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Fibre fragment pollution: source directed intervention through design

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ABSTRACT

This study analyses the difference in fibre fragment pollution generated during the laundering of woven and knit fabrics for clothing and the influence of fabric parameters on the amount of pollution released. 100% polyester single jersey knit and 2/2 twill woven fabrics were created and washed according to AATCC TM212-2021. Results indicated more tightly woven structures released over three times less pollution than looser knit structures, releasing 6.41 mg of fibre fragments per kg of woven fabric (mean ± 1.50 SD, $n = 8$) compared to 21.21 mg of fibre fragments per kg of knit fabric (mean ± 1.80 SD, $n = 8$). The first wash for both knit and woven fabrics shed significantly more fibre fragments than subsequent washes. By the fifth wash both fabrics released under a tenth of the amount of pollution released in the first wash. To mitigate fibre fragment pollution that is released by fabrics designed for clothing this work recommends designing out pollution using more tightly constructed fabrics. Furthermore, the implementation of technology in fabric and garment manufacturing processes (e.g. fibre catching devices) should be utilised specifically during first washes allowing pollution to be filtered from the wastewater to stem the flow of contaminants into the environment.

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Microfibre pollution; fibre fragment; textile manufacturing; eco-design; source directed pollution intervention

Introduction

Laundering textiles has been identified as a major source of microscopic pollution to our environment (Boucher & Froit, 2017; EEA, 2022). Historically, 'microscopic fibres' identified in water samples consisted of common polymers that had a wide range of uses including 'clothing, packaging and rope' (Thompson et al., 2004, p. 1). Browne et al. (2011) conducted the first study to directly correlate microscopic fibres contaminating our shorelines to clothes laundering. Scientists have since been analysing the breakdown and release of these fibre fragments from textiles and apparel (i.e. Cai et al., 2020a; Dalla Fontana et al., 2021; Özkan & Gündoğdu, 2020; Raja Balasaraswathi & Rathinamoorthy, 2021; Yang et al., 2022).

Within the literature a variety of terms are used, including, but not limited to microscopic fibres, fibre fragments, or microfibres. Yet, some of these can be defined in distinct terms. Fibres that are less than 5 mm in length are commonly referred to as 'microfibres' (or 'microfibers' in the US; Cai et al., 2021; Napper et al., 2020a). More recently, the term 'fibre fragments' has been used by the American Association of Textile Chemists and Colourists (AATCC) to distinguish between the textile industry's use of microfibres in the context of a textile made up of 'fibres with a linear density less than 1 denier or 1 dtex' and the fibres that fragment off textiles and apparel as pollution (AATCC, 2021, p. 455). The term fibre fragment has also been utilised in recent international test methods, procedures, and publications (BSI, 2023; Periyasamy & Tehrani-Bagha, 2022; Palacios-Marín & Tausif, 2022). Thus, in line with recent terminology changes, this research will use the term fibre fragment to describe textile fibres below 5 mm in length that have been released or broken off from the main textile construction (Cai et al., 2021).

Fibre fragments can be created throughout the textile and apparel lifecycle whereby any interaction of the fabric with chemical and mechanical stress can lead to the fibres of the yarn breaking and releasing fragments, regardless of their origins being staple or filament (Allen et al., 2024; Hernandez et al., 2017; Volgare et al., 2021). Design and production processes can influence fibre shedding (e.g. textile structure, the polymer used), as well as consumer usage (e.g. laundering temperature, duration and agitation speed and style) (Periyasamy & Tehrani-Bagha, 2022). Overall, fibre fragment pollution has been assessed and identified in many different locations in the marine and terrestrial environment such as within snow and ice in the Arctic ocean (Ross et al., 2021), at the peak of Mount Everest (Napper et al., 2020b), and in the deepest parts of the ocean (Jamieson et al., 2019). Fibre fragments pose a threat as a source of toxic chemicals as well as being vectors for adsorbed pollution when ingested or when transferred within the environment (Barnes et al., 2009; Carney Almroth et al., 2018). Carney Almroth and Athey (2022)

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state how 'many chemicals used in the production of textiles have been shown to cause toxic effects in numerous organisms' (p. 112). For example, exposure to polyester fibre fragments decreased the growth and survival rate of water fleas and increased mortality in crustaceans (Jemec et al., 2016; Su et al., 2018; Kwak et al., 2022). Walkinshaw et al. (2023) based their research on, what they term, 'realistic future scenarios' whereby they assume an environmental concentration of 80 polyester fibre fragments L^{-1}, which led to decreasing the growth rate of juvenile mussels by over 30%, which can have both commercial and environmental compound implications. This therefore highlights the importance of mitigating fibre fragment pollution from the source.

Strategies to moderate this pollution have been highlighted as a high priority and have been integral to emerging international policy interventions such as the EEA (2022) 'Microplastics from textiles: towards a circular economy in Europe'. National policies are also emerging, for example as of January 2025, it will be mandatory in France for all new washing machines to include a fibre fragment catching device to curb the amount of pollution entering the marine environment (Hailstone, 2022). However, there are issues with the deployment of filtration devices such as their efficiency, and currently creating a circular loop of recycling or reuse of the collected fibres is not available (McIlwraith et al., 2019).

Additionally, fibre fragment pollution cannot be solved with a singular magic bullet solution (Forum For the Future (FFF), 2023; Liu et al., 2021). Researchers have identified that multifaceted approaches involving designers, producers and consumers are necessary to effectively reduce fibre fragment pollution (Kentin & Battaglia, 2022). Current efforts to reduce shedding are focussed on consumer responsibility; however, there have been calls for greater source directed interventions to design out fibre fragmentation (Ellen MacArthur Foundation, 2021; FFF, 2023).

