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Microplastic fiber fragment release from dry-state textiles: A novel peeling-based evaluation

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Abstract

While standardized methods exist for evaluating microplastic fiber fragment (MPFF) release during textile washing, dry-state release during garment manufacturing and use remains poorly understood. In this study, MPFF release from raw and finished knitted fabrics, including dyed and hydrophilic-softened (S), and dyed, softened, and antibacterial-finished (SP) samples, was investigated using novel peeling, cutting, and Martindale abrasion tests. The results demonstrate that fabric finishing alters MPFF release behavior: it reduces MPFF release during peeling but increases release under abrasion. In addition, cutting generates substantial emissions, particularly for raw fabrics and in the course direction. These findings highlight the importance of considering multiple mechanical actions when assessing MPFF release and indicate that considerable emissions occur during both manufacturing and use. The proposed approaches contribute to the development of more comprehensive testing methods and support the development of improved mitigation strategies in the textile industry.

Keywords

Microplastic, fiber fragment, knitted fabric, finishing, dry-state, original testing, sustainability

Microplastic fiber fragments (MPFFs) released from textiles represent one of the most significant environmental challenges associated with the fashion industry, which is considered one of the most polluting industries.[1-3] As research on the release of microplastics from textiles has only recently emerged,[4] there is currently no unified definition for the objects under investigation. In the literature,[5-9] tiny and fine fibers that can be released (shed or emitted) from textiles under both wet and dry conditions are described using varying terminology. These include terms such as microplastics or microfibers,[6,7,10,11] small fibrils,[8] fiber fragments,[5-7,10] or microlitter.[9] Microplastic fibers are small, predominately synthetic fibers[1,2,12] originating from materials such as polyester, nylon, and acrylic, and are typically less than 5 mm in length.[6,7] In general, microplastic is defined as "a material consisting of a solid polymer containing particles, to which additives or other substances may have been added, and where a weight fraction of 1 % particles has all sizes of 100 nm $\leqslant x \leqslant$ 5 mm, or for fibers, a length of 300 nm $\leqslant x \leqslant$ 15 nm and a length/diameter ratio >3".[10] Thus, the released microplastic fiber fragments are abbreviated in this research as MPFFs.

Owing to their small size, MPFFs can reach even the most remote areas of the ecosystem and exert physical, chemical, and biological effects.[9] Synthetic MPFFs are among the most widespread contaminants in aquatic microplastics, contributing approximately 35 % of total ocean microplastics.[13] They persist in the environment for decades, adsorb toxic chemicals, and enter the food

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chain through aquatic organisms, ultimately reaching humans.[3,14] It has also been estimated that humans may be exposed to 3187 ± 594 microplastics per year due to atmospheric contamination,[15] while approximately 0.28 million tons of MPFFs can enter aquatic environments globally through domestic laundering.[16] In addition, it is stated that the textile printing and dyeing industry can release (489 ± 36) million particles per day into the aquatic environment.[17]

MPFF release occurs throughout the entire life cycle of textile products, including fiber production, fabric manufacturing, garment assembly, consumer use, and end-of-life degradation.[2,18] Mechanical stresses generated during processes such as spinning, knitting, weaving, brushing, sanding, sewing, abrasion, and cutting can promote fiber fragmentation and release.[18–21] The extent of MPFF shedding is influenced by numerous factors, including fiber composition, yarn characteristics, fabric construction, and finishing treatments.[12,18] Recent studies have identified garment manufacturing processes as important sources of dry-state MPFF emissions, highlighting the need for reliable methods capable of evaluating fiber release under these conditions.[3,20]

Historically, domestic laundering has received the greatest attention as a source of textile-derived microplastics. Consequently, the earliest and most widely adopted methodologies for MPFF quantification were developed specifically for washing experiments. Typically, fibers released during laundering are collected from wastewater by filtration and subsequently quantified using microscopic and spectroscopic techniques.[21,22] Although standardized methods for washing-based release have only recently been introduced (ISO 4484-1:2023[6] and ISO 4484-3:2023[7]) and currently represent among the most robust and reliable approaches for quantifying fragmented fibers, these methods remain labor-intensive, time-consuming, and may limit their wider implementation in large-scale research and industrial applications.

Despite these advances, equivalent methodologies for dry-state MPFF release remain largely undeveloped. The quantification approaches established for laundering studies cannot be directly transferred to dry-state conditions, where fiber generation, transport, suspension, and deposition occur through fundamentally different mechanisms. Consequently, the ability to reliably quantify fiber fragmentation under dry-state conditions remains limited, and no standardized methods currently exist for evaluating dry-state MPFF emissions.

Several studies have demonstrated that abrasion, cutting, and other mechanical actions can generate substantial quantities of airborne MPFFs. In some cases, abrasion has been reported to release significantly more fibers than laundering,[8,21] while cutting a medium-sized T-shirt may generate up to 1.09×10^6 MPFFs, approximately 50 times more than the quantity released during washing.[9] Furthermore, 40–70% of fibers generated during garment manufacturing may be transported beyond production facilities.[9] These findings indicate that dry-state processes may represent a major but insufficiently characterized source of textile-derived microplastic pollution.

However, current investigations of dry-state MPFF release employ highly diverse experimental configurations, including abrasion devices, cutting simulations, passive collection methods, active air-sampling systems, and various particle characterization techniques.[23–26] Analytical approaches commonly rely on Fourier-transform infrared (FTIR) spectroscopy, Raman spectroscopy, or pyrolysis–gas chromatography–mass spectrometry (Py-GC/MS), while different studies report results using varying sampling strategies and release metrics.[24–26] This methodological diversity complicates direct comparison between studies and introduces uncertainty regarding the reproducibility and reliability of reported emission values.

An additional challenge lies in distinguishing textile-derived MPFFs from other airborne particles and in differentiating natural fibers from synthetic ones, particularly after environmental degradation and surface modification.[23,27,28] As a result, the lack of harmonized sampling procedures, analytical workflows, and reporting methodologies continues to hinder the development of a consistent understanding of dry-state MPFF release.

