{-1})]	Total [MPFs/(g min^{-1})]
PET4-w	585	42.51	4.25	890	64.68	1.85	1475	107	4,25	1,85	2,38
PP-w	698	50.73	5.07	1063	77.25	2.21	1761	128	5	2	2,84
A3-w	1119	95.80	9.58	1286	110.10	3.15	2405	206	10	3	4,58
PET2-k	191	17.56	1.76	417	38.33	1.10	608	56	2	1	1,24
A2-k	714	111.56	11.16	741	115.78	3.31	1455	227	11	3	5,05
PET1-k	407	63.59	6.36	565	88.28	2.52	972	152	6	3	3,38
A1-k	160	50.00	5.00	308	96.25	2.75	468	146	5	3	3,25
PA-w	551	172.19	17.22	508	158.75	4.54	1059	331	17	5	7,35
PET3-w	365	152.08	15.21	543	226.25	6.46	908	378	15	6	8,41
RPET-w	416	173.33	17.33	777	323.75	9.25	1193	497	17	9	11,05

microfiber release if used in a blend with natural fibers (Napper and Thompson, 2016). When comparing PET1-k and A2-k samples in knitted fabric structure with the same basis weight (200 g/m^2) and thickness (0.15 mm) values, it was observed that the A2-k sample with acrylic raw material (416 and 777 MPFs) released more microfibers than the PET1-k sample with polyester raw material (365 and 543 MPFs) in both prewashing and soaping&rinsing, respectively. When the results obtained from samples with both woven and knitted structures are evaluated, it is obvious that samples containing acrylic release more fibers, regardless of the structure of the fabrics. It is possible to come across studies in the literature stating that acrylic fiber is the fiber with the highest fiber release among synthetic fibers (Raja Balasaraswathi & Rathinamoorthy, 2021).

When PET3-W and RPET-W samples, both of which have a plain weave structure and have exactly the same thickness (0.05 mm) and basis weight (75 g/m^2) values, are compared, it has been observed that the recycled polyester sample releases more microfibers than virgin polyester sample, regardless of the washing stages. During the recycling process, polyester fiber is subjected to heat and shear degradation, which reduces the average molecular weight, the length of the molecular chains, and the crystallinity, hence a decrease in the strength of recycled polyester. This reduction in mechanical properties is the reason why recycled polyester releases more microfibers compared to virgin polyester (Julienne et al., 2019; Özkan & Gündoğdu, 2020). Recycled polyester recently gained increasing attention from consumers (and textile companies) as “environmentally friendly” alternative to virgin polyester. However, recycled polyester should be carefully compared with the virgin fiber about MPFs’ release across the whole life cycle. Future research should explore specific finishing treatments, already under investigation for polyamide (De Falco et al., 2018; De Falco et al., 2019a,b) and the release during use (in air and in household washing and tumble drying), as well as the role of detergents and softeners. Microfibers are released into the environment at various phases in the lifecycle of textiles, such as during manufacturing, processing, use, and disposal. Production is responsible for the largest portion (49%) of microfiber release during these stages, while laundering contributes 28% and usage contributes 23% (Salvador Cesa et al., 2017; Lim et al., 2022).

3.2.2. *Influence of fiber and yarn properties*

The results of SEM/IMAGE J analyses (Table 2) indicated that the fibers’ diameter ranged 10–20 μm for knitted fabrics and 10–23 μm for woven fabrics, independently of thickness and basis weight of the fabrics. PET samples were composed of the finest fibers (diameter was about 10 μm for 3 samples out of 5), while other samples showed fiber diameters between 10 and 22.5 μm. Considering the yarn structure, the samples can be categorized in two groups: one having yarn diameter below 0.5 mm (PET1-k, PET3-w, RPET-w, PA-w, A1-k) and another above 1 mm (PET2-k, PET4-w, PP-w, A2-k, A3-w). The largest yarn diameters (>2 mm) belonged to PP-w, PET4-w, and A3-w, also characterized by the chenille yarn structure.

The relationship between yarn diameter/yarn count and microfiber release was related to the number of fibers in the cross-sectional area of the yarn. It is interpreted that as the yarn count or yarn diameter increases, microfiber release will also increase, as it is thought to contain more fibers with the same diameter (Belzagui & Gutiérrez-Bouzán, 2022; Çeven & Özdemir, 2006). Although a clear comparison cannot be made within the scope of the study since the fiber and fabric parameters are variable, it can be stated that for all samples except the PET2-k sample, samples with a yarn diameter greater than 1 mm cause more total MPFs release (in a range of 1455–2405 except PET2-k (608)) than samples with a yarn diameter less than 0.5 mm (in a range of 468–1193). On the other hand, it is known that the yarn type also affects the yarn count, independent of the number of fibers in the yarn cross-section. It is seen that especially the samples with a yarn diameter over 2 mm consist of chenille yarns with a hairier structure. Chenille fabric is characterized by a pile that protrudes all around at right angles, giving it a plush and velvety look. This pile is created by the way the chenille yarn is constructed. The yarn consists of a core wrapped with short lengths of thread or yarn, which are then twisted together to form the fuzzy surface. This construction method gives chenille fabric its characteristic softness and texture (Çeven and Özdemir, 2006). This hairy structure is also the reason for the increase in yarn diameter, and these yarns are suitable for releasing high amounts of microfibers due to their structure.