Understandable and attainable sustainability objectives that designers and producers can follow regarding reducing fibre fragment shedding are currently unavailable (Liu et al., 2021). This has meant that even if designers and producers of textiles and apparel wish to reduce the amount of fibre fragments shed from garments over the products lifetime, there are currently no clear and concise advisories to follow. This is due to the ranges of methodologies used and the complexities imbedded within textile science. For example, information surrounding the structure of the fabric, or the yarn characteristics may not be listed and therefore will impede comparability and concise conclusions on reduction techniques (Napper & Thompson, 2022).

Whilst fibre fragments have been shown to be released during garment construction and production, 'a higher amount of mechanical stress is applied during the use phase of a garment through the wearing and laundry process' (Ramasamy & Subramanian, 2023, p. 41599). The research found that 'the laundry process causes 90% of the damages to the textile' (Ramasamy & Subramanian, 2023, p. 41599) and thus is a major area of interest for mitigation strategies that warrants further exploration. Complex interactions between material characteristics or parameters take place when washing textiles and apparel. For example, how tightly a yarn is twisted can have an influence on the amount of fibres that are released during washing (Cesa et al., 2020); however, studies may then also change multiple parameters i.e. the polymer used, or the fabric structure such as whether it is woven or knit fabric (Kelly et al., 2019; Volgare et al., 2021). This makes it difficult to compare studies and should be addressed in future research. For example, Dalla Fontana et al. (2021) examined two knitted 100% polyester fabrics, however the fibre parameters differed with changes in fibre length, twist of the yarn, and density of fabric alongside changes to the hemming technique (double heat-sealed vs overlock). The multiple parameter changes can cause complications in understanding the true causations to results found (Napper & Thompson, 2022). Further examples of the complexities in textile design in relation to fibre fragment shedding can be found in Allen et al. (2024). Seeing as small changes to textile design can influence shedding rates, it is vital to conduct studies in which singular parameters are changed and assessed to test the relationship to fibre fragment pollution released. Moreover, information published should be thorough and consistent between studies so conclusions can be accurately drawn (Periyasamy & Tehrani-Bagha, 2022).

Additionally, units of findings vary between studies which can complicate comparability. For example, past studies have used gravimetric analysis such as mg of fibre fragments shed per garment, per kg or per wash (e.g. Lant et al., 2020; Vassilenko et al., 2021) whilst others use imaging analysis or numerical conversions and state findings as number of fibres shed per garment, per kg, per wash (e.g. De Falco et al., 2018; Kärkkäinen and Sillanpää, 2020). Sometimes the information needed to alter units for consistency is omitted or a lengthy process.

This study aimed to conduct a systematic analysis of the differences in fibre fragmentation generated by woven and knitted fabrics during laundering. Keeping yarn parameters constant and creating the fabric structures in-house allowed control of the fabric and yarn, as factors such as pre-washing and surface treatments can impact fibre fragmentation behaviour (Carney Almroth et al., 2018). Thus, this study addressed calls for research to provide comparable results between different material structures and their impact on fibre fragment pollution.

Due to it currently being unknown how individual parameters can alter fibre fragment shedding during laundering, this work forms a basis for future studies to identify how fabric creation under systematic and consistent conditions will help identify key areas for intervention and mitigation of pollution. Thus, this work will provide evidence and suggestions for enhanced standards on fibre fragment release, shaping eco-design measures to reduce shedding during fabric laundering.

Materials and methods

Textiles

In order to address the previous gap identified in terms of a lack of comparability, this research sought to systematically assess parameters impacting fibre fragment shedding. Thus,

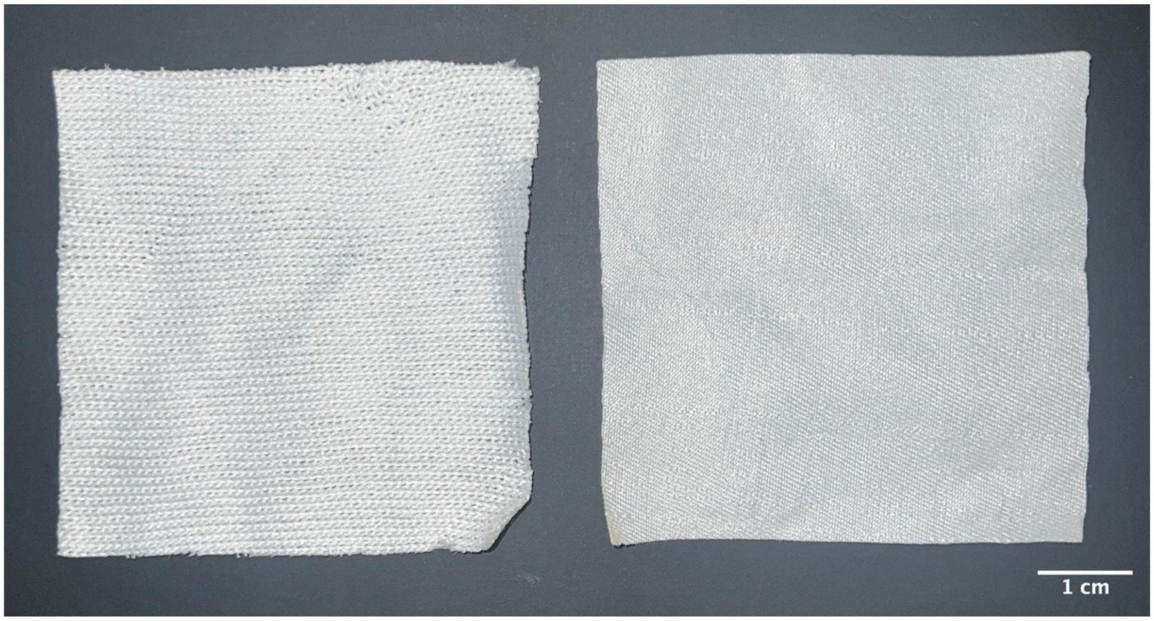

Figure 1. Single Jersey knit fabric (left) and 2/2 twill woven fabric (right).

both knit and woven textiles were created in-house at The University of Manchester, Department of Materials (see Figure 1).