Although considerable research has examined the mechanisms and influencing factors governing MPFF release,[8,29–31] the primary limitation is no longer the lack of evidence that dry-state MPFF release occurs. Rather, the key unresolved challenge is the lack of robust, reproducible, and application-oriented methodologies capable of quantifying dry-state MPFF emissions under controlled condition. This methodological gap limits the comparison of textile materials and processes, constrains the evaluation of mitigation strategies, and hinders future standardization efforts.

Therefore, the aim of this research was to address the current methodological gap in dry-state MPFF quantification by developing and applying novel experimental approaches for measuring fiber release from textiles under controlled peeling, abrasion, and cutting conditions and determine whether there are some limitations of the suggested methods due to the different treatment of knitted fabrics. Thus, the developed methodology was subsequently used to compare the MPFF release behavior of differently finished knitted fabrics and to evaluate its suitability as a practical tool for characterizing dry-state textile emissions.

Materials and methods

Materials and fabric preparation

Knitted fabrics were selected for this study due to their higher propensity for MPFF release compared to woven structures, as reported in the literature.[32] Three fabric variants were manufactured under controlled conditions: raw (R), dyed and hydrophilic softened (S), and dyed, softened and treated with an antibacterial finish (SP).

All samples were produced in a 1 × 1 rib structure using three-ply Z-twist yarns (Haining Taierxin New Material Co. Ltd., China). The yarns consisted of 65% cotton and 35% polyester, with the polyester component containing 0.6 wt.% conductive carbon black. The selected yarn composition represents a commercially available blended textile material relevant for durable and technical textile applications, including workwear and upholstery-related products. The selection of more complex knitted fabrics composed of cotton fibers and polyester fibers containing conductive carbon and functional finishing was intentionally intended to represent a realistic worst-case scenario, where fiber mobility and detachment are expected to be more pronounced due to modified surface properties. Knitting was carried out using a fully automatic flat knitting machine (M-100, 14E, Matsuya, Japan).

Dyeing and finishing processes were performed using THIES MINISOFT equipment (Germany, model 1995), Santex CH-9555 Tobel (Switzerland), and a Santex padder, following standard textile processing procedures. The chemicals used included SARABID TS 300 (CHT R. Beitlich GmbH, Germany), wrinkle resistant agent W BREVIOL® PAM-N (Pulcra Chemicals GmbH, Germany), anionic dispersing agent MEROPAN DPE (CHT R. Beitlich GmbH, Germany), salt, reactive BEZAKTIV dyes (CHT R. Beitlich GmBH, Germany), SECURON540 and BREVIOL® PAM-N (Pulcra Chemicals GmbH), and Polygiene VO-600. Polygiene VO-600 was applied to the antistatic knitted fabric by pad dry cure method using these technological conditions: 25 g/l concentration at 10:1 liquor ratio and 5–6 pH; 40°C temperature, and 20–30 min duration.

Fabric morphology was examined using a Quanta 200 FEG scanning electron microscope at a magnification of 2000×. Structural parameters were determined according to standardized methods: yarn linear density (ISO 7211-5:2000),[33] wale and course density (EN 14971:2006),[34] thickness (ISO 5084:2000),[35] and area density (EN 12127:1999).[36]

Determination of MPFF release by peeling test

An experimental method was developed to quantify MPFF release from dry-state textiles based on the mass of fiber fragments collected using a tape commercially available from the OKKO company (Poland) made of polyisoprene-based pressure sensitive adhesive coated on a paper substrate. The method for collecting MPFFs from dry-state textiles was adapted from established peeling test standard methods that are applied for the evaluation of the quality of self-adhesive tapes, i.e., ISO 29862:2024 standard,[37] touch and close fasteners, i.e., EN 12242:1999 standard,[38] and earlier experimentally approved methodology for the evaluation of the quality of textile adhesive bonds.[39] Based on the analysis performed, it was noticed that the defined values of the peeling rate, gauge length, specimen preparation conditions (bonding pressure and mode, etc.) were different, but a computerized constant-rate-of-extension (CRE)-type tensile machine used for the peeling process was general. Thus, in this research, the testing conditions that were closest to the quality assessment of the textile adhesive bonds were chosen.[39] For each fabric variant (i.e., R, S and SP), five specimens with dimensions of 50 mm × 60 mm were prepared along the wale direction. A paper tape coated with pressure sensitive adhesive was applied to the fabric face under controlled conditions. Bonding was achieved using a Stirovap press (Reggio Emilia, Italy) with a pressing duration of 40 min to ensure consistent adhesion without heating (at ambient temperature) (Figure 1a).

Subsequently, peeling tests were then performed using a computer-controlled CRE-type tensile testing machine (H10KT, Tinius Olsen Ltd., UK) at a constant rate of 50 mm/min (Figure 1b,c) to ensure the same testing conditions for each peeled-off specimen. The peeling force was recorded as the force per unit width (N/mm). Finally, MPFF release was quantified as the difference between the mass of the adhesive tape after peeling and the initial mass of the tape. All measurements were carried out using a precision balance (EG420-3NM, Kern & Sohn, Germany) with an accuracy of 0.001 g. It should be noted that, due to the blended composition of the fabrics (cotton/polyester), the collected fiber fragments may include both natural and synthetic fibers; however, the term MPFF is used throughout this study to denote the total released fiber fragments.

Martindale abrasion test for mass loss determination

Abrasion behavior and associated MPFF release were evaluated using the Martindale method in accordance with ISO 12947-3:1998.[40] Testing was conducted under a nominal pressure of 9 kPa, corresponding to 2.5 ± 0.5 kg, using a loading head with a diameter of 120 ± 10 mm. A porous support layer was introduced to ensure uniform contact conditions, as the area density of the tested fabrics did not exceed 500 g/m^2, in accordance with the standard requirements.[40] A circular

