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PAPER

Comparative microfiber shedding from natural, virgin and recycled synthetic textiles under standardised laundering conditions

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Abstract

Microfiber release from synthetic textiles is increasingly recognized as a major source of microplastic pollution, yet the performance of recycled materials relative to virgin and natural remains contested. This study provides standardized evidence on microfiber shedding from commercially available garments, comparing recycled and virgin synthetic fibers alongside natural alternatives. A total of 51 garments from five global fashion brands were analyzed, including cotton, polyester (virgin and recycled), and polyamide (virgin and recycled). To capture complementary shedding metrics, two internationally recognized laundering methods were applied: ISO 105-C06 to quantify fiber number and length, and ISO 6330 to measure total fiber number and mass loss under simulated domestic-scale washing conditions. Descriptively, recycled polyester (rPET) released the highest mean number of microfibers (12430 fibers·g^{-1}), approximately 55% more than virgin polyester (8028 fibers·g^{-1}); however, this difference was not statistically significant across material categories, reflecting high within-group variability. In contrast, fiber length differed significantly by material type, with rPET and recycled polyamide producing significantly shorter fibers (mean 0.42 mm) than cotton and virgin polyester (mean 0.52 mm). Recycled polyamide showed a similar descriptive trend of higher fiber counts relative to its virgin counterpart. While cotton released a greater total fiber mass (1.85 mg·g^{-1}), these fibers were longer and fewer in number. Statistical analysis indicated that microfiber shedding was largely driven by fiber type and material properties rather than brand-specific differences. Nevertheless, some garments -particularly from one brand (B-5)- consistently exhibited higher fiber release across both virgin and recycled synthetic materials, suggesting that textile design and manufacturing practices may also influence shedding intensity. These findings challenge assumptions that rPET is a sustainable alternative and emphasize the need for performance-based evaluation of textile materials in efforts to reduce microfiber emissions.

1. Introduction

In 2020, for the first time, the total mass of human-made objects-a total of 1.2 trillion metric tons-exceeded the total biomass of all living things on Earth. The vast majority of this human-made mass, including billions of tons of plastic, has been produced in the last 100 years. Despite its recent advent as a material, with a mere 80 years of existence, the production of plastic has undergone a substantial expansion, growing from 2 million tons per year in 1950 to nearly 500 million tons per year in 2025, a development that has led to its pervasive presence in various aspects of society (Elhacham *et al* 2020, Landrigan *et al* 2023, PEW 2025), Roughly 8000 Mt of plastic waste now contaminate the planet's land, air, and oceans (Landrigan *et al* 2025). These plastics break down into microplastics, now recognized as

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one of the most pervasive forms of pollution (Gündoğdu *et al* 2024). They contaminate soil, water, air, and food, with growing evidence of harm to ecosystems and human health (Gündoğdu *et al* 2023, Terzi *et al* 2024 , Coşgun *et al* 2025, Gündoğdu *et al* 2026a, 2026b). A considerable amount of microplastics in the environment occurs in the form of microfibers (Allen *et al* 2024). It is estimated that 0.48–4.28 million metric tons of microfibers enter the environment each year, and approximately 35% of these originate from washing synthetic textiles (Allen *et al* 2025). The problem will worsen as clothing production rises with fast fashion trends; under a business-as-usual scenario, plastic use in the textile sector is projected to increase by approximately 88% by 2040 (Pew Charitable Trusts 2025).

The global expansion of textile production over the past decades has been accompanied by a rapid increase in microfiber pollution, now recognized as one of the dominant forms of anthropogenic particulate contamination in aquatic, terrestrial, and atmospheric environments (Allen *et al* 2025). Microfibers-defined as fibrous particles shorter than 5 mm-are consistently reported as the most abundant particle morphology in environmental microplastic surveys, particularly in wastewater effluents (Gündoğdu *et al* 2018), surface waters (Imbulana *et al* 2024), sediments (Serra *et al* 2025), soils (Singh *et al* 2024), and biota (Bergami *et al* 2023).

Synthetic fibers, especially polyester, dominate global textile production (Textile Exchange 2025) and are disproportionately represented among environmental microfibers. Synthetic fibers derived from fossil fuels constitute approximately 69% of all textile production, with polyester accounting for 59% of global fiber production (Textile Exchange 2025). Since the early 2000s, the rise of polyester has led to a doubling of global fiber production and has become the primary driver of growth in the fashion industry (Changing Markets Foundation 2021). This dependency is pervasive throughout the sector, with major fast fashion companies utilizing polyester-derived fibers in 45%–82% of their total production (Changing Markets Foundation 2024a). A substantial body of evidence identifies domestic laundering of textiles as a primary source of these emissions, accounting for a significant share of primary microplastics entering the environment (Wang *et al* 2024).

During washing, mechanical and chemical stresses cause fibers to fragment from yarns and fabrics, generating large quantities of microfibers that are only partially retained by wastewater treatment plants (Napper and Thompson 2016, Mishra *et al* 2020, Özkan and Gündoğdu 2021, Alex *et al* 2024). Removal efficiencies decrease sharply with decreasing fiber size, allowing the smallest and most numerous fibers to pass through treatment systems and disperse widely (Pedrotti *et al* 2021). As a result, microfibers are detected across food webs and have been shown to induce physical, chemical, and biological effects in a range of organisms, with toxicity often linked to particle number, size, and surface properties rather than total mass alone (Avio *et al* 2020).

In response to mounting scrutiny of growing synthetic fiber use, the fashion industry has increasingly promoted recycled polyester (rPET) as a 'preferred' or 'sustainable' alternative. Survey data indicate that a majority of brands report plans to reduce virgin synthetic use by substituting rPET (Özkan and Gündoğdu 2021, Changing Markets Foundation 2024b, Patel *et al* 2025). However, industry-wide production data reveal a more complex picture: while rPET output increased modestly from 8.9 to 9.3 million tonnes between 2023 and 2024, virgin polyester production expanded more rapidly, causing rPET's market share to decline from 12.5% to 12% (Textile Exchange 2025). Furthermore, approximately 98% of rPET is derived from PET bottles, effectively diverting material from closed-loop bottle-to-bottle recycling into textiles that cannot be efficiently recycled at end-of-life (Plastics Recyclers Europe 2022). This 'bottle-to-textile' pathway represents downcycling rather than circularity, locking plastics into products with high shedding potential and limited recovery options. However, recycling processes-particularly mechanical recycling-alter polymer structure through repeated thermal and mechanical stress, potentially reducing molecular weight and increasing brittleness (Tapia-Picazo *et al* 2014, Julienne *et al* 2019, Majumdar *et al* 2020, Özkan and Gündoğdu 2021). These changes raise critical questions regarding the propensity of recycled fibers to fragment and shed during use.

Early experimental evidence demonstrated that knitted fabrics produced from rPET released substantially more and shorter microfibers than those made from virgin polyester under controlled washing conditions, highlighting a potential trade-off between circularity claims and pollution outcomes (Özkan and Gündoğdu 2021, Akyildiz *et al* 2024). To expand on this issue, the environmental performance of mechanically recycled textiles, particularly in terms of their microfiber emission potential, remains an open question. Some studies suggest that recycled yarns with lower tensile strength release more microfiber during use (Frost *et al* 2020), while others report no significant difference. For instance Persson *et al* (2026) reported no clear difference in microfiber release between primary PES and once-recycled PES. However, in contrast, fabrics with fibers recycled twice and three times released about 4.3-fold and 6.2-fold more MPFs than PES, respectively (Persson *et al* 2026). In some cases, recycled fibers have been shown to release longer microfiber, which then degrade into secondary microplastics

(Frost *et al* 2020). Remarkably, much of this research has focused on textiles produced from thermomechanically recycled PET bottles, which does not accurately reflect the behavior of mechanically recycled textiles from fiber to fiber (Persson *et al* 2026). However, when considering the percentage of the bottle to fiber recycling percentage of the recycled PET markets it reflects the market situation (Majumdar *et al* 2020). The first of its kind study on rPET and PET comparison in terms of fiber release, Özkan and Gündoğdu (2021) reported that knitted fabrics produced from recycled PET released 2.3 times more microfiber than those produced from primary polyester. Akyildiz *et al* (2024) also reported similar results, observing that rPET fabrics released more microfiber during washing compared to primary PET fabrics. These findings reveal that differences in material source or recycling cycle number and method and other structural or processing factors have an impact on microfiber release. For instance, Persson *et al* (2026) analyzed fabrics containing mechanically rPET that were subjected to one, two, and three recycling loops. According to their results second and third recycling cycles resulted in up to a 4–6 fold increase in microfiber emissions compared to virgin polyester.