For the knit fabric, a single jersey fabric was chosen as this is a popular structure for tops and T-shirts and make up 8% of apparel sold in Europe, North America and Australia and have previously been studied (Cesa et al., 2020; Cotton et al., 2020; Kelly et al., 2019; Volgare et al., 2021). The knit fabrics were created on an 8-gauge Dubied knitting machine using four cones of undyed intermingled filament polyester yarn (1 end, 167 Decitex with 48 filaments per end) sourced from J.H. Ashworth and Son Ltd. Whilst T-shirts can be produced in a range of materials (e.g. 100% cotton, poly-cotton blend), 100% polyester material was chosen as polyester represents the most widely produced and used fibre within the textile and apparel industry (Opperskalski et al., 2022). Additionally, polyester fibre fragments released from textiles have been shown to cause numerous environmental impacts and thus mitigating the release of these fibres is of particular concern (Kwak et al., 2022).

For the woven fabric, a 2/2 twill structure was investigated as this is a popular structure found in trousers and similar to that used in denim jeans (Athey et al., 2020). Denim jeans represent the most worn item of clothing globally and cover around 5% of the total textile and apparel market (Athey et al., 2020; Raina et al., 2015). It is noted that true denim is made of 100% cotton, however polyester yarn was chosen to keep fabric parameters consistent between the woven and knit fabric samples to allow for comparability. Additionally, polyester in a twill structure is a durable fabric commonly used in workwear.

The 2/2 twill structure (50 picks/cm and 50 ends/cm) woven fabric was created using an ARM AG CH-3507 BIGLEN semi-automatic hand weaving machine connected to ScotsWeave software (ScotCad Textiles LTD). The warp was comprised of Isacord 40 0017 in paper white (Barnyarns Ripon LTD). The weft (undyed intermingled polyester 1/167/48 yarn) comprised of the same yarn used in the knitted textiles. Full fabric specifications are outlined in Table 1. This research only focuses on two different fabric structures (knit and woven) in order to not only allow for comparability, if all other parameters remain the same, but also to gain a better understanding of the impact fabric structures have on fibre fragment pollution and inform future studies.

Eight replicates of knit fabrics and woven fabrics of the same parameters were created. Each sample was stored within tin foil to reduce contamination during the transportation of fabric samples. Each fabric was heat set at 180 °C for 45 s to remove residual shrinkage using a Beta Major (pneumatic swing head) press (Adkins, UK). The fabric was then laser cut (FB1500 series, CadCam Technology, UK) into 9 cm-by-9cm swatches with a maximum velocity of 90 mm/s and a maximum power of 20%. This allowed cutting and edge serging to be obtained. At the same time this ensured fibres were not disproportionally shed from the raw edges rather than the fabric structure (Carney Almroth et al., 2018).

Washing of fabric samples

During the preparation of the swatches, the fabrics were exposed to environments high in airborne fibre fragments (e.g. textile knitting and weaving labs). To remove potential contamination (e.g. dust, residue, airborne fibre fragments), the fabrics were held up using stainless-steel tweezers in the laminar flow cabinet and rinsed with distilled water in a pressurised wash bottle prior to machine washing them to remove residual loose dust and contamination. The fabric swatches were then dried in a laminar flow cabinet overnight to prevent further contamination, and the weight of

Table 1. Fabric specifications.

Reference	Structure		Fibre type	GSM (g/m^2)	Thickness (mm)	Warp/weft count (ends/ picks per cm)	Weight of fabric sample (g)	
This study	2/2 twill woven	Warp	100% Polyester Isacord 40 0017	143	0.73	50/50	Total: 1.16	Warp: 0.41
		Weft	undyed intermingled 100% polyester 1ply 167 Decitex with 48 filaments per end					Weft: 0.75
	Single Jersey knit		undyed intermingled polyester 1ply 167 Decitex with 48 filaments per end	207	1.23	–	1.68	

For the woven fabric, the fabric swatch was unravelled to weigh the warp and weft. The GSM was calculated using the total weight of the fabric swatch.

Table 2. Washing specifications and experimental groups for fabric samples.

	Washing Procedure							
Textile Type	Temperature (°C)	Time (minutes)	Water volume (mL)	Number of stainless steel balls	Detergent/ softener	Washing Parameters (consecutive cycles)	Replicates	Total cycles per experiment group
100% Polyester woven	40	45	360	50		5	8	40
100% Polyester knit	40	45	360	50		5	8	40

each swatch was recorded using a balance with an accuracy of 0.1 mg (PS-60, Fisher, UK).

The washing procedure was conducted in accordance with the AATCC TM212-2021 'Test Method for Fibre Fragment Release During Home Laundering' (AATCC, 2021). The eight fabric replicates of both knit and woven fabric were added to individual stainless steel wash pots (550 mL) with 50 steel balls and 360 mL of filtered water. The swatches were laundered in line with the AATCC standard within a laboratory wash stimulator (Washtec, Roaches UK) for 45 min at 40 °C (Table 2).

To examine the effect of repeated washing on the fabric samples, each replicate of fabric swatches was washed five times consecutively for each individual fabric swatch.