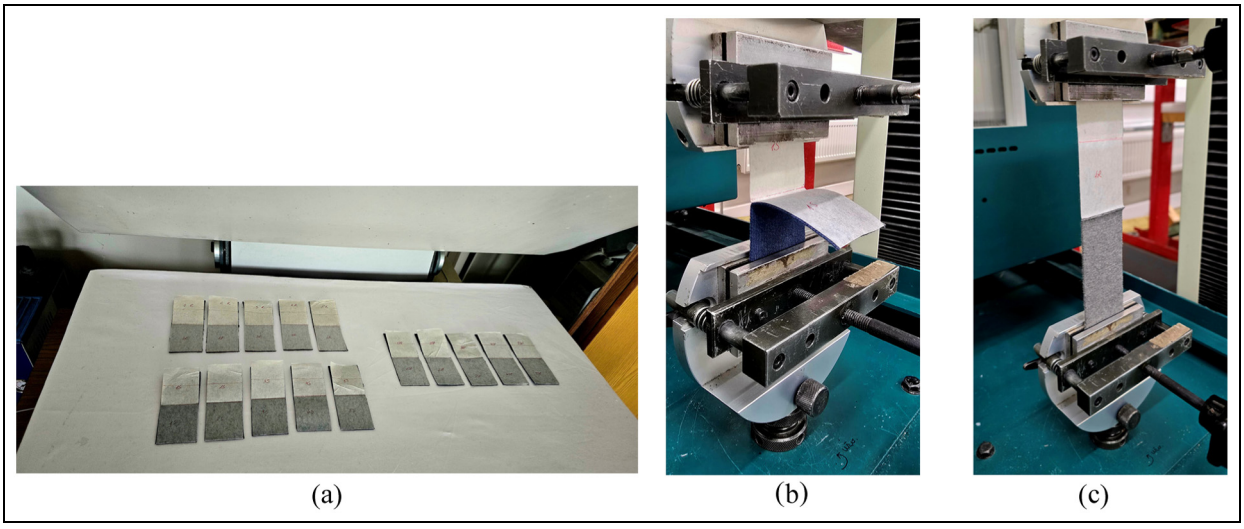

Figure 1. Photographs of the peeling test procedure: (a) preparation of bonded fabric–adhesive tape specimens prior to testing; (b), (c) peeling test performed using a CRE-type tensile testing machine.

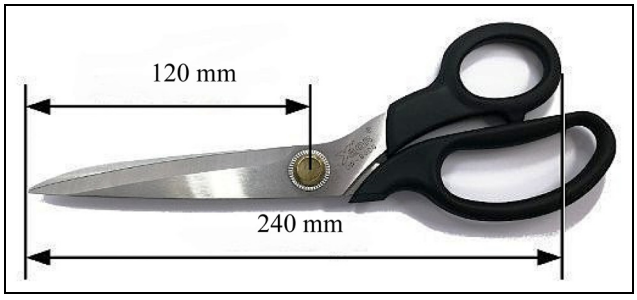

Figure 2. Scissors X'sor model DW-9001.

wool felt abrasive with a diameter of 140 mm was used, and a load of 595 ± 7 g was applied as recommended for clothing and household materials. Abrasion was performed using cycle type C, corresponding to 5000–10,000 revolutions or until specimen rupture. The mass of the specimens was determined after 1000, 5000, 7500, 10,000, and 15,000 cycles. In cases where specimen rupture did not occur, testing was continued at intervals of 5000 cycles up to a maximum of 90,000 cycles. At each interval, specimen mass was measured to evaluate mass loss. Measurements were carried out using the precision balance EG420-3NM.

Cutting-induced microplastic fiber fragment release

MPFF release during cutting was evaluated by simulating garment manufacturing conditions using manual scissors (X'SOR 9001) equipped with a stainless-steel blade (420J2, hardness 52–55 HRC) (Figure 2).

For each fabric variant (i.e., R, S, and SP), 12 specimens with dimensions of 50 mm × 50 mm were prepared. Specimens were cut along two orientations, namely the wale and course directions, to assess the influence of fabric structure on MPFF release. All specimens were prepared with identical dimensions and tested using the same cutting and collection procedure to ensure repeatability (Figure 3).

To collect the MPFFs released in the cut edges of the specimens, the self-adhesive tape, identical to that used in the peeling test, was gently applied to the fabric face prior to cutting. To determine the influence of fabric orientation on MPFF release, 5 of the 10 specimens were cut in the direction of fabric course and the other 5 in the direction of fabric wale. Following cutting, each specimen was divided into two pieces, and the freshly exposed edges were brought into contact with the adhesive surface to ensure transfer of detached microfibers. Following cutting, the released fibers were collected using the same collection and weighing procedure for all specimen to ensure consistency of the measurement and minimize cross-contamination. Subsequently, the mass of the adhesive tape before and after fiber collection was determined using the precision balance (EG420-3NM). MPFF release was quantified gravimetrically as the difference between the mass of the tape after fiber collection.

Results and discussion

Fabric structure and fiber morphology

The structural characteristics of the investigated knitted fabrics are summarized in Table 1.

The results presented in Table 1 indicate that wet treatment of the investigated knitted fabrics resulted in a slight increase in the number of wales and courses, which can be attributed to the high content of

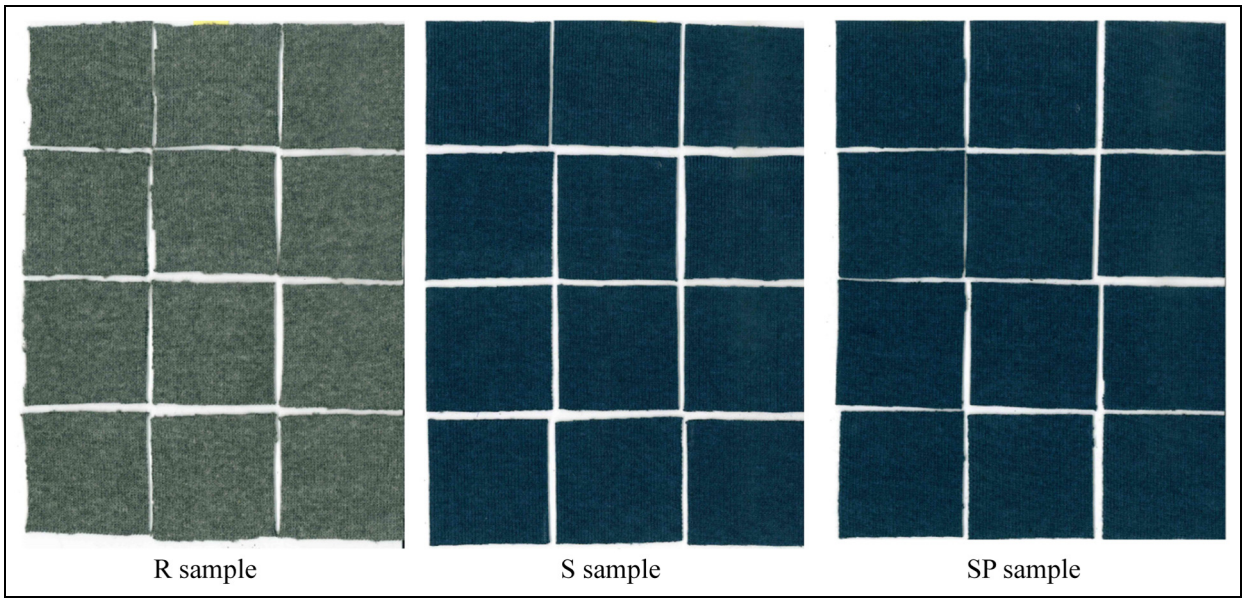

Figure 3. Specimens tested in the cutting test.