Mechanical recycling generally produces shorter fibers, which also contributes to increased yarn hairiness. Nevertheless, some studies comparing virgin and mechanically recycled PET have not considered yarn hairiness as a variable and their results showed no difference in terms of microfiber release. For example, Gao *et al* (2024) found no difference in microfiber release between primary and mechanically recycled PET; however, they analyzed very limited samples (only eight pieces of garments) and they did not characterize yarn hairiness or evaluate the potential effect of including fibers from multiple recycling cycles.

This study provides a systematic comparison of microfiber release from commercially available garments made from virgin and recycled synthetic fibers, alongside cotton, using internationally standardized washing methods. By quantifying both fiber number and mass, and by examining fiber length distributions, this work aims to clarify how material choice influences microfiber emissions under realistic laundering scenarios. In doing so, it contributes empirical evidence to an increasingly polarized debate and underscores the need to evaluate textile sustainability claims not only through material sourcing, but also through performance-based assessments of pollution potential.

2. Materials and methods

2.1. Purchasing samples

This study analyses a total of 51 garments from five major global fashion companies covering cotton, polyester (virgin and recycled), and polyamide (virgin and recycled). The sample distribution was as follows: B-1 (9), B-2 (13), B-3 (11), B-4 (9) and B-5 (9) (table 1). These companies were selected because they are among the world's largest fashion retailers and most are significant users of synthetic fibers (Changing Markets Foundation 2024a). We tried to select garments of comparable size and type (namely. t-shirts, tops, dresses and shorts), but this was not always possible due to limited information about production methods. Our goal was to test at least nine items per brand, which for most brands meant: three predominantly-or fully-cotton garments, three predominantly or fully virgin polyester garments, and three predominantly or fully rPET garments. The main exception was B-2: because we were unable to source virgin-polyester items from its online store, we included virgin-polyamide and recycled-polyamide garments to allow for a fair comparison (table 1).

2.2. Washing standards and experimental design

Microfiber release was quantified using two internationally standardized laundering methods to capture complementary shedding metrics at different scales. Laboratory-scale fiber number and length were assessed according to TS EN ISO 105-C06:2010 (Textiles-Tests for color fastness-Part C06: Color fastness to domestic and commercial laundering), while mass-based fiber loss under domestic-scale conditions was quantified using TS EN ISO 6330:2012 (Textiles-Domestic washing and drying procedures for textile testing). For ISO 105-C06, the A1S washing protocol was applied, representing mild domestic laundering conditions. Washing was conducted at 40 $\pm$ 2 °C for 30 min, using 150 ml of filtered water per test vessel and 10 stainless-steel balls ($\approx$6 mm diameter) to provide controlled mechanical agitation and abrasion. No detergents or auxiliary chemicals were added, ensuring that fiber release resulted solely from mechanical and thermal stresses. Identical washing temperature, duration, and mechanical action were reproduced in the ISO 6330 procedure to ensure comparability between laboratory-scale and domestic-scale laundering.

Table 1. Purchased garments properties.

Sample ID	Fiber composition (%)	Item name/description
B-1	Cotton	Lune Boho Women Clothing Spring Break Tops Women's Organic Cotton White Tank Top & Vest,
	Cotton	Lune Guipure Lace Panel Sleeveless Blouse
	Cotton	Vcay Holiday Solid Color Woven Linen Spaghetti Strap Short Dress
	Polyester	Classic Solid V Neck Satin Sleeveless Blouse For Holiday Party Clothes, Sleeveless Tops
	Polyester	Manfinity Homme Men's Solid Color Round Neck Short Sleeve T-Shirt
	Polyester	Young Girl Floral Print Dress
	Recycled Polyester (rPET)	Tall Women's Solid Color Casual V-Neck Sleeveless Cardigan Vest
	Recycled Polyester (rPET)	Lune Woven Solid Color Casual Versatile Hollow Hem Tank Top
	Recycled Polyester (rPET)	Vcay Solid Top
B-2	Cotton	Washed-Effect Text Sweatshirts
	Cotton	Washed Reverse Effect Sweater
	Cotton	Textured Piqué Polo Shirt
	Polyamide	Ruffled Knit Cardigan
	Polyamide	Lightweight Technical Gilet
	Polyamide	Polyamide Top With Wide Straps
	Polyamide	Polyamide Top With Thin Straps
	Recycled Polyester (rPET)	Printed Pleated Trousers
	Recycled Polyester (rPET)	Basic Satin Shirt
	Recycled Polyester (rPET)	V-Neck Top With Ruffles
	Recycled Polyamide	Polyamide Strappy Bodysuit
	Recycled Polyamide	Polyamide Halter Bodysuit
	Recycled Polyamide	Polyamide Halter Bodysuit
B-3	Cotton	Loose Fit T-shirt
	Cotton	Cotton Sleeveless Top
	Cotton	T-Shirt That Fits The Body
	Polyester	Suspended Top
	Polyester	Regular Fit Drymove
	Polyester	T-Shirt That Fits The Body
	Recycled Polyester (rPET)	Regular Fit Drymove
	Recycled Polyester (rPET)	Sports Top With Hanger Softmove™
	Recycled Polyester (rPET)	Riban Sleeveless Top
	Recycled Polyester (rPET)	Gathered Sleeveless Top
	Polyester	Short Tights With Ribbed
B-4	Cotton	Loungewear Essentials Slim 3-Striped T-Shirt
	Cotton	Sportswear Photo Real Two-Tone T-Shirt
	Cotton	Trae Foundation Tee
	Polyester	Premium Sprinter Shorts
	Polyester	Premium Sprinter Shorts
	Polyester	Premium Sprinter Shorts
	Recycled Polyester (rPET)	Aeroready Made For Training Minimal T-Shirt
	Recycled Polyester (rPET)	Adizero Essentials Running Tank Top
	Recycled Polyester (rPET)	Tiro 25 Essentials Form
B-5	Cotton	Sportswear Women's T-Shirt
	Cotton	Jordan Essentials Above Women
	Cotton	Sportswear Club Men's T-Shirt
	Polyester	Academy Dri-FIT Men's Soccer Top
	Polyester	Sportswear Wind runner Normal Waisted 5 Cm Women's Shorts
	Polyester	Academy Dri-FIT Men's Football Shorts
	Recycled Polyester (rPET)	Academy Dri-Fit Young Kids Football Top
	Recycled Polyester (rPET)	Academy Dri-Fit Women's Football Top
	Recycled Polyester (rPET)	Academy Dri-Fit Short Sleeve Men's Football Top
	Recycled Polyester (rPET)	Dry Fit Elastico

2.3. Washing devices

Two standardized laundering systems were employed:

GyroWash laboratory laundering unit (ISO 105-C06 compliant)

The GyroWash system consisted of two independent thermostatically controlled baths, each accommodating eight sealed stainless-steel test vessels (16 vessels in total). Individual vessels (diameter ≈75 ± 5 mm; height ≈125 ± 10 mm; capacity ≈550 ml) rotated at 40 ± 2 rpm in a water bath maintained at 40 ± 2 °C.