Blank samples ($n = 4$, wash tests following the same procedures but no fabric sample added to the stainless-steel wash pots) were conducted to determine contamination; referred to as procedural or control blanks (Özkan & Gündoğdu, 2020; Woodall et al., 2015). The results from control blanks were subtracted from test results (Özkan & Gündoğdu, 2020).

Due to the nature of the work, where fabric creation, wash tests, filtering and quantification were occurring within the same building contamination control was important. Therefore, to reduce contamination, canisters, steel balls, filter funnel and glass petri dishes were triple rinsed with filtered water before use. Additionally, the set up and preparation of samples took place within a laminar flow cabinet and procedures from Woodall et al. (2015) were adopted such as minimising air exposure to samples, cleaning of the surfaces, wear cotton lab coats and gloves to try and protect the sample from researcher and clothing.

Filtering and fibre quantification

Following the wash test, the test liquor was filtered through a pre-weighed Whatman GF/C 55 mm glass microfibre filter with a pore size of 1.2 µm with the aid of a vacuum filter apparatus to capture the shed fibre fragments (Carney Almroth et al., 2018; Zambrano et al., 2021). The steel balls, canister, canister lid, and fabric swatch were rinsed three times with filtered water to ensure all shed fibre fragments were captured. Additionally, the glass filter funnel was carefully rinsed with a pressurised wash bottle to ensure no fibres had adhered to the glass. The filter membranes were put into individual glass petri dishes to dry within the laminar flow cabinet until there was no further decrease in mass.

The mass of the contamination from blanks (expressed in mg) was subtracted from the average of the collected fibre fragments (mg) to create a post wash mass of dry filter membrane.

The change in pre-filtering weight represented the mass of fibre fragments shed during laundering and presented as mg of released fibre fragments per kg of washed fabric (as shown in Figure 2).

Statistical analysis

Results were mean average calculated to show the emission of fibre fragment in mg/kg ± standard deviation (SD, $n = 8$) for the first wash (results section, Figure 3). For the consecutive five wash tests, the eight replicates were averaged and displayed with the standard deviation (results section, Figure 4).

Significant differences between data acquired was analysed by a One-way Analysis of Variance (ANOVA). A significant difference between knit and woven structures was identified with p values $<.05$. This is consistent with past research (Cui & Xu, 2022; Palacios-Marín et al., 2022).

Results

The amount of fibre fragments shed from the knit and woven fabrics are shown in Figure 3. The knit fabrics released over three times more fibre fragments on average than woven fabrics. The single jersey knit polyester fabrics

$$Mf = \frac{W_2 - W_1}{P}$$

Mf= Fibre fragments shed (mg kg^{-1})

W_1= Pre-wash mass of dry filter membrane and weighing dish (mg)

W_2= Post-wash mass of dry filter membrane and weighing dish (mg)

P= Pre-wash weight of fabric swatch (kg)

Figure 2. Calculation for the percentage mass of fibre fragment release from each fabric swatch.

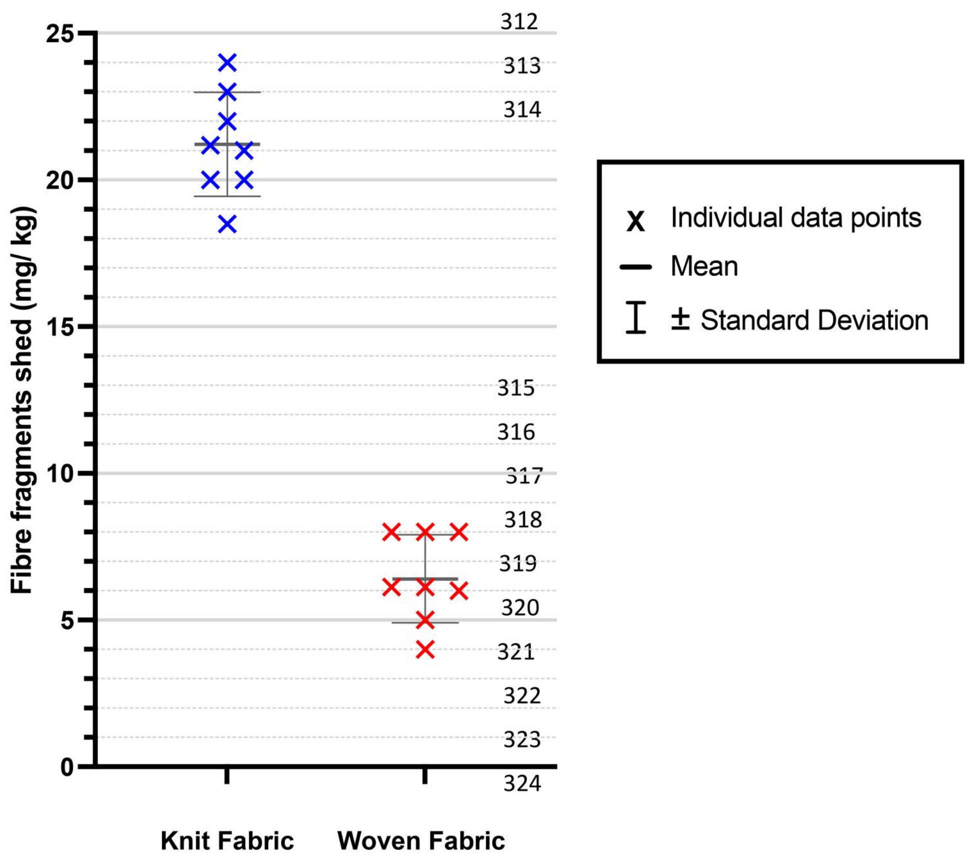

Figure 3. Knit and woven fabrics shedding rate of fibre fragments shown in mg per kg of fabric. The bar represents the mean fibre fragment loss for the two fabric structures ($n = 8$) and the standard deviation is shown with whiskers.

released 21.21 mg of fibres per kg of fabric (mean ± 1.80 SD, $n = 8$) compared to 6.41 mg/kg (mean ± 1.50 SD, $n = 8$) shed from the 2/2 twill woven polyester fabric. Statistical analysis showed a significant difference between the fibre fragments shed from knit and woven fabrics with a p value $<.0001$. These findings are consistent with similar research studies which found knit fabric to shed more than woven fabrics (Cui & Xu, 2022; Yang et al., 2019).