Table 1. Structural characteristics of the investigated knitted fabrics.

Fabric characteristics and the standard methodology applied for their determination	Fabric sample code		
	R	S	SP
Linear density of yarn, tex (ISO 7211-5: 2020)[33]	(24 ± 1)′3	(24 ± 1)′3	(24 ± 1)′3
Number of wales, cm^{-1} (EN 14971:2006)[34]	15.8 ± 0.5	16.5 ± 0.5	16.0 ± 0.5
Number of courses, cm^{-1} (EN 14971:2006)[34]	11.6 ± 0.6	12.0 ± 0.5	12.0 ± 0.5
Thickness, mm (ISO 5084:2000)[35]	1.94 ± 0.02	1.68 ± 0.02	1.73 ± 0.01
Area density, g/m^2 (EN 12127:1999)[36]	523 ± 0	511 ± 0	507 ± 0

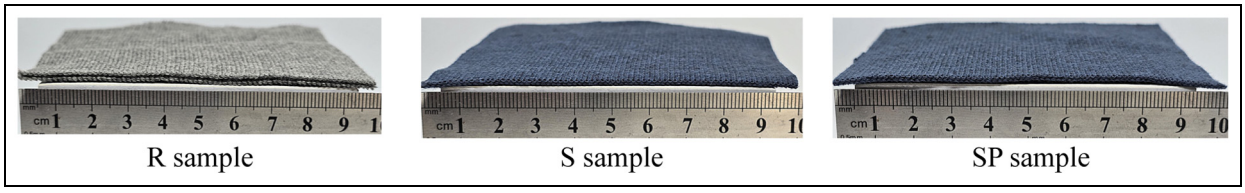

Figure 4. Cross-sectional images of the tested fabrics: (R) raw; (S) dyed and softened with hydrophilic softener; and (SP) dyed, softened, and treated with an antibacterial finish.

hydrophilic cellulosic cotton fibers in the fabric structure, i.e., 65%. In addition, shape stabilization processes and the removal of impurities and waxes led to a decrease in fabric thickness and area density in the finished samples. With an area density of approximately 500 g/m^2, the investigated fabric can be considered heavyweight knitted fabrics, which are relevant for durable applications.

To further examine the fabric structure, cross-sectional images of the investigated fabrics, cut along the course direction, are presented in Figure 4. The images indicate that all fabric variants (R, S, and SP) exhibit a stable and well-defined knitted structure, with no pronounced distortion of the loops.

The fiber morphology was further examined using scanning electron microscopy (SEM), and representative images are shown in Figure 5. Cotton fibers exhibited a characteristic twisted ribbon-like structure with a central lumen, whereas polyester fibers displayed a more uniform and circular cross-section. The presence of carbon black within the polyester fibers was observed as dispersed dark inclusions. No significant morphological

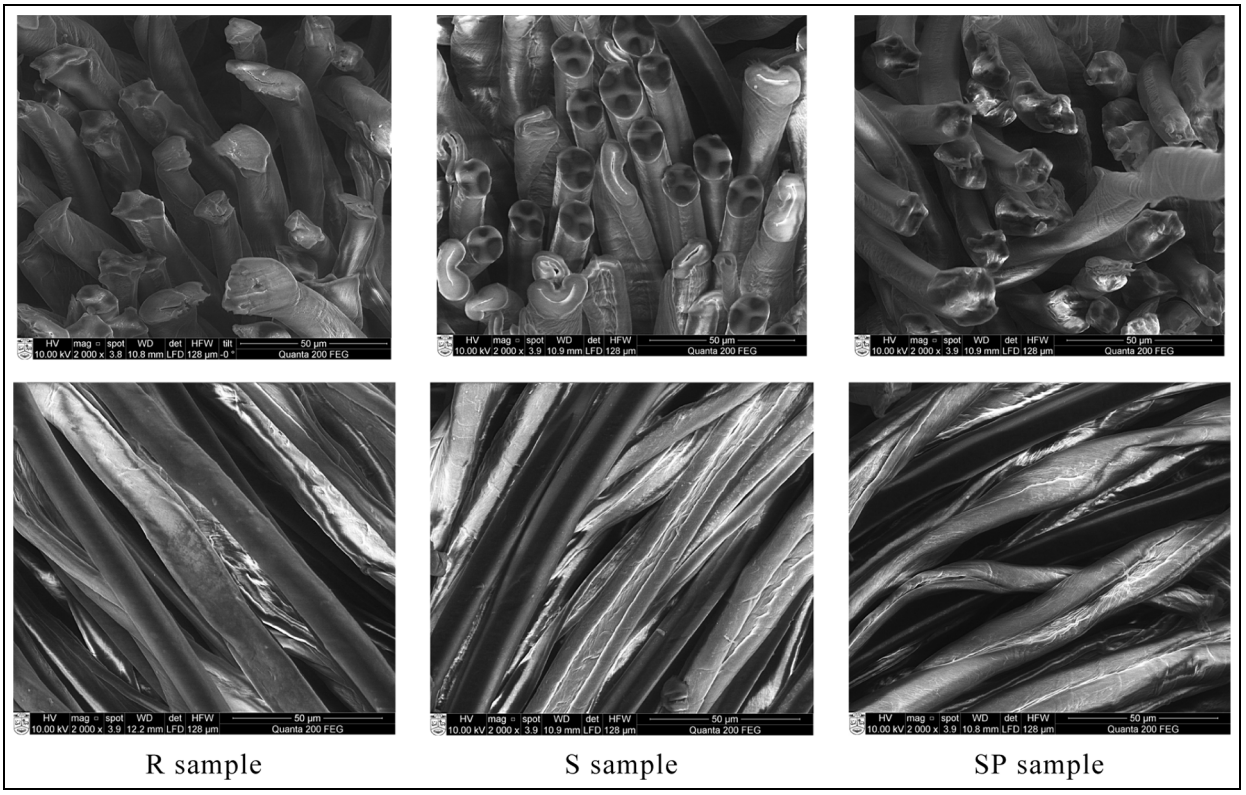

Figure 5. SEM images of the fiber morphology of the investigated fabrics: (R) raw; (S) dyed and hydrophilic-softened; and (SP) dyed, softened, and antibacterial-finished. Scale bar: 50 μm.