Wascator domestic laundering simulator (ISO 6330 compliant)

The Wascator system was a front-loading, horizontal-drum washer equipped with a stainless-steel drum (diameter ≈520 mm, depth ≈315 mm, volume ≈61 l). The system operated at programmable washing speeds (20–59 rpm) and extraction speeds (200–1100 rpm), with temperature control between 4 °C and 97 °C (±1 °C). The A1S washing conditions were reproduced at domestic scale.

2.4. Sample selection and preparation

A total of 51 commercially available garments composed of cotton, polyester, rPET, polyamide, and recycled polyamide were analyzed. For ISO 105-C06 testing, fabric samples measuring approximately 4 × 10 cm were prepared in accordance with the standard.

Each garment designated for Wascator testing served as the source material for three GyroWash specimens (4 × 10 cm each), cut from representative regions of the garment. Following sample removal, all cut edges on both the GyroWash samples and the remaining garment were sealed using a fast-curing adhesive to prevent fiber release from exposed yarn ends. The remaining garment body was rejoined along the cut lines and washed as a whole item in the Wascator under equivalent temperature and duration conditions. This approach enabled direct comparison between laboratory-scale and domestic-scale laundering outcomes from the same garment.

Prior to washing, all samples were conditioned at 20 ± 2 °C and 65 ± 5% relative humidity and weighed using an analytical balance with a precision of ±0.001 g.

Eleven garments exhibited printed areas or pronounced local structural heterogeneity that could not be represented by small subsamples; these garments were therefore analyzed only in the Wascator system as intact items. The remaining 40 garments underwent both GyroWash (three replicates per garment) and Wascator testing.

2.5. Washing and rinsing procedures

For GyroWash experiments, each test vessel contained 150 ml of filtered water, 10 stainless-steel balls, and one fabric sample, and was rotated for 30 min at 40 ± 2 °C. In each eight-vessel bath, one vessel served as a blank control, containing only water and steel balls. After washing, the contents of all vessels were transferred to the filtration system. Vessel walls were rinsed with filtered water using a handheld pressure sprayer, and the rinsed water was filtered to ensure complete fiber recovery.

For Wascator experiments, the same washing temperature and duration were applied. Ballast fabrics were enclosed in triple-layer, leak-proof polyethylene bags to prevent cross-contamination. After each wash cycle, the Wascator performed an automatic 120 s rinse program, and the rinse water was collected and combined with the wash effluent of the corresponding sample.

2.6. Effluent collection and filtration

All wash and rinse effluents were filtered using a vacuum manifold filtration apparatus. Wascator effluents were first passed through a 25 μm mesh-size sieve to remove water. Final filtration employed self-gridded mixed cellulose ester (S-Pak Membrane Filter, 0.45 μm, 47 mm, white, self-gridded 2*2 mm-HAWG047S6) filters mounted on stainless-steel filtration bases under 0.7 bar vacuum pressure. For GyroWash washing, washing and rinsed water were filtered together. For Wascator tests, combined wash and rinse effluents were filtered through the same system. Filters were retrieved using stainless-steel forceps, placed in sterile Petri dishes, and air-dried at room temperature.

The 0.45 μm pore size retains particles down to roughly this diameter, encompassing the majority of microfibers reported in textile-washing studies, but is not expected to efficiently capture nanoplastic fibers (sub-micron diameter), which likely pass through into the filtrate (Yang *et al* 2021). Our reported fiber counts and masses should therefore be interpreted as representing the microfiber and coarse-fibril fraction; the nanoscale fraction was not captured or quantified in this study, and its assessment would require complementary techniques such as nanoparticle tracking analysis or Py-GC/MS.

2.7. Fiber quantification and analysis

Each filter membrane was divided into approximately 130 grid fields. Thirteen fields were randomly selected and examined under an optical microscope. Fiber counts were extrapolated to the total filter area. Fiber length (μm–mm) was measured using a calibrated microscope scale.

Fiber release was expressed as fibers per gram of fabric (fibers·g^{-1}) for GyroWash tests. For Wascator tests, dried filters were reweighed to determine mass-based fiber release (mg·g^{-1}). All results are reported as mean ± standard deviation ($n = 3$).

For GyroWash tests, the total number of fibers on each filter (N_{filter}) was extrapolated from counted fields:

$$N_{\text{filter}} = \frac{G}{k}\sum n_i$$

where G is the total number of grid fields (130), k is the number of counted fields (13), and n_i is the fiber count in field i. Blank-corrected values were obtained by subtracting blank control counts. Normalized fiber release was calculated as:

$$R_{\text{count}} = \frac{N_{\text{filter}}}{w}$$

where w is the sample mass (g).

Mean fiber length and standard deviation were calculated from measured fibers. For Wascator tests, mass-based release was calculated as:

$$R_{\text{mass}} = \frac{(M-b)}{W} \times 1000$$

where M is collected fiber mass (g), b is blank mass, and W is garment mass (g).

2.8. Contamination control

Contamination control measures were applied throughout. Each GyroWash bath included a blank control vessel, and filtered blank effluents were examined microscopically. After each Wascator run, the automatic rinse cycle ensured removal of residual fibers, with rinse water analyzed alongside sample effluents. These controls confirmed that collected fibers originated exclusively from the tested textiles.

2.9. Statistical analysis

All statistical analyses were conducted using IBM SPSS Statistics (version 27), and graphical visualizations were generated using Tableau (version 2025.1). Prior to analysis, data were screened for completeness, and only samples with valid measurements were included in the corresponding tests. Statistical significance was assessed at a threshold of $p < 0.05$. Pearson correlation analysis was used to evaluate the relationship between fiber count (fibers·g^{-1}) measured during GyroWash tests and fiber mass release (mg·g^{-1}) measured during Wascator washing. Correlations were assessed for the full dataset and, where sample size permitted ($n \geqslant 3$), separately by material type and by brand. One-way analysis of variance (ANOVA) was applied to assess differences in fiber count (fibers·g^{-1}) and mean fiber length (mm) between material types and between brands. When statistically significant effects were detected, post hoc multiple comparisons were performed using Tukey's honestly significant difference (HSD) test. Effect sizes for ANOVA models were calculated using eta squared (η^2) to quantify the proportion of variance explained by material type or brand. Multivariate ANOVA (MANOVA) was performed to evaluate the combined effects of material type and brand on fiber count (fibers·g^{-1}), mean fiber length (mm), and fiber mass release (mg·g^{-1}). Wilks' lambda was used as the primary multivariate test statistic. Multiple linear regression analysis was conducted to examine whether recycling status (virgin vs recycled), mean fiber length, and fiber mass release independently predicted fiber count. Model fit was evaluated using the coefficient of determination (R^2). Cluster analysis was performed using k-means clustering ($k = 3$) on standardized variables (fiber count, mean fiber length, and fiber mass release) to identify distinct fiber shedding profiles across the tested garments. Finally, a normalized fiber release metric was calculated by expressing fiber count per unit fiber mass released (fibers·mg^{-1}) to compare shedding intensity independently of total mass loss.

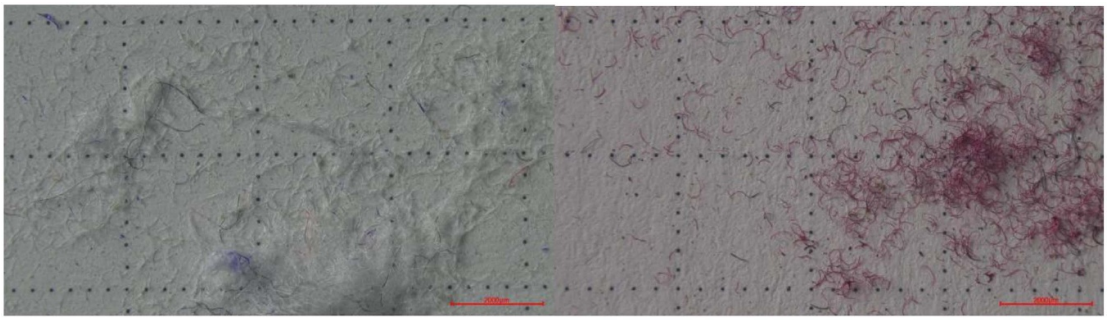


Figure 1. The appearance of microplastic fibers deposited on filter paper visualized under microscope (each dotted square is 2 × 2 mm).