3.2.3. *Influence of fabric properties*

The effect of fabric properties on microfiber release was examined under two separate headings: physical properties of the fabric such as thickness/basis weight and structural properties of the fabric depending on the production technology such as knitted and woven.

In order to examine the effect of basis weight/thickness on the MPFs release, A1-k and A2-k samples were compared since they are composed of both knitted fabrics and acrylic fibers. The results showed that a 50% increase in fabric thickness and a reduplication in basis weight led to a 210% increase (from 468 to 1455) in total MPFs’ release which corresponds to 55% increase in MPF/g. The result that fabrics with higher basis weight release more microfibers was also declared by Periyasamy (2021).

On the other hand, it has not been possible to specifically examine the effect of knitted and woven fabric structures because it is very difficult to obtain samples in which the basis weight/thickness, yarn and fiber properties and raw materials are exactly the same in different fabric structures. However, the most meaningful comparison can be made in PET2-k and PET4-w samples, which have the closest thickness (0.50 vs. 0.80 mm) and basis weight (340 vs. 430 g/m^2) values. The results revealed that the PET2-k sample released significantly less MPFs than the PET4-w sample in both prewashing (191 vs. 585) and soaping&rinsing (417 vs. 890). This is consistent with literature, which reports less MPFs shed by knitted fabrics, compared to woven, due to higher flexibility and lower surface rupture during friction (Periyasamy & Tehrani-Bagha, 2022) and lower number of fibers per square meter ((Carney Almroth et al., 2018)Almroth et al., 2017).

3.2.4. *Influence of washing cycle phase*

Within the scope of the study, two different washing phases were tested. One of these is the 10-min pre-washing phase, and the other is the 35-min soaping and rinsing phase. In order to compare these two stages in the best possible way without being affected by other variables, the unit “MPFs/g min^{-1}″ was accounted. The results proved that for all samples (Table 3), the MPFs released in pre-washing from the unit sample weight and unit time is much higher (in a range of 2–17) than the MPFs released in soaping and rinsing (in a range of 1–9) consistent with other studies (Lim et al., 2022; Napper and Thompson, 2016; Pirc et al., 2016; Periyasamy & Tehrani-Bagha, 2022; De Falco et al., 2019a,b) reported that most MPFs are shed in the first phases of the washing cycle.

4. Conclusions

Within the scope of the study, both raw material variables and fabric construction properties were varied, and the effects of these parameters on MPFs release were examined. On the other hand, pre-washing and soaping/rinsing stages were studied separately in order to examine the effect of the washing cycle on MPFs release. The highlighted findings are as follows.

- When evaluated on the basis of the raw material used, it was concluded that the least microfiber release was observed in the samples containing polyester, and the maximum release was observed in the sample containing A3-w coded acrylic sample. Moreover, recycled polyester has been shown to release more MPFs than virgin polyester. This can be explained by the fact that recycled polyester, which is exposed to thermo-mechanical effects during washing, exhibits lower strength compared to virgin polyester as a result of shortening polymer chains. Although recycling of polymers is seen as an environmentalist point of view, the reduced mechanical strength with the recycling process should be taken into account and attention should be paid to the extra MPFs pollution that it may cause.

- Considering the fabric parameters, it was observed that knitted fabrics caused less MPFs release compared to woven fabrics. This is thought to be due to the low friction among yarns in knitted fabrics, which have a more flexible structure compared to woven fabric. In addition, it was concluded that the increase in fabric thickness and weight in the compared samples also increased the MPFs release.
- Finally, pre-washing in washing machines releases almost as much microplastic as soaping and rinsing. Thus, eliminating pre-washing may reduce the amount of microplastics released by residential washing machines.

The main findings of this study showed that the microfibers released from the fabrics could be directly related to both structural properties and washing conditions and emphasized that many key issues should be considered, from the looseness of the fabric structure to whether the raw material used was virgin or not. In addition, the results obtained reveal the negative effects of the pre-washing stage applied in household washing. This should concern washing machine manufacturers and also discloses the need to change consumers' behavior.

CRediT authorship contribution statement

Sinem Hazal Akyildiz: Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation. **Silvia Fiore:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Data curation. **Martina Bruno:** Writing – original draft, Visualization, Data curation. **Hande Sezgin:** Writing – review & editing, Writing – original draft, Methodology. **Ipek Yalcin-Enis:** Writing – review & editing, Writing – original draft, Supervision, Methodology. **Bahattin Yalcin:** Supervision. **Rossana Bellopede:** Supervision, Methodology, Formal analysis, Conceptualization, 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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2024.124455.

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