changes were observed after treatment of the S and SP samples. Both fiber types retained their original structural characteristics, indicating that the applied finishing processes did not substantially alter fiber geometry. A thin layer of finishing agents was observed on the fiber surfaces; however, the interfiber spaces remained largely unfilled.

MPFF release by peeling test

The MPFF release behavior of the investigated fabrics was evaluated using the peeling test method described previously, in which the mass of fiber fragments collected on an adhesive substrate was used as a quantitative measure.

As discussed previously, the investigated fabrics exhibit differences in structural parameters and surface characteristics resulting from the applied finishing treatments. In particular, the presence of finishing agents on the fiber surfaces and the variation in fabric density are expected to influence fiber–fiber interactions and, consequently, the detachment of MPFF from the fabric surface.

The applied method was developed based on principles of peeling mechanics commonly used in the evaluation of adhesive systems, including self-adhesive tapes,[37] touch-and-close fasteners,[38] and textile adhesive bonding.[39] Although testing parameters such as peeling rate, gauge length, and specimen preparation vary across these applications, the use of a CRE tensile testing machine is a common feature. Based on this analysis, the selected testing conditions were chosen to approximate those used for textile bonding systems, ensuring controlled and reproducible detachment of fiber fragments from the fabric surface.

The results of the peeling tests, which simulate MPFF release under dry-state conditions during clothing wear (e.g., lint removal), are presented in Tables 2 and 3, while representative images of the adhesive tapes with the collected MPFF are presented in Figure 6.

The results presented in Table 2 indicate that the highest peeling strength (F) was observed for the raw knitted fabric (R), while the lowest value was obtained for the dyed, softened, and antibacterial-finished fabric (SP). The dyed, softened sample (S) exhibited intermediate behavior. Specifically, the peeling strength decreased by approximately 40% for sample S and more than 55% for sample SP compared with the raw fabric (R). These results demonstrate that fabric finishing treatments may reduce the adhesion between the pressure sensitive adhesive tape and the fabric surface, supposedly due to decreased surface free energy, thus

Table 2. Peeling strength testing results. The results are reported as mean values ± standard deviation (n = 5).

	Fabric sample code		
Parameter	R	S	SP
Peeling strength F (N/mm)	0.077 ± 0.001	0.046 ± 0.002	0.033 ± 0.002

Table 3. MPFF release in the peeling test for the investigated fabrics: (R) raw; (S) dyed and hydrophilic-softened; and (SP) dyed, softened, and antibacterial-finished. The results are reported as mean values ± standard deviation, n = 5.

	Fabric sample code		
Mass (g)	R	S	SP
Mass of released MPFFs collected on a self-adhesive tape of 3000 mm^2 area, m_{MPFF} (g)	0.006 ± 0.000	0.001 ± 0.000	0.000 ± 0.000
Mass of MPFFs released calculated per 1 m^2 of knitted fabric, m_{MPFF} (g)	2.000	0.333	0.000

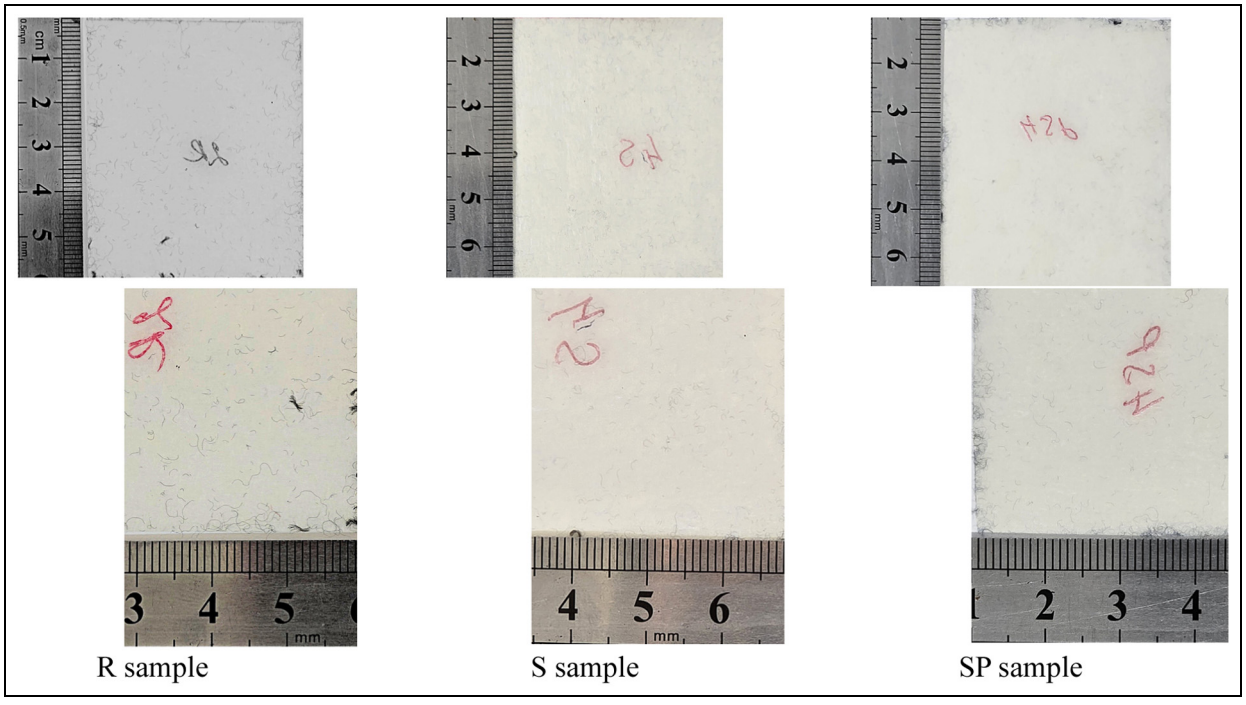

Figure 6. MPFFs collected on self-adhesive tapes in the peeling test for the investigated fabrics: (R) raw; (S) dyed and hydrophilic-softened; and (SP) dyed, softened, and antibacterial-finished.