3. Results

Visual inspection of the filter papers following both GyroWash and Wascator washing tests revealed pronounced differences in fiber accumulation between garments, with some samples exhibiting dense fiber deposition indicative of substantial microfiber release (figure 1).

3.1. Cotton-based fabrics

Microfiber release from cotton-based garments was quantified using both GyroWash and Wascator systems (tables 2). In the GyroWash tests, the number of released fibers showed substantial variability among individual garments and brands, ranging from 3433 to 30 909 fibers·g^{-1}. The highest fiber count was observed for a B-5 garment, while lower values were recorded for several B-2 and B-4 items. When results were averaged at the brand level, B-5 exhibited the highest mean fiber release (17439 ± 12 728 fibers·g^{-1}), whereas B-2 showed the lowest average values (6799 ± 2914 fibers·g^{-1}).

The mean length of cotton fibers released during GyroWash washing varied between 0.32 and 0.94 mm across brands (figure 2). B-4 garments released the shortest fibers on average (0.40 ± 0.02 mm), while B-5 garments released the longest (0.85 ± 0.19 mm).

In the Wascator tests, mass-based fiber release from cotton garments ranged from 0.26 to 17.46 mg·g^{-1}. The highest individual mass loss was recorded for a B-5 garment (table 2). At the brand level, B-5 exhibited the highest mean fiber mass release (7.00 ± 9.13 mg·g^{-1}), while B-4 showed the lowest (1.65 ± 1.15 mg·g^{-1}).

3.2. Virgin polyester-based fabrics

Virgin polyester garments were analyzed for four brands, as no suitable virgin polyester garments were available for B-2. GyroWash testing was conducted for B-1, B-3, and B-5, while B-4 samples were analyzed only using the Wascator due to fabric heterogeneity (tables 2).

In the GyroWash tests, fiber release ranged from approximately 1081 to 21 469 fibers·g^{-1}. B-5 garments exhibited the highest fiber counts, with a maximum of 21 469 fibers·g^{-1} for a 100% polyester item. B-1 and B-3 garments showed lower average fiber release, generally below 7000 fibers·g^{-1}.

Mean fiber lengths for virgin polyester ranged from 0.38 to 0.65 mm. B-5 and B-3 garments released longer fibers on average (0.64 ± 0.17 mm and 0.52 ± 0.10 mm, respectively), whereas B-1 garments released shorter fibers (0.49 ± 0.07 mm). In Wascator tests, mass-based fiber release from virgin polyester garments was relatively low, ranging from 0.12 to 0.42 mg·g^{-1}. B-4 garments showed the lowest mass loss (0.12–0.14 mg·g^{-1}), while B-1 garments showed the highest (up to 0.42 mg·g^{-1}). B-5 and B-3 exhibited intermediate values.

3.3. rPET -based fabrics

rPET garments were tested using both GyroWash and Wascator systems (table 2; figure 1). In GyroWash tests, fiber release varied widely between brands and individual garments, ranging from 1731 to 50 971 fibers·g^{-1}. The highest fiber counts were recorded for B-5 and B-4. B-3 and B-1 garments generally exhibited lower fiber counts.

In Wascator tests, mass-based fiber release from rPET garments ranged from 0.10 to 1.63 mg·g^{-1}. B-4 and B-5 garments exhibited the highest mean mass losses (0.83 ± 0.70 mg·g^{-1} and 0.34 ± 0.21 mg·g^{-1}, respectively), whereas B-3 and B-2 showed lower values. B-1 garments displayed

Table 2. Summary statistics (minimum, mean, median, and maximum) of microfiber release from cotton, polyester (virgin and recycled), and polyamide (virgin and recycled) garments quantified using GyroWash (fiber count, fibers·g^{-1}) and Wascator (mass-based release, mg·g^{-1}) washing systems. Mean sample weights for GyroWash and Wascator tests are also reported for each brand and material.

Material	Brand	Mean sample weight in Wascator (gr)	Mean sample weight in Gyrowash (gr)	Fibers·g^{-1}				mg·g^{-1}			
				Min	Avg	Median	Max	Min	Avg	Median	Max
Cotton	B-1	126.4	0.843	6525	9920	9053	14 182	1.193	1.419	1.424	1.638
	B-2	309.7	1.690	3433	5664	3950	9610	1.491	1.802	1.674	2.240
	B-3	141.4	1.092	3948	9172	10 984	12 585	0.266	1.800	1.958	3.176
	B-4	138.5	0.965	8169	8169	8169	8169	0.833	1.649	1.649	2.466
	B-5	97.8	0.833	3968	17 439	17 439	30 909	0.653	7.001	2.893	17.457
	Mean	162.8	1.085	3433	10 073	8611	30 909	0.266	2.734	1.656	17.457
PET	B-1	101.7	0.701	2802	6931	3307	14 684	0.334	0.376	0.374	0.419
	B-3	78.7	1.073	1081	2737	3003	3863	0.163	0.228	0.232	0.287
	B-4	251.6	NA	NA	NA	NA	NA	0.122	0.179	0.133	0.330
	B-5	110	0.794	19 047	20 258	20 258	21 469	0.193	0.209	0.209	0.225
	Mean	135.5	0.856	1081	9975	3474	21 469	0.163	0.271	0.225	0.419
rPET	B-1	82.7	0.666	3175	3853	3878	4505	0.232	0.300	0.249	0.421
	B-2	184.1	1.107	2900	4243	3035	6794	0.162	0.258	0.206	0.406
	B-3	82	1.14	1731	8790	5236	22 954	0.102	0.176	0.184	0.234
	B-4	126.8	0.574	14 998	26 517	26 517	38 035	0.338	0.828	0.521	1.625
	B-5	113.4	0.921	10 573	30 772	30 772	50 971	0.123	0.338	0.270	0.689
	Mean	117.8	0.882	1731	14 835	5649	50 971	0.102	0.380	0.234	1.625
PA	B-2	256.9	0.887	1240	1564	1564	1889	0.050	0.086	0.097	0.101
rPA	B-2	106.9	1.302	3555	5133	5770	6074	0.131	0.203	0.175	0.304