These results are comparative to studies such as Pirc et al. (2016) and Hernandez et al. (2017) as shown in Figure 5. Contrarily to other studies (Kelly et al., 2019; Vassilenko et al., 2021) the results presented within this study suggest much less fibre fragments are released.

The investigation of the behaviour of the two fabrics over five consecutive washes is shown in Figure 4. Fibre fragments released during washing of the knit and woven fabric samples were significantly higher in the first wash compared to the four following washes (Cai et al., 2020a; Dreillard et al., 2022). For the knit fabrics and woven fabrics, the difference between the first and second wash saw a reduction of pollution released by 60% and 70% respectively. By the fifth wash, the amount of fibre fragments (mg) per kg of fabric washed was less than a tenth of the amount of pollution released from the first wash (9% for knit fabrics, 7.95% for woven fabrics).

Discussion

Discussion of technical results from studies that have the potential to improve the standards used for fibre fragment release testing

As the yarn and pre-treatment processes were the same for both the knit and woven fabrics, it has been hypothesised

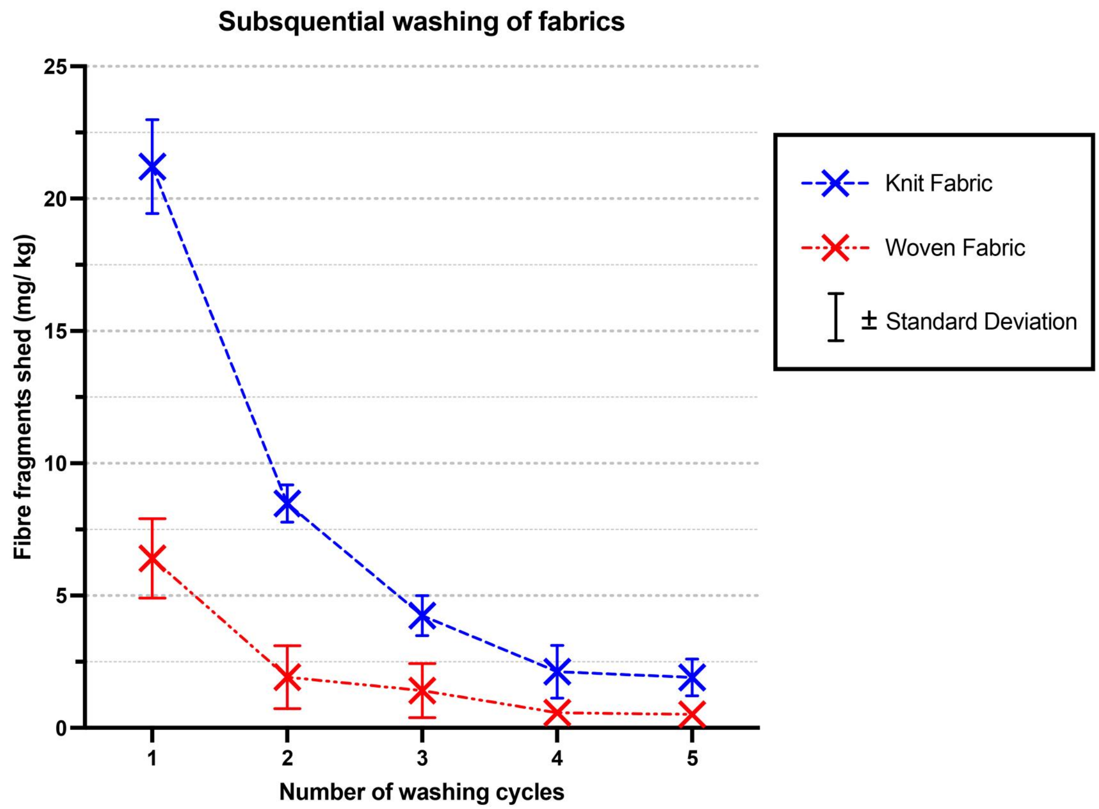

Figure 4. Average fibre fragment loss ($n = 8$) for consecutive washing of knit and woven fabrics over five wash cycles, shown with standard deviation. Where standard deviation is smaller than the X then the standard deviation bars are not shown.