affecting adhesion and wettability, as stated in the literature.[41]

The results of the peeling test further confirm that as the peeling strength F (Table 2) decreases, the mass of released MPFF also decreases (Table 3). The highest MPFF mass was observed for the raw fabric (R). For the S sample, it was approximately six times lower than that of the R sample, whereas for the SP sample, the measured MPFF mass was equal to zero. This can be attributed to the limited precision of the balance used, as collected MPFF were still observed on the surface of the adhesive tape (Figure 6).

The results obtained in this study are consistent with trends reported in the literature, indicating a reduction in MPFF release following chemical treatment of textiles.[32,42] For example, Ramasamy and Subramanian[42] stated that pectin-based finishes, poly(lactic acid) (PLA) and poly(butylene succinate-co-butylene adipate) (PBSA)

Table 4. Mass loss of fabric in the Martindale test for the investigated fabrics: (R) raw; (S) dyed and hydrophilic-softened; and (SP) dyed, softened, and antibacterial-finished.

	Fabric sample code					
	R		S		SP	
Number of abrasion cycles	Mass loss with respect to initial mass m_{R0} (g)	Mass loss with respect to initial mass m_{R0} (%)	Mass loss with respect to initial mass m_{S0} (g)	Mass loss with respect to initial mass m_{S0} (%)	Mass loss with respect to initial mass m_{SP0} (g)	Mass loss with respect to initial mass m_{SP0} (%)
0	—	—	—	—	—	—
1000	0.000	0.00	0.000	0.00	0.003	0.41
5000	0.001	0.20	0.002	0.33	0.004	0.67
7500	0.004	0.61	0.006	1.04	0.007	1.08
10,000	0.005	0.71	0.008	1.31	0.008	1.18
15,000	0.005	0.76	0.010	1.70	0.020	3.03
20,000	0.009	1.31	0.012	1.91	0.022	3.34
25,000	0.012	1.77	0.016	2.57	0.024	3.75
30,000	0.014	2.07	0.019	3.12	0.027	4.21
35,000	0.017	2.58	0.022	3.61	0.030	4.57
40,000	0.017	2.58	0.025	4.05	0.034	5.24
45,000	0.020	3.08	0.027	4.38	0.038	5.91
50,000	0.021	3.19	0.028	4.65	0,042	6.47
55,000	0.025	3.74	0.034	5.58	0.048	7.45
60,000	0.033	4.95	0.039	6.46	0.053	8.22
65,000	0.035	5.31	0.042	6.84	0.054	8.37
70,000	0.036	5.46	0.042	6.95	0.062	9.60
75,000	0.041	6.17	0.049	8.10	0.068	10.48
80,000	0.046	6.98	0.055	9.03	0.088	13.61
85,000	0.051	7.74	0.061	10.01	0.092	14.12
90,000	0.056	8.49	0.066	10.89	0.102	15.72
Variation coefficient	(1.2,1.8) %		(0.1,0.6) %		(0.2,1.1) %	

Note: m_{R0} = 0.659 ± 0.021 g (an initial mass of a sample with a radius of 38 ± 5 mm cut from the knitted fabric (R); m_{S0} = 0.609 ± 0.004 g (an initial mass of a sample with a radius of 38 ± 5 mm cut from the knitted fabric (S); m_{SP0} = 0.649 ± 0.004 g (an initial mass of a sample with a radius of 38 ± 5 mm cut from the knitted fabric (SP).

finishes reduced MPFF release by up to 90% in polyamide fabrics, while chitosan treatments resulted in reduction of up to 27%. In addition, the application of silicon emulsions led to a marked decrease in MPFF shedding, whereas mechanical processes such as brushing and shearing increased MPFF release. Furthermore, other studies[32] have determined that alkali treatment of knitted and woven polyester fabrics can reduce MPFF release, by up to 68% and 89.6%, respectively.

Results of the abrasion testing and their discussion

The results of MPFF release from dry-state fabric abrasion, determined using the Martindale method in accordance with ISO 12947-3:1998,[40] are presented in Table 4, with the recorded mass loss values corresponding to MPFF released onto the surface of the abrasive pads (Figure 7).

The analysis reveals that after 90,000 abrasion cycles (Table 4), the highest mass loss was observed for the fabric treated with the antibacterial finish (SP), while the lowest was recorded for the raw fabric (R). After 90,000 abrasion cycles, the SP sample released approximately 1.9 times higher mass loss than the R sample, while the S sample showed 1.3 times higher mass loss compared with the R sample. These results are opposite to those obtained using the peeling test method (Table 3). This confirms that textile chemical finishing reduces the adhesion between the fabric surface and the adhesion tape, likely due to changes in surface wettability[41] and roughness. As a result, lower peeling strength values (Table 2) and reduced MPFF release from the fabric surface (Table 3) are observed. In contrast, under Martindale testing, the treated fabrics become softer and more flexible, making them more susceptible to fiber breakage and, consequently, increased MPFF release compared with the peeling test.