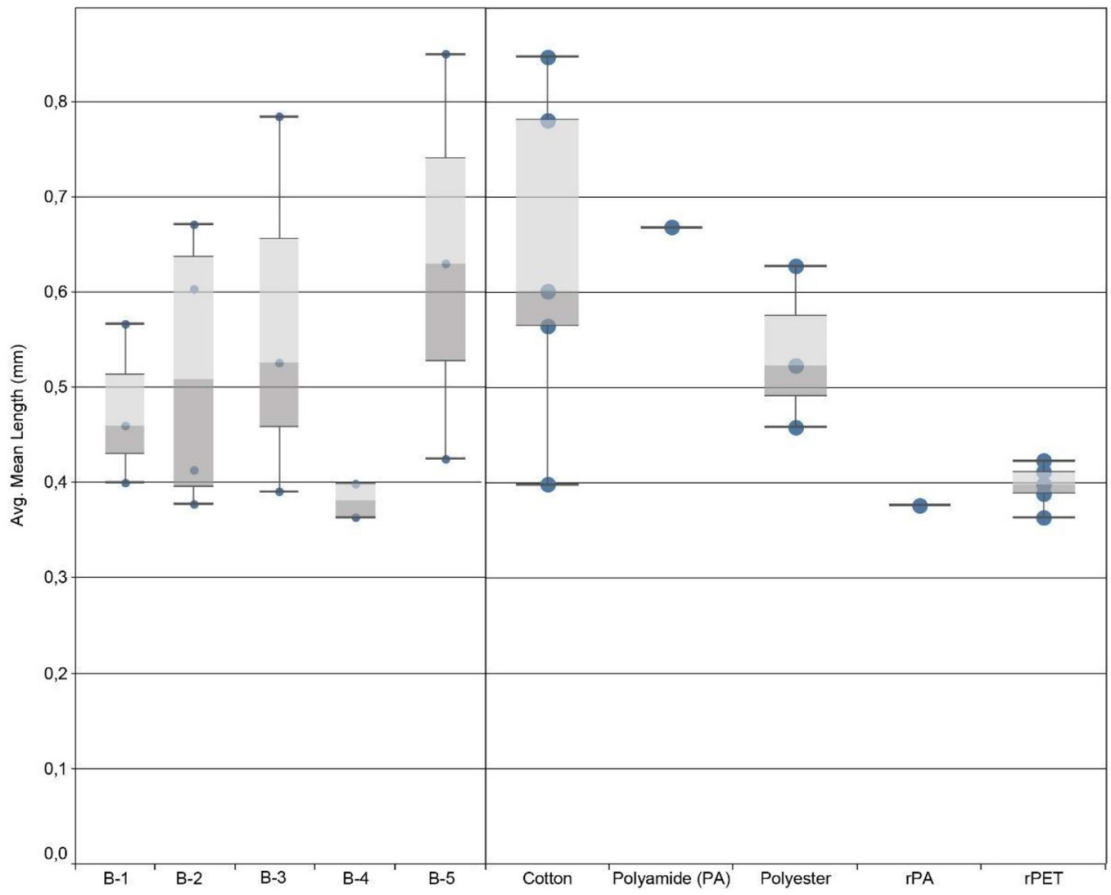


Figure 2. Mean fiber length (mm) of microfibers released during GyroWash washing for different brands and material types (cotton, virgin polyester, recycled polyester, virgin polyamide, and recycled polyamide).

intermediate mass loss levels. Across both washing systems, B-4 and B-5 consistently exhibited the highest fiber release among rPET garments in terms of both fiber count and mass loss.

3.4. Virgin polyamide-based fabrics

Virgin polyamide garments were analyzed primarily from B-2 (table 2). In GyroWash tests, fiber release ranged from approximately 1240–1889 fibers·g^{-1}, with mean fiber lengths between 0.63 and 0.71 mm. In Wascator tests, mass-based fiber release was low, ranging from 0.05 to 0.10 mg·g^{-1}. Across all virgin polyamide garments, fiber release levels were consistently lower than those observed for cotton and polyester fabrics.

3.5. Recycled polyamide-based fabrics

Recycled polyamide garments (table 2) released higher numbers of fibers than virgin polyamide in GyroWash tests, with values ranging from 3555 to 6074 fibers·g^{-1}. Mean fiber lengths were short and uniform across samples (0.36–0.39 mm). In Wascator tests, mass-based fiber release from recycled polyamide ranged from 0.13 to 0.30 mg·g^{-1}, exceeding values observed for virgin polyamide.

3.6. Comparative overview across fiber types and brands

The relationship between fiber count (fibers·g^{-1}) measured by GyroWash and fiber mass release (mg·g^{-1}) measured by Wascator was evaluated using Pearson correlation analysis. When all materials and brands were pooled ($n = 40$), no statistically significant correlation was observed between fiber count and fiber mass release ($r = 0.17$, $p = 0.29$). Correlation analyses conducted separately by material type also revealed no statistically significant relationships. Cotton-based fabrics showed a moderate positive correlation ($r = 0.58$), which did not reach statistical significance ($p = 0.050$). Virgin polyester, rPET, and recycled polyamide fabrics exhibited weak to moderate correlations ($|r| < 0.40$), all of which were non-significant ($p > 0.20$). When analyzed by brand across all material types, no statistically significant correlations were detected ($p > 0.15$ for all brands). Additional brand–material subgroup analyses

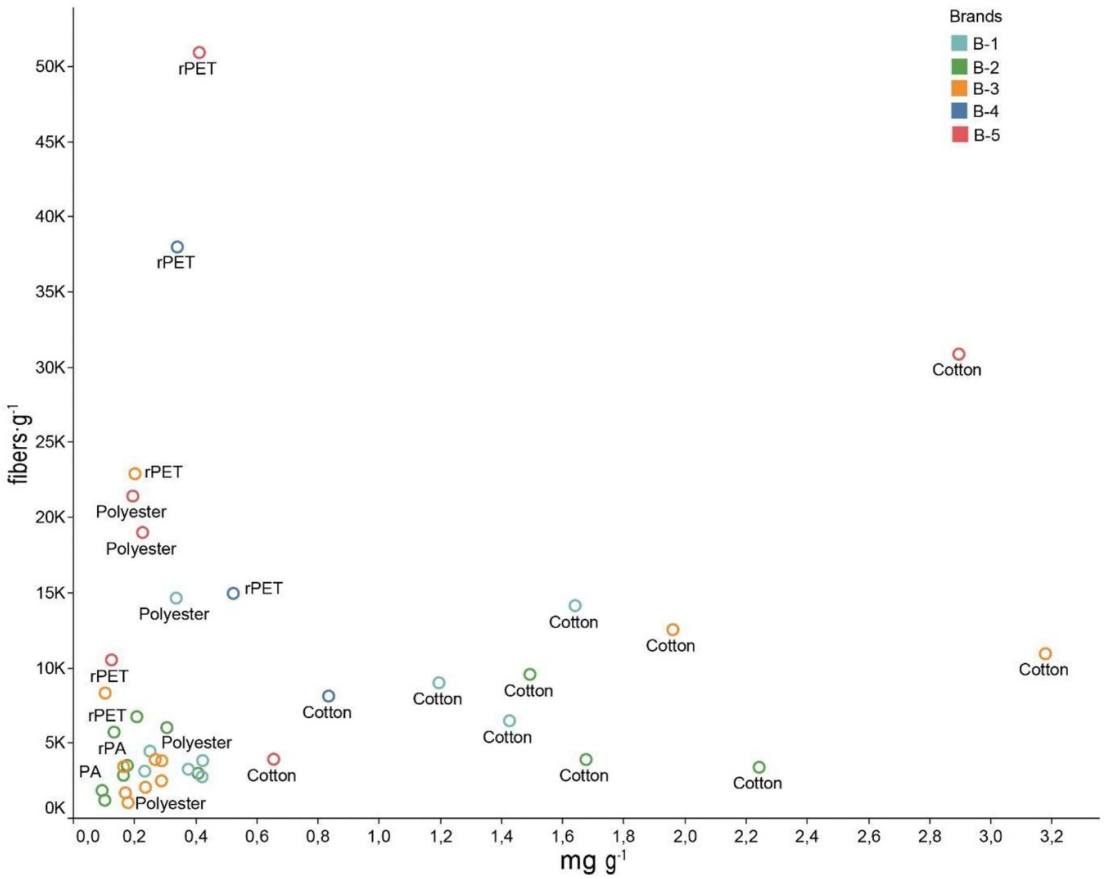


Figure 3. Relationship between fiber count (fibers·g^{-1}) measured by GyroWash and fiber mass release (mg·g^{-1}) measured by Wascator for all tested garments. Data points represent individual samples across all material types and brands.

were performed where sample size permitted ($n \geqslant 3$), and none showed a statistically significant relationship between fiber count and mass-based fiber release (figure 3).

One-way ANOVA was used to assess differences in fiber count among material types and between brands. Although rPET showed higher average fiber counts than several other material types in the dataset, these differences were not statistically significant when all material categories were compared (cotton, virgin polyester, rPET, virgin polyamide, recycled polyamide) ($F_{4,35} = 0.69$, $p = 0.60$), reflecting the high variability observed within material groups. In contrast, fiber count differed significantly between brands ($F_{4,35} = 6.38$, $p < 0.001$). Post hoc Tukey HSD analysis indicated that B-5 garments released significantly more fibers than B-3 garments ($p = 0.006$), while B-2 garments released significantly fewer fibers than B-4 garments ($p = 0.049$). Other pairwise comparisons were not statistically significant.