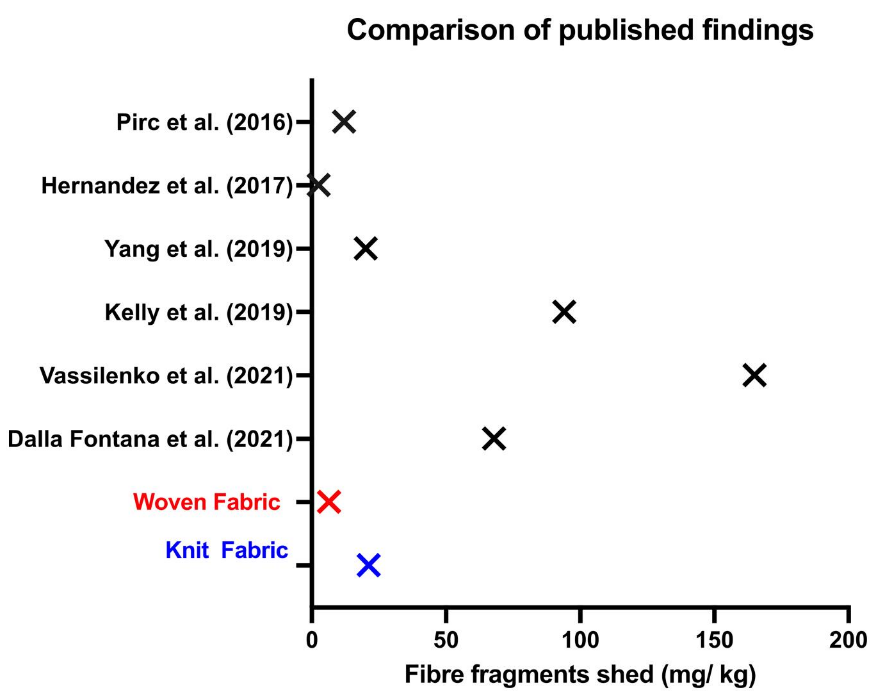

Figure 5. Comparison of published average shedding rates in mg of fibre fragments shed per kg of fabric. Woven fabric and knit fabric relate to the fabrics within this study and are shown with the red and blue crosses. Some studies were omitted due to insufficient information to convert data to common units for comparison.

that structural differences between the two fabrics caused the differences in the quantity of fibre fragments shed. It has previously been shown that looser knit structures allow greater movement of water into the fabric structure alongside fibres moving around, breaking off and being released from the fabric structure (Cui & Xu, 2022; Yang et al., 2019). Tightly woven structures have been shown to have a greater ability to hold fibres within the fabric structure when undergoing laundering (Cui & Xu, 2022; Yang et al., 2019) which can explain the results seen within this study.

For example, Cui and Xu (2022) investigated 100% polyester woven and knit fabrics, in addition to Yang et al. (2019) whereby polyester, acetate, and polyamide woven fabrics were investigated; both studies showed how textile geometry and structure caused differences in amounts of fibre fragments released during laundering. However, due to fabrics being bought from manufactures or from textile markets, the full history and production process may differ between fabric samples which could interfere with results (Cai et al., 2020b; Cui & Xu, 2022; Yang et al., 2019). Full descriptions of fabrics used within previous studies are outlined in Table 3. As shown in this table, the lack of detail provided within previously published studies omits opportunities for a full understanding of fibre fragment release but alludes to certain reasons. This validates the rationale in this study to ensure yarn and production techniques were kept transparent and constant, to explore how structural changes impact the amount of fibre fragments released during laundering, and why future published research should include full textile characteristics to allow comparability between studies. The methodology outlined in this study whereby fabrics are created with known fabric parameters, systematic and limited changes enable greater understanding and foundation for future research into the individual influences on fibre fragment shedding.

On the other hand, Frost et al. (2020) found that there was no significant difference between fibre fragments shed from knit fabrics compared to twill woven fabrics. Furthermore, De Falco et al. (2018) found that woven polyester fabrics shed more than knitted polyester fabrics, disagreeing with the findings within this study. However, De Falco et al. (2018) notes that the higher shedding rate could be due to fabric characteristic differences between the assessed knitted and woven fabrics. In De Falco et al. (2018) study, the woven fabrics assessed had a higher hairiness and thus more protruding fibres from the fabric structure. Therefore, more fibre fragments were released when compared to the lower hairiness knit fabric. This shows the need for more systematic studies where parameters are individually and independently changed.

As noted, due to differences in methodologies and fabrics tested, relating results to former studies is complex. When comparing results to similar studies (Figure 5), complexities arise around methods and units used to express results. Briefly, the results from this study are compared to other studies in Figure 5 where the units have been harmonised for ease. Hernandez et al. (2017) studied single jersey knit fabrics made of polyester with a 2% spandex plating and found that on average 2.5 mg of fibre fragments were released for every kg of fabric washed (0.0025 mg/g). This is considerably less than the release of 21.21 mg/kg fibre fragments noted in this study. Notably, Hernandez et al. (2017) used similar wash methods such as 40 °C for 45 min, however 200 mL of wash fluid was used and 10 stainless steel balls for agitation. The differences between the results could be due to the reduced wash liquor or the higher number of steel balls used within this experiment (360 mL and 50 stainless steel balls, 6 mm diameter). Kelly et al. (2019) records the importance of water volume on fibre fragmentation during laundering. Additionally, agitation has a correlation to fibre fragment release and thus as less stainless-steel balls were used, this could explain the differences in fibre fragments shed (Hartline et al., 2016) compared to this study. However, other studies found the number of steel balls did not significantly change fibre release (Cai et al., 2020a).

Other complexities within fibre fragment studies also arise with studies showing that results can vary significantly (e.g. Yang et al., 2019; Volgare et al., 2021 cited in Palacios-Marin et al., 2022). For instance, Vassilenko et al. (2021) showed that fibre fragment loss can range from 9.6 mg/kg to 1240 mg/kg. Thus, Figure 5 highlights higher shedding amounts shown by Vassilenko et al. (2021) in comparison to the results within this study. On investigation of methods and materials used, the differences in results (Figure 5) can be attributed to polyester fleece being used as the fabric (Table 3), which has been found to shed significantly higher amounts than knit and woven structures, alongside the use of a top load washing machine, which has been shown to impact shedding amounts (Cai et al., 2020a; Yang et al., 2019). Similarly, Pirc et al. (2016) used fleece as a test fabric and recorded an average of 12 mg/kg of fibre fragment loss, however the wash time was only 15 min and set at a temperature of 30 °C (Table 4).