Results of the fabric cutting test and their discussion

The mass of MPFFs released during dry-state fabric cutting is presented in Table 5. Images of the tested specimens cut from R, S, and SP samples in both the

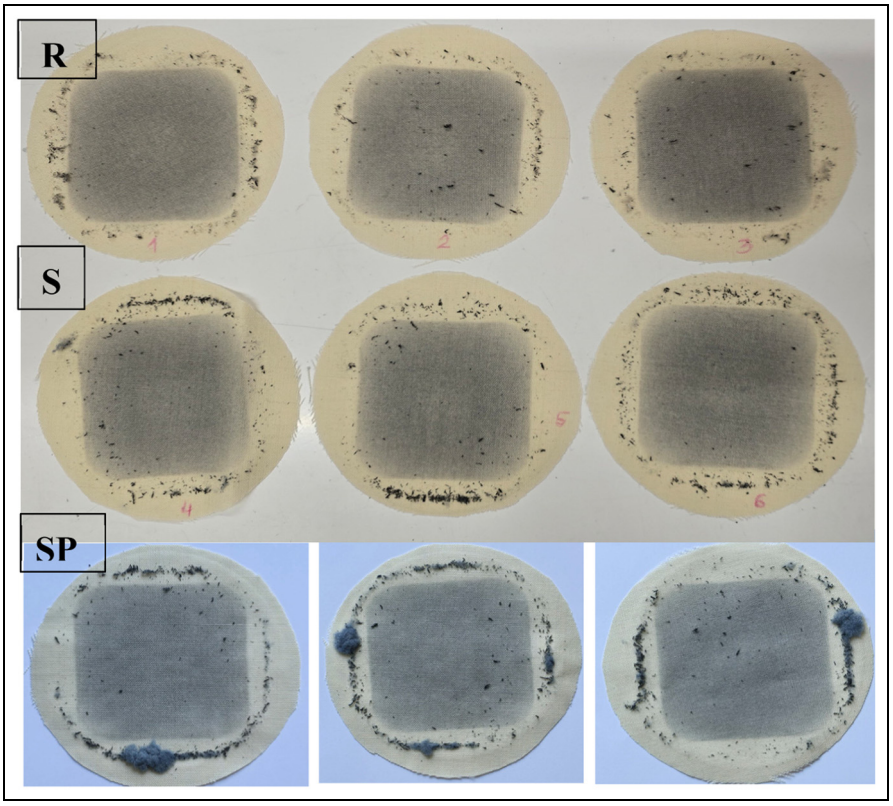

Figure 7. Images of 140 mm diameter pads used in the Martindale abrasion test after 90,000 cycles of abrasion: (R) raw fabric; (S) dyed and softened fabric; (SP) treated with antibacterial finishing fabric.

Table 5. MPFF release in the cutting test for the investigated fabrics: (R) raw; (S) dyed and hydrophilic-softened; and (SP) dyed, softened, and antibacterial-finished. The results are reported as mean values ± standard deviation (n = 5).

		Sample code		
Mass (g)		R	S	SP
Mass of released MPFFs (g)	Course	0.020 ± 0.005	0.005 ± 0.002	0.005 ± 0.000
	Wale	0.009 ± 0.004	0.002 ± 0.001	0.003 ± 0.001

course and wale directions are shown in Figure 8. The results indicate that the quantity of released MPFF is strongly influenced by both fabric orientation and the applied finishing treatments.

The results presented in Table 5 revealed that the raw fabric (R) released the highest mass of MPFFs, whereas the finished fabrics (S and SP) released substantially less. This behavior is due to structural modifications occurring during the finishing process. The application of dyes, softeners, and antibacterial agents produce smoother fiber surface and partially fill interfiber spaces, thereby stabilizing the fabric structure.[43] In contrast, the raw fabric (R) contains a higher number of loose fibers ends, which are more readily released during cutting.

In the cutting experiment, the R sample released 4 times more MPFF than the S sample in the course direction and 4.5 times more in the wale direction. Similarly, the SP sample showed lower MPFF release than the R sample in both fabric directions, with approximately 4 times lower values in the course direction and 3 times lower in the wale direction.

Fabric orientation also had an effect on MPFF release. Cutting in the course direction resulted in higher MPFF release compared with the wale direction for all tested fabrics. This can be explained by the knitted structure, where the wale direction consists of vertically aligned loops, resulting in fewer yarn strands being disrupted during cutting. Quantitatively, cutting in the course direction