Differences in mean fiber length released during GyroWash washing were assessed using one-way ANOVA. Mean fiber length differed significantly between material types ($F_{4,34} = 10.16$, $p < 0.001$). Tukey HSD post hoc comparisons showed that cotton fabrics released significantly longer fibers than rPET ($p < 0.001$) and recycled polyamide ($p = 0.005$), indicating that recycled synthetic materials tended to generate shorter fragments during washing. No other material-level comparisons were statistically significant. In contrast, no statistically significant differences in mean fiber length were observed between brands ($F_{4,34} = 1.56$, $p = 0.21$).

Effect size estimates (η^2) were calculated to quantify the proportion of variance explained by material type and brand for fiber count and mean fiber length. For fiber count (fibers·g^{-1}), material type accounted for a small proportion of the total variance ($\eta^2 = 0.074$), whereas brand explained a substantially larger proportion ($\eta^2 = 0.422$), indicating a large effect size. In contrast, for mean fiber length, material type explained more than half of the total variance ($\eta^2 = 0.544$), corresponding to a very large effect size, while brand accounted for a smaller proportion of the variance ($\eta^2 = 0.155$) and did not reach statistical significance. Together, these results indicate that while rPET garments tended to release higher numbers of shorter fibers in descriptive comparisons, fiber length differences were primarily

Table 3. Characteristics of fiber shedding clusters identified by *k*-means analysis ($k = 3$) based on fiber count (fibers·g^{-1}), mean fiber length (mm), and fiber mass release (mg·g^{-1}). Values are reported as means, with ranges shown for fiber count.

Cluster	Fiber count (fibers·g^{-1})	Mean fiber length (mm)	Fiber mass release (mg·g^{-1})
0	10 964 (3433–30 909)	0.71	1.88
1	6234 (1,081–21,469)	0.48	0.31
2	37 320 (22 954–50 971)	0.34	0.32

Note: All variables were standardized prior to clustering. Clusters represent distinct combinations of fiber number, size, and mass-based release.

driven by material type, whereas variability in fiber count was more strongly associated with brand-level differences within the tested garments.

MANOVA was used to assess the combined effects of material type and brand on fiber count (fibers·g^{-1}), mean fiber length (mm), and fiber mass release (mg·g^{-1}). The multivariate effect of material type was statistically significant (Wilks' $\lambda = 0.195$, $F_{(12,\,84.96)} = 6.05$, $p < 0.001$), indicating that the combined shedding characteristics differed across fiber materials. A significant multivariate effect was also observed for brands (Wilks' $\lambda = 0.390$, $F_{(12,\,84.96)} = 3.02$, $p = 0.001$). These results demonstrate that both material type and brand contribute to variability in microfiber shedding when fiber count, fiber length, and mass-based release are considered simultaneously.

Multiple linear regression was performed to assess whether recycling status, mean fiber length, and fiber mass release independently predicted fiber count (fibers·g^{-1}). The overall model was not statistically significant ($F_{(3,35)} = 1.25$, $p = 0.31$), explaining approximately 9.7% of the variance in fiber count ($R^2 = 0.097$). Recycling status was not a significant independent predictor ($\beta = 4474$ fibers·g^{-1}, $p = 0.35$), nor was mean fiber length ($\beta = -8237$ fibers·g^{-1}, $p = 0.59$). Fiber mass release showed a positive but non-significant association with fiber count ($\beta = 4312$ fibers·g^{-1}, $p = 0.10$).

Cluster analysis was performed to classify garments according to their fiber shedding characteristics using fiber count (fibers·g^{-1}), mean fiber length (mm), and fiber mass release (mg·g^{-1}). Three distinct clusters were identified (table 3). Cluster 0 was characterized by relatively high fiber mass release (mean 1.88 mg·g^{-1}) and longer fibers (mean 0.71 mm), despite moderate fiber counts. Cluster 1 exhibited moderate values across all three metrics, with a mean fiber count of 6234 fibers·g^{-1} and mean fiber length of 0.48 mm. Cluster 2 was distinguished by very high fiber counts (mean 37 320 fibers·g^{-1}) combined with short fiber lengths (mean 0.34 mm) and moderate mass-based release. These clusters illustrate distinct shedding profiles that emerge when fiber number, size, and mass are considered jointly.

Fiber shedding was further evaluated using a normalized metric expressing fiber count per unit mass released (fibers·mg^{-1}). Substantial differences were observed between material types. rPET exhibited the highest normalized release, with a mean of 50 245 fibers·mg^{-1}, followed by virgin polyester (33 928 fibers·mg^{-1}) and recycled polyamide (28 089 fibers·mg^{-1}). Cotton showed the lowest normalized values (6871 fibers·mg^{-1}), reflecting the release of fewer, heavier fibers per unit mass. When grouped by recycling status, recycled materials released more than twice as many fibers per milligram of shed material compared with virgin materials (46 091 vs 18 286 fibers·mg^{-1}). These results demonstrate that materials with similar mass-based shedding can differ markedly in the number of individual fiber particles generated.

4. Discussion

Synthetic fibers such as polyester, polyamide (nylon), and acrylic dominate global textile production, with polyester alone accounting for approximately 59% of total fiber output worldwide (Textile Exchange 2025). Since the early 2000s, the rapid expansion of polyester production has driven a doubling of global fiber volumes and represents the largest projected source of growth in textile manufacturing (Changing Markets Foundation 2024b). This expansion has been accompanied by an increasingly recognized but largely externalized environmental cost: the continuous release of microplastic fibers throughout the textile life cycle. Microfiber emissions occur during fiber and fabric production, including cutting, weaving, and finishing, where fibers enter industrial wastewater streams before garments reach consumers (Napper and Thompson 2016). During use, domestic laundering constitutes a major release pathway, with individual wash cycles reported to emit hundreds of thousands of microplastic fibers into wastewater systems (Napper and Thompson 2016). End-of-life processes further exacerbate emissions: landfilled garments fragment progressively into smaller plastic particles, while incineration releases hazardous substances

Table 4. Overview of selected studies on microfiber release during domestic laundering and comparison with the present study.

Study	Materials tested	Washing system	Quantification metric	Reported microfiber release	Key methodological notes
Napper and Thompson (2016)	PE, PE–cotton blends	Domestic washing machine	Fiber count	Up to ∼728 000 fibers·kg^{-1}	Edge-finished samples; count-based
Hartline *et al* (2016)	Fully synthetic garments	Front- and top-loading machines	Mass	0.3% mass loss (∼3300 mg kg^{-1})	Whole garments; no fiber sizing
De Falco *et al* (2019)	Polyester garments	Domestic washing machine	Mass → count conversion	640 000–1500 000 microfibetoprs/kg 48.6–307.6 mg kg^{-1}	Mass-based, converted to counts
Zambarano *et al* (2019)	Polyester fleece	Launder-Ometer	Mass	16 000 microfibers/g 0.2–4 mg g^{-1}	Laboratory-scale washing
Özkan and Gündoğdu (2021)	Virgin vs recycled PES knits	GyroWash	Fiber count	rPET > virgin PES 4489.93 fiber l^{-1}; 368 094.07 fiber kg^{-1}> 26 fiber l^{-1}; 167 436.58 fiber kg^{-1}	Controlled yarn and fabric structure
Akyildiz *et al* (2024)	Acrylic, polyamide, polyester, recycled polyester and polypropylene	Launder-Ometer	Fiber count	Woven acrylic (2405 fiber) Recycled polyester (193 fiber) polyester (908 fiber)	The effects of materials, fabric properties (woven, knitted), thickness and basis weight values on MPFs release at different washing stages (pre-washing, soaping/rinsing)
Gao *et al* (2024)	Virgin vs recycled PES	Laboratory washing	Mass & 'fibrils'	No significant difference between rPET and PET	Pre-washing; $n = 8$; fiber sub-categorization
Eamrat *et al* (2025)	Real fully synthetic cloth (T-shirt, Long trousers, etc)	Domestic washing machine	Mass	12.73–62.82 mg kg^{-1}	Quantify and characterize microfibers generated from different washing programs
Theeratampitak and Charusiri (2025)	Cotton, PET, PET–cotton	Domestic washing	Fiber count (pieces·l^{-1})	126–295 fibers·l^{-1}	Detergent type effects
Vragkalis *et al* (2025)	Mixed household textiles	Real households	Fiber count	>6.3 × 10^4 fibers per wash	City-scale emission extrapolation
da Costa *et al* (2025)	PET, PA and PET:PA	Accelerated washing	Fiber count & ID	Polyester (135 mg·kg^{-1}) Polyamidetop (9.77 mg kg^{-1}) PET:PA (60 mg·kg^{-1})	FTIR-based polymer identification
Persson *et al* (2026)	Virgin PET, rPET (1–3 cycles)	ISO 4484–1, abrasion	Fiber count	Up to 6.2× increase after recycling	Multi-cycle recycling effects

(Continued.)