This highlights the complexities around fibre fragment shedding and the need for standardised fibre fragment wash tests such as AATCC TM212-2021 and ISO 4484-1:2023 (AATCC, 2021; BSI, 2023). Future work should continue the use of these standardised testing within wash test stimulators as these allow for greater control over factors such as temperature, duration, and agitation (Hazlehurst et al., 2023; Allen et al., 2024). Additionally wash simulators have been shown to allow easier fibre fragment collection compared to commercially available washing machines and greater repeatability between research groups (Tiffin et al., 2021; Zambrano et al., 2019). The complexities within the fabric parameters themselves communicate the importance for further research to assess the causes of fibre fragment loss, including systematic comparisons between characteristics and factors of yarn, fabric structure, and washing parameters which could then be used for sustainable advancements in procedures. Therefore, when future research extrapolates the findings of this study, there needs to be careful verification when applying the proposed recommendations to different types of fibres.

Future work should also ensure in-depth detail is provided on the washing procedure and equipment used alongside the fabric parameters tested including any pre-wash treatments (Allen et al., 2024; Napper & Thompson, 2022). Table 3 shows how the exclusion of fabric parameters from published work limits research understanding of their influence on fibre fragment shedding, as well as comparability between studies. With the knowledge of the specific yarn and fabric parameters and fabric treatments known, future research should further compare more and different samples of fabrics in order to allow for greater applicability.

Table 3. Comparison of fabric properties.

Reference	Structure	Fibre type	GSM (g/m^2)	Thickness (mm)	Courses per inch (CPI)	Wales per inch (WPI)	Warp/weft count (Ne)	Weight of fabric swatch (g)
This study	2/2 twill woven	Warp: 100% Polyester Isacord 40 0017	143	0.73	66	75	50/50	Warp: 0.41
		Weft: undyed intermingled 100% polyester 1ply 167 Decitex with 48 filaments per end						Weft: 0.75 Total: 1.16
	Single Jersey knit	undyed intermingled polyester 1ply 167 Decitex with 48 filaments per end	207	1.23	29	15	–	1.68
Cui and Xu (2022)	Plain flat knit	100% Polyester	–	0.42	–	–	–	–
	Woven twill	100% Polyester	–	0.43	–	–	30/20	–
Dalla Fontana et al. (2021)	Knit	100% polyester (30 tex), 736 twists/meter, tenacity of 28.28 centinewton per tex	243	–	–	–	–	–
	Knit	100% polyester continuous filament (9 tex), without twisting with a tenacity of 34 centinewton per tex	125	–	–	–	–	–
Vassilenko et al. (2021)	2 sided brushed fleece knit	100% polyester filament	200	–	–	–	–	502.3 (load weight)
	Plaid woven	100% polyester spun stable	170	–	–	–	–	503 (load weight)
Yang et al. (2019)	Plain woven	100% Polyester	108.56 ± 5.18	–	–	–	–	97.71 ± 4.66
Kelly et al. (2019)	Knit	100% polyester filament	140	–	–	–	–	20 ± 0.10
De Falco et al. (2018)	Plain woven	100% polyester, 35 mm fibre length	126	–	–	–	–	–
	Double knit jersey	100% polyester continuous filament	200	–	–	–	–	–
Hernandez et al. (2017)	Interlock knit	100% polyester spun fibre staples with a fibre diameter of 20 mm and density of 950 kg/m^3	–	–	–	–	–	7
	Plain single jersey	98% polyester, 2% spandex spun fibre staples with a fibre diameter of 20 mm and density of 950 kg/m^3	–	–	–	–	–	7
Pirc et al. (2016)	Weft knit fleece	100% polyester, texturised, multifilament yarn, 2.5 dtex, diameter ∼15 mm	–	–	–	–	–	–

Information omitted or not published is indicated with a –.

Table 4. Comparison of estimated fibre fragmentation released within current literature, showing fabric properties, and washing style.

Publication	Polymer	Fabric details	Washing style	Wash time (minutes)	Temperature (°C)	Agitation style	Water volume (mL)	Filter pore size (μm)	Fibre fragmentation (mg/kg)
This study	PET	Single jersey knit	Wash stimulator	45	40	50 Stainless steel balls	360	1.2	21.2
This study	PET	Twill	Wash stimulator	45	40	50 Stainless steel balls	360	1.2	6.4
Cui and Xu (2022)	PET	Knit and twill	Wash stimulator	20, 40, 60, 80	40, 50, 60, 70	0, 10, 20, 30			
Dalla Fontana et al. (2021)	PET	Knit	Washing machine	90	40	1400 rpm	40,000- 50,000		
Vassilenko et al. (2021)	PET, recycled and virgin	Knit filament, jersey and fleece	Top load washing machine	12	41	645 rpm	34,100	20	161
Kelly et al. (2019)	PET	Textured T-shirt	Wash stimulator	15 60	15 30	100 rpm 200 rpm	300 600	22	94
Yang et al. (2019)	PET	Plain woven	Washing machine	15	30, 40, 60		15,000 water, 5000 detergent	5	20.1
De Falco et al. (2018)	PET	Plain woven and double knit jersey	Wash stimulator	45	40	10 Stainless steel balls	150 mL of liquor per gram of fabric	5	
Hernandez et al. (2017)	PET, 2% Spandex plating	Plain single knit Jersey	Wash stimulator	45	40	10 Stainless steel balls	200	0.45	2.5
Pirc et al. (2016)	PET	Texturised PET fleece blanket	Front load washing machine	15	30	600 rpm	N/A	200 μm sieve (custom built set up)	12

Furthermore, future research should consider investigating fibre pollution of nonwoven materials, including, but not limited to electro-spun fibrous membranes and melt-blown nonwovens, and test whether the results may differ to the ones presented in this paper.