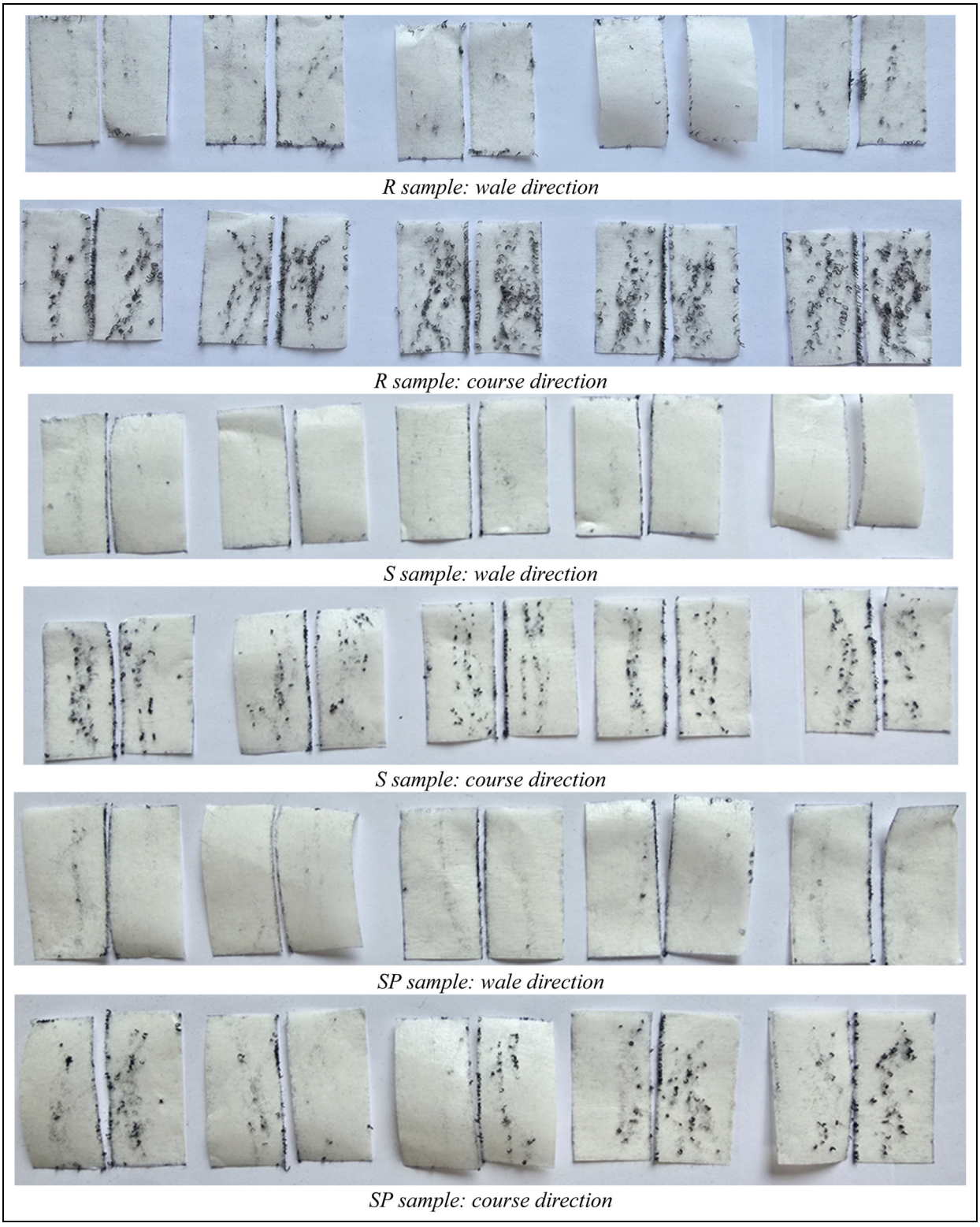

Figure 8. Self-adhesive paper tape specimens with the collected MPFFs: (R) raw; (S) dyed and softened; (SP) treated with antibacterial finishing.

produced 2.2 times more MPFFs for the R sample, 2.5 times more for the S sample, and 1.7 times more for the SP sample (Table 5). These findings indicate that, in the industrial manufacturing involving large-scale cutting operations, the cutting process represents a major source of MPFF release into the

surrounding environment, including the facility air and floor.

It should be noted that the cutting tests were conducted under controlled laboratory conditions to ensure reproducibility and to enable a systematic evaluation of the influence of fabric orientation and finishing treatments on MPFF release. Therefore, the results should be interpreted within the scope of controlled mechanical damage of precisely prepared specimens. Nevertheless, the observed differences between fabric directions and treatments highlight the importance of cutting-related processes as a source of MPFF generation. Industrial cutting operations, which typically involve higher cutting speeds, greater mechanical forces, and multilayer fabric assemblies, may generate even higher levels of MPFF emissions. Further investigations under industrial-scale conditions are needed to better understand the magnitude of MPFF release during textile manufacturing.

In addition, it should be assumed that the newly proposed methods were not performed on standard cotton and polyester knitted and woven fabrics. Therefore, their effectiveness must be evaluated on commonly used commercial products, not just functional knitted fabrics with different treatments tested in this research. Changes in fiber mobility in the yarn or fabric structure also must be evaluated in the future for each particular case, e.g., commercial cotton, polyester, and blended fibers. Furthermore, it should be added that the relevance of the peeling test under commercial conditions lies within its suitability to simulate the real-time condition under dry-state emission during the wearing or drying of garments or when removing the lint using a commercially available tape made of pressure sensitive adhesive coated on a paper substrate.

Conclusions

In this research, the release of MPFFs from dry-state knitted fabrics was evaluated using an originally developed peeling method, manual cutting, and the standard Martindale abrasion tests across three fabric variants with different finishing treatments. The influence of fabric finishing, fabric orientation (wale and course), and testing method on MPFF release was systematically analyzed.

The results obtained using the proposed peeling method, based on adhesion and peeling principles, showed that the highest peeling strength (0.077 N/mm) was determined for the raw fabric (R), while the lowest value (0.003 N/mm) was recorded for the dyed, softened, and antibacterial-finished fabric (SP). Correspondingly, the highest mass of released MPFFs (2.000 g/m^2) was measured for the R sample. These findings show that fabric finishing processes modify the surface properties of knitted fabrics, reducing the adhesion between the fabric and the self-adhesive tape and leading to lower MPFF release during peeling. In contrast, the results of the Martindale abrasion test treated fabrics showed increased MPFF release from the knitted fabrics. It was determined that after 90,000 abrasion cycles, the SP sample released 1.9 times more MPFF than the R sample, and the S sample 1.3 times more than the R sample.

The results from the manual cutting test further demonstrated that fabric finishing influences MPFF release. The raw fabric (R) released the highest mass of MPFFs compared with chemically treated fabric samples (S and SP). Fabric orientation also influenced the MPFF release, with the course direction consistently producing higher MPFF release than the wale direction, which can be attributed to the geometry of the 1 $\times$ 1 rib knit structure.

The literature analysis has shown that the release of MPFFs is significantly dependent on the textile structure and properties; therefore, the results of this study should be interpreted taking into account the MPFF release characteristics determined for the knitted fabrics studied here, which depend on the direction of the material, the treatment, and the laboratory conditions simulated in the dry state. The research results obtained applying the newly developed methodology can be interpreted as the trend for the differently treated knitted fabrics, as finishing is a key factor that influences the amount of MPFF. In addition, the carbon particles that are inserted into the structure of polyester fibers and fabric treatment can modify the friction between fibers of the fabric, surface energy and electrostatic behavior, and can potentially increase the fiber mobility of the fiber and the number of MPFF. Therefore, the absolute MPFF values should not be directly extrapolated to untreated cotton or polyester fabrics or to textiles with different fiber compositions or finishing treatments. Despite this, the peeling method itself remains applicable, but the amount of MPFF release depends on the properties of the knitted fabric.

In summary, these findings indicate that notable MPFF release occurs at early stages of the garment production as well as during use. Cutting processes generate dry-state MPFF which spread through the working environment and potentially enter the surrounding environment. While applying finishing treatments can reduce MPFF release during wear, effective measures are required to manage emissions generated during manufacturing processes. In particular, garment manufacturers should implement strategies for the collection and control of MPFF released during cutting operations. In addition, the textile industry could reduce MPFF release during wear by applying appropriate finishing treatments.

Therefore, future research should explore a holistic approach to MPFF mitigation across the entire life cycle of textile products. The results of this research contribute to the development of more comprehensive testing methods for evaluating MPFF released from dry-state textiles and support the advancement of mitigation strategies.

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Supplemental material

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