Table 4. (Continued.)

This study	Cotton, PET, rPET, PA, rPA	GyroWash & Wascator	Count, length, mass	∼1,000–50 000 fibers·g^{-1}; 0.05–17.46 mg·g^{-1}	Commercial garments; multi-metric

into the atmosphere (Wagner *et al* 2024). Recycling, often presented as a mitigation strategy, has also been shown to generate substantial microplastic emissions during mechanical processing (Landrigan *et al* 2025).

Consistent with this systemic emission pathway, our washing experiments on commercially available garments ($n = 51$) demonstrated measurable microfiber release across all tested fiber categories, with fiber-count emissions spanning approximately 1000–50 000 fibers·g^{-1} in GyroWash and mass-based losses ranging from 005–1746 mg·g^{-1} in Wascator, indicating that routine laundering constitutes a direct and quantifiable source of fiber emissions from modern apparel. The magnitude and variability of microfiber release observed in this study are consistent with, but extend beyond, previously published washing and abrasion experiments on synthetic textiles. The fiber counts and size distributions observed in this study fall within the broad range reported in previous laundering experiments, while highlighting systematic differences associated with material type and recycling status. Reported fiber releases from domestic washing typically range from hundreds to tens of thousands of fibers per wash or per kilogram of fabric, depending on washing conditions, textile construction, and quantification method (Hartline *et al* 2016, Napper and Thompson 2016, De Falco *et al* 2019, table 4). Our GyroWash results (≈1000–50 000 fibers·g^{-1}) and Wascator mass-based releases (0.05–17.46 mg·g^{-1}) are consistent with these magnitudes, but further demonstrate that rPET releases a descriptively higher mean number of shorter fibers than virgin polyester under comparable washing conditions. Several interrelated mechanisms likely explain why rPET sheds more, and shorter, fibers than virgin polyester. First, the mechanical recycling process itself -shredding, opening, carding, and re-spinning- subjects fibers to repeated thermal and shear stress, which reduces average molecular weight, chain length, and crystallinity (Özkan and Gündoğdu 2021). This structural degradation lowers breaking strength and elongation at break, making recycled fibers inherently more prone to fracture into shorter fragments under the mechanical agitation of washing. Second, the recycling process measurably shortens staple fiber length and increases the proportion of short fibers in the feedstock even before spinning (Persson *et al* 2026), which in turn elevates yarn hairiness the degree to which fiber ends protrude from the yarn surface. Higher hairiness reflects weaker fiber-to-yarn cohesion and provides more loose fiber ends that can be abraded and detached during laundering. Third, SEM imaging has shown that rPET fibers exhibit duller, more irregular surface morphology and visible surface deformation compared to virgin fibers (Özkan and Gündoğdu 2021), which may create additional stress-concentration points that promote fragmentation. Finally, progressive/cumulative recycling (as opposed to a single recycling pass) compounds these effects: fibers subjected to multiple mechanical recycling cycles show a stepwise increase in both hairiness and microfiber release, indicating that structural degradation accumulates rather than plateaus after one cycle (Persson *et al* 2026). Together, these factors-reduced polymer integrity, shorter starting fiber length, elevated yarn hairiness, and surface damage-provide a plausible mechanistic basis for the higher number and shorter length of fibers released from rPET observed in our study.

In contrast, studies reporting negligible differences between virgin and rPET often rely on small sample sizes, pre-washed fabrics, or mass-based metrics that mask particle-number effects (Gao *et al* 2024). In particular, the use of pre-washed or pre-conditioned fabrics can substantially reduce measured fiber release by removing loosely attached surface fibers and fibrils that originate during yarn spinning, knitting, cutting, and finishing processes. These weakly bound fibers are typically detached during the first laundering cycles, resulting in lower emissions in subsequent experimental washes. While this approach may reflect reduced shedding after initial consumer use, it does not eliminate microfiber emissions; rather, it shifts a substantial portion of fiber release to earlier washing stages. The fibers removed during prewashing still enter wastewater systems and contribute to environmental contamination. Consequently, prewashing protocols may underestimate the total microfiber emissions associated with new garments and obscure differences between material types. In contrast, our results indicate that first-wash emissions remain substantial across synthetic textiles and are particularly pronounced for rPET fabrics. Moreover, by analyzing a broader set of commercially available garments ($n = 51$) and quantifying both fiber count and length, our study demonstrates that differences between virgin and rPET become apparent when particle-based metrics are considered, reinforcing the importance of fiber number and size as key indicators of environmental exposure.

Micro- and nanoplastics including microfibers are not inert particles but complex matrices composed of polymer backbones, embedded additives, degradation products, and adsorbed contaminants. It has been estimated that more than 16 000 chemicals can be associated with plastic materials, many of which are hazardous to human and environmental health (Wagner *et al* 2024). In many researches, elevated concentrations of toxic substances-including PFAS, plasticizers, and heavy metals-in ultra-fast-fashion garments have been identified and the majority of these garments are manufactured from petroleum-based synthetic fibers (Global2000, Global2000 2024). Recent analytical evidence further indicates that mechanically rPET contains significantly higher concentrations of non-intentionally added substances, including volatile organic compounds and phthalate esters, compared with virgin PET, with contaminant levels increasing as recycled content and processing intensity rise (Di Duca *et al* 2025). This chemical enrichment of recycled polymers provides a mechanistic context for our results, as the elevated fiber counts and shorter fiber lengths observed for rPET garments suggest that chemically and structurally degraded fibers are more prone to fragmentation and release during laundering, thereby acting not only as physical microfibers but also as vectors for a more complex and potentially hazardous chemical mixture. Smaller fibers exhibit higher surface-area-to-volume ratios, enhancing their capacity to adsorb metals, polycyclic aromatic hydrocarbons, and persistent organic pollutants (Wagner *et al* 2024). Short fibers are also more readily inhaled and ingested across a wide range of taxa, from soil invertebrates to fish and mammals (Soltani *et al* 2021, Değirmenci *et al* 2026, Gündoğdu *et al* 2026a). Consistent with these mechanisms, our results show that rPET predominantly shed shorter fibers (mean ≈0.42 mm) than virgin polyester and cotton, thereby increasing the proportion of released particles falling within biologically relevant and highly mobile size classes. Several textile processing and end-use factors beyond fiber and yarn type also modulate microfiber release, though they were not directly manipulated in the present study. Synthetic dyeing and finishing treatments can alter fiber surface chemistry and mechanical integrity; dye penetration and subsequent thermal fixation processes may weaken the fiber cortex or introduce microscale surface defects that act as fracture initiation points during mechanical agitation, while some finishing agents (e.g. softeners, anti-pilling or durable-press resins) can either coat and reinforce fiber surfaces, reducing shedding, or embrittle them over repeated laundering cycles. Natural dyes, which typically require different mordanting and fixation chemistries than synthetic dyes, may interact differently with fiber surfaces, though comparative data on their effect on microfiber shedding remain scarce. Chemical additives in detergents -particularly alkaline builders in powder formulations- have been shown to hydrolyze and degrade polyester and polyamide surfaces, increasing fiber fragment release, whereas surfactant-based liquid detergents and softener-containing formulations tend to reduce fiber–fiber friction and fibril detachment (Theeratampitak and Charusiri 2025). The mechanical intensity of washing-governed by rotational/spin speed, agitation type (drum rotation versus central agitator), and cycle duration-consistently emerges as a dominant driver of shedding, with higher speeds and longer cycles increasing both fiber count and mass release (Eamrat *et al* 2025). Similarly, the mode of dehydration and drying can substantially affect total fiber emissions: spin-drying subjects garments to additional centrifugal and frictional stress that generates further microfibers released to wastewater, while tumble drying has been identified as a comparable or even larger source of airborne microfiber emissions, particularly for looser knit structures and worn/aged garments. Collectively, these factors indicate that garment-level microfiber emissions are governed not only by intrinsic material properties (virgin vs recycled, fiber type) but also by the cumulative processing and care history of the textile, underscoring the need for standardized reporting of dyeing, finishing, detergent, and drying conditions in future comparative studies.