Figure 4 shows that as new polyester textile and apparel are created and then washed, a higher amount of pollution is released in comparison to subsequent washes. The results show that within the first wash more pollution is released in comparison to the subsequent four washes combined. Furthermore, there was no significant difference between the behaviour of the knit and woven samples fibre fragment loss when consecutively washing the samples five times. Whilst the values are different, the trend and release of fibres decreases over the five washes can be seen with both fabrics, this could be due to the same yarn being used in both the knit and woven fabric, and thus the ageing effects, pilling functions and breaking strengths being the same. Future research could focus on the behaviours of differing polymer blends and yarn conditions. The fabrics tested within this study were also not 'worn' or 'aged' as a real-life consumer garment would be between real-life washing, therefore this purely shows the behaviour of the fabric itself. This is an area of future scope suggested to be explored.

Discussion of government regulatory and industrial practice that have the potential to reduce the release of fibre fragments to the environment

From the findings within the research outlined above, extended producer responsibility is suggested as a source directed intervention i.e. requirement of industrial washing of garments before they are sold to consumers. It has been theorised that the 'majority of [fibre fragments] are loosely held in the fabric and yarn structure, and these are released relatively easily and quickly early on in the washing cycle' (Hazlehurst et al., 2023, p. 11). This has importance when relating to ever increasing global production volume of polyester fibres which was around 61 million tonnes in 2021 (Opperskalski et al., 2022) and expected to continue to rise. With the increase of fast fashion production and consumption, polyester fabrics of textiles and apparel, these results highlight that there are opportunities to capture the pollution before release to the environment, alongside implementing design techniques that lead to reduced fibre fragment loss during laundering. This is advocated by the EEA and the European Parliament (2023) where they acknowledge that 'fast fashion is based on mass production, low prices and high sales volumes that promotes many first washes' and therefore accounts for high levels of such releases of fibre fragmentation.

Furthermore, whilst this study focuses on design and manufacturing techniques that relate to fibre fragment pollution released during the laundering phase, it is highlighted that there are many other avenues of potential mitigation strategies throughout the entire lifecycle of the textile. For instance, there has been work relating other production techniques to fibre fragmentation, as well as within the usage and disposal stage. This work also only focuses on pollution released into wastewater, whereas there will also be fibre fragments released into the air during the production, usage, and disposal stage. A comprehensive analysis of the entire lifecycle of textiles, and their individual implications to fibre fragment pollution, to both air and water is a suggested area of future research with the same standardised and consistent methodology as outlined within this research.

Firstly, if policies or subsidised incentives were put into place which encouraged investment in wastewater management infrastructure, this would allow the first wash of garments, which has been shown to release the highest amount of fibre fragments (Figure 4), to be controlled and fibre fragments to be captured. This could allow the capture and reuse or safe disposal of a significant amount of fibre fragment pollution (Choi et al., 2022; Hazlehurst et al., 2023; Kelly et al., 2019; Napper et al., 2016). Secondly, increasing awareness of the pollution released during the first wash of clothing to consumers to change consumer behaviour and extend lifespans of clothing and textiles would be beneficial to stem the flow of pollution into our environment (EEA, 2022).

Conclusion

This is one of the first research papers that has investigated the impact of fabric structure on fibre fragment shedding. Past papers, whilst instructive and informative, have changed parameters, which thus did not allow for comparability of the results. Moreover, this research created its own fabric, which implies that all parameters could be accounted for. Whilst keeping washing conditions, and yarn characteristics constant between the two fabric structures, this research shows that single jersey fabrics released over three times more fibre fragments (21.21 mg/± 1.80 SD, $n = 8$) when compared to 2/2 twill fabrics (6.41 mg/kg ± 1.50 SD, $n = 8$). Due to the in-house creation of fabrics and the minimisation of differing parameters between fabrics tested, this work advances the knowledge within this field by allowing direct comparison and causation of fabric structure to changing pollution shedding rates. To mitigate fibre fragment pollution at the source, tightly designed structures could be offered as a strategy to reduce pollution, by reducing fibre slippage.

At present, as the understanding of individual fabric parameters relationships to pollution release is still in its infancy, further investigations with systematic changes to fabric parameters are of high priority in order to build comprehensive regulations or recommendations for the textile and apparel industry to effectively reduce fibre fragment pollution. In the meantime, further pressure is needed on key stakeholders in textile production to increase responsibility to monitor and moderate fibre fragment release to the environment by implementing a controlled wash to capture the large quantity of fibre fragments shed from textiles during the first wash. The results within this study show that the amount of pollution released during the first and second wash of knit and woven fabrics reduced by 60% and 70% respectively. The amount of pollution released appears to plateau by wash five and therefore highlights the importance of implementing capture of pollution from the first wash as well as education to limit over-consumption of new textiles and apparel. Combinations and co-ordination of mitigation actions throughout the textile's life cycle are needed to tackle fibre fragment pollution to our environment.

The findings presented in this study serve as evidence advocating for the enhancement of standards concerning fibre fragment release. Furthermore, the insights collated from our research can be harnessed as a valuable resource for consumer education initiatives which could allow conscious consumerism. In essence, the findings provide a basis for collaborative efforts within the textile industry to address the challenges associated with fibre pollution through innovative and improved fabric designs, alongside enhancing evidence-based and standardised standard for wash tests, consumer awareness and encouraging industrial incentives for a more sustainable textile system.

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Data availability statement

Data is available on request through the corresponding author.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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