The present findings must also be interpreted in the broader context of the fast fashion business model, which is structurally dependent on fossil-fuel-based synthetic fibers to enable rapid production cycles, low unit costs, and high garment turnover (Changing Markets Foundation 2024a). Our results demonstrate that both virgin and recycled synthetic textiles consistently release substantial quantities of microfibers during laundering, indicating that the environmental burden is intrinsic to the material choice rather than an anomaly of specific products. This aligns with the concept of plastic addiction in the fashion sector, whereby incremental substitutions -such as replacing virgin polyester with rPET - are promoted as sustainability solutions without addressing the underlying growth in synthetic fiber production (Özkan and Gündoğdu 2021). Pew projections further indicate that global plastic pollution could more than double by 2040 under business-as-usual conditions, with rapidly expanding sectors such as textiles contributing significantly to this growth (Pew 2025). As fossil-based fiber production continues to expand, incremental mitigation measures-such as pre-washing garments, improving fiber construction, or modifying yarn and fabric design-may reduce the release of loosely bound fibers during laundering but are unlikely to offset rising absolute microfiber emissions at the system level. Our results further

indicate that both virgin and rPET garments consistently shed large numbers of microfibers, suggesting that substitution within synthetic materials alone does not resolve the underlying pollution pathway. While partial substitution of synthetic fibers with natural materials may reduce microplastic emissions in some applications, the current fast-fashion production model remains fundamentally enabled by low-cost synthetic polymers. Consequently, the continued expansion of fast fashion perpetuates structural dependence on fossil-based textiles and locks in a persistent and cumulative source of microfiber pollution, reinforcing the need for demand-side interventions, reduced reliance on synthetic fibers, and broader material-use reduction strategies alongside technical mitigation measures.

This study did not systematically characterize or control for fabric construction parameters - including fabric structure (woven vs knitted), yarn linear density, fabric areal weight, surface finishes, or functional treatments- across the tested garments. Garments were purchased and tested as sold, reflecting the declared material composition provided on brand labeling, in order to evaluate real-world shedding behavior associated with brands' material and recycled-content claims rather than to isolate the effect of fiber origin under controlled construction conditions. Consequently, the substantial brand-level variance observed in fiber count may partly reflect differences in fabric construction, garment design, or finishing between brands, rather than fiber source alone. Eleven garments were excluded from GyroWash testing due to printed areas or pronounced local structural heterogeneity that precluded standardized specimen cutting; while these exclusions were applied consistently across material categories, we cannot rule out that they introduce a modest systematic bias. Future work aimed at isolating the independent effect of recycled fiber content on microfiber shedding should employ garments or fabric swatches with standardized, controlled construction parameters.

Particle identity in this study was determined on the basis of morphological characteristics (fibrous shape, color, and size) under optical microscopy, consistent with the declared fabric composition provided on official garment labeling by each brand. No spectroscopic confirmation (e.g. ATR-FTIR, Raman) was performed to independently verify polymer identity or to rule out cross-contamination between sample types or background fibers. Consequently, our fiber count and length data should be interpreted as reflecting the declared material category of each garment rather than independently confirmed polymer composition. We note that cotton fibers, while quantified using the same morphological count metric as synthetic fibers for comparative purposes, are cellulosic and biodegradable, and are not classified as microplastics. Their inclusion in this study serves to benchmark natural-fiber shedding behavior against synthetic alternatives, not to equate the two in terms of environmental persistence. Future work aimed at independently verifying brand-level material claims, particularly in the context of emerging recycled-content labeling regulations, should incorporate spectroscopic or thermoanalytical confirmation (e.g. FTIR, Raman, or Py-GC/MS) for a representative subset of samples.

The 25 μm mesh-size sieve used to reduce bulk water volume prior to final filtration may have retained a portion of coarser fibers before the sample reached the 0.45 μm membrane filter. While this step was intended solely for water-volume reduction rather than particle fractionation, we cannot fully rule out selective retention of larger fibers, which could result in a modest underestimation of total fiber mass in the Wascator tests, particularly for material categories shedding longer, coarser fibers (e.g. cotton).

All reported data reflect first-wash fiber release. Shedding in subsequent washes is known to decline and may not follow the same pattern across material types, so our results should be interpreted as characterizing first-wash emissions rather than the general, long-term shedding potential of these materials. Additionally, GyroWash specimens were cut and edge-sealed, whereas Wascator testing used whole garments. While both protocols were applied consistently across all samples, this methodological difference may affect absolute fiber release values and should be considered when comparing results across the two test systems. Future studies incorporating pre-washing and repeated wash cycles would help clarify whether the material-type differences observed here persist beyond initial use.

5. Conclusion

By simultaneously quantifying fiber count, length, and mass across a broader set of commercially available garments, our study demonstrates that recycling-related differences become evident when particle-based indicators are considered, which are more directly relevant for environmental exposure and ecotoxicological risk. Taken together, the findings demonstrate that recycled synthetic fibers -particularly rPET- released descriptively higher fiber counts and, more robustly, significantly shorter fibers (material-type effect on fiber length) than their virgin counterparts. The multivariate analysis confirmed that

material type significantly affects the combined shedding profile (fiber count, length, and mass considered jointly), and the shorter fiber length associated with recycled materials is itself a relevant indicator of environmental exposure potential given the greater surface-area-to-volume ratio and bioavailability of smaller particles. These results are consistent with, though do not statistically confirm on a per-metric basis, prevailing industry narratives that equate recycled content with environmental benefit being oversimplified, and highlight the limitations of end-of-pipe solutions such as washing-machine filters.

Effective mitigation requires upstream interventions, including reducing fossil-based fiber production, eliminating downcycling pathways, improving textile design to minimize shedding, and regulating microplastic emissions at the product level. Beyond material-specific comparisons, our findings point to microfiber shedding as one facet of a broader problem rooted in the overproduction and rapid turnover of low-quality, fast-fashion textiles.

The study shows microfiber shedding is a bigger problem for recycled materials than cotton shedding. So, reducing reliance on synthetic fibres, which are set to grow, is another strategy to consider. Addressing microfibre pollution will require a combination of measures across the textile value chain, including more durable designs and manufacturing standards, lower consumption and production volumes, improved recycling processes that limit fibre degradation, and consumer-level laundering practices that reduce mechanical stress on garments. In other words, technical measures -such as industrial prewashing or improved fiber and yarn construction- may reduce the release of loosely attached fibers during consumer laundering, but they do not address the total volume of fibers entering wastewater systems across the product life cycle. Future research should compare such measures and their contribution to reducing microfibre emissions.

Policy frameworks such as the EU Ecodesign for Sustainable Products Regulation offer potential mechanisms for setting emission limits, while PEF could be a pathway for incorporating microplastic impacts into life-cycle assessments.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Conflict of interest

Urška Trunk and Nusa Urbancic are employees of the Changing Markets Foundation, which provided financial support for this study.

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