Forensic Science International 367 (2025) 112369

Contents lists available at ScienceDirect

Forensic Science International

journal homepage: www.elsevier.com/locate/forsciint

A novel method for assessing the shedding of fibre in forensic science: Investigating the effects of washing

Virginie Galais [a,*], Stephanie Wilson [b], Patricia Dugard [a], Chris Gannicliffe [c], Bronagh Murphy [b], Niamh Nic Daéid [a], Hervé Ménard [a]

[a] Leverhulme Research Centre for Forensic Science, Department of Science and Engineering, University of Dundee, Dundee DD1 4HN, UK
[b] Centre for Forensic Science, Department of Pure and Applied Chemistry, University of Strathclyde, G1 1XW, UK
[c] Scottish Police Authority Forensic Services, Aberdeen Laboratory, Aberdeen AB24 5EQ, UK

ARTICLE INFO

Keywords:
Forensic science
Fiber
Shedding
Washing
Transfer
Automated data collection

ABSTRACT

The evaluation of the shedding capacity of a garment is crucial in forensic analysis to understand fibre transfer mechanisms during contact activities. While adhesive tapes are commonly used, the lack of standardised pressure application -often done manually- poses a challenge. In addition, while previous studies have examined the effects of washing on fibre evidence, there is a notable absence in the literature regarding its impact on garment shedding capacity. This study aims to address these gaps by proposing a practical method to assess garment shedding capacity. Conventional tape lifting experiments, involving manual pressure application, were conducted for comparison with the novel method proposed in this study. Controlled conditions for reproducible experiments were achieved using a cost-effective friction tester and automated data collection through photography and ImageJ image processing software. Through controlled simulations, this study seeks to examine the relationship between garment shedding capacity, fibre transfer dynamics, and the effects of textile washing during laundry cycles.

1. Introduction

All textiles contain fibres which are often transferred between surfaces, resulting in fibres being one of the most common evidence types encountered at crime scenes. In forensic science, fibres can be crucial evidence, helping to establish connections between individuals, objects, and locations. Evaluating the transfer of fibres is crucial in fibre examination, as various factors influence the transfer of specific fibre types during physical contact. Important considerations include the nature of the contact (intensity, pressure, and duration) and the size of the area of contact [1].

Another important factor in the examination of fibre evidence is the shedding capacity of a garment [2–7]. The shedding capacity refers to the potential of a garment to shed fibres, which depends on factors such as fibre type, knit and yarn construction, and fibre staple length [8]. To assess this shedding capacity of a garment, De Wael et al. [7] proposed a method involving placing a tape lift on the garment, applying hand pressure, and visually comparing the tape to a shedding scale. This method was adopted by several studies [9–12]. An alternative approach described in the literature involves counting the fibres on the tape lift under a stereomicroscope to evaluate the shedding capacity [4,13–15]. While the method proposed by De Wael et al. [7] is more efficient than manually counting fibres, both approaches involve applying pressure on tape lifts by hand. This can introduce potential issues when assessing shedding capacity, as manual pressure cannot be precisely controlled or standardised.

Previous research by Coxon et al. [5] and Skokan et al. [11] indicated that the current assessment methods using tape lifts overestimate the shedding capacities as the adhesive of the tape removes embedded fibres in addition to recovering loose fibres on the surface of the garment [5]. Coxon et al. [5] suggested another method to address this issue, by dragging manually a recipient fabric over the donor garment surface, although this approach still faces reproducibility and replicability challenges. Different studies have shown that contact pressure affects the transfer of fibres [4,16–19], but the impact of varying pressures applied on tape lifts during the shedding assessment is not well established. The lack of standardised pressure application could lead to variability in assessments both between different individuals and within

* Corresponding author.
E-mail address: vgalais001@dundee.ac.uk (V. Galais).

https://doi.org/10.1016/j.forsciint.2025.112369
Received 9 October 2024; Received in revised form 29 November 2024; Accepted 7 January 2025
Available online 9 January 2025

repeated tests by the same individual. Some authors, such as Skokan et al. [11], used a specific mass per taping area (417 kg/m2) to standardise this pressure, however, this methodology is not widely adopted in forensic examination of fibres.

In addition, there is a lack of understanding of how the history of a garment (age, general condition, and number of washes undergone) may affect its shedding capacity. While previous studies have investigated the effects of washing conditions on the transfer of fibres and the persistence of transferred fibres [18–23], its impact on the shedding capacity remains unclear. The ENFSI best practice manual for the forensic examination of fibres [24] recommends recreating the activities leading to the transfer of fibres without altering the original evidence. Consequently, practitioners often purchase a similar garment to the recovered one to perform these activity experiments. However, as highlighted by Galais et al. [19], using a new garment may not accurately represent the recovered characteristics of the donor garment of interest due to the accumulated effects of wear and washing. Repeated washing, as shown in controlled studies [19], leads to a decrease in fibre transfer from donor garments, underscoring the importance of a garment's history in forensic investigations. Furthermore, new garments may still retain protective treatments from manufacturing that may affect fibre shedding or retention, potentially leading to inaccurate forensic examination results.

In forensic examinations, the likelihood ratio approach is one of the methods used to assess the evidential significance of findings. The likelihood of the findings is evaluated under at least two competing propositions, as described by Cook et al. [25]. At the activity level, the shedding capacity of the garments involved plays a fundamental role in assessing the likelihood of fibre transfers under each proposition. Reliable shedding assessments are crucial in assigning probabilities to potential fibre transfers, such as fibre type and quantity, under the competing propositions. Later, once findings are available, these probabilities, along with the findings, can be used to assign a likelihood ratio, which measures the relative strength of support that the fibre transfer evidence provides for one proposition over the alternative(s). Care should be taken to ensure that shedding capacity is accurately assessed, as incorrect evaluations can lead to misinterpretations of fibre evidence, as demonstrated by Schnegg et al. [10] who observed similar fibre recovery from both legitimate and criminal scenarios depending on the shedding capacity of pillowcases used. The ENFSI Guidelines for Evaluative Reporting in Forensic Science (2015) provide further guidance on this approach [26].

This study aimed to assess the variability in shedding capacity using two tape lift methods—one employing manual pressure and the other using controlled weights - as well as a simulated transfer method. The simulated transfers were conducted using a transfer device to provide controlled conditions and precise measurements, resulting in repeatable experiments [19]. Additionally, this research explored the impact of different washing activities (i.e., load size, detergent, and softener) on the transfer of fibres and the shedding capacity of different types of donor garments (i.e., knitted jumpers made of 100 % virgin cotton and 65 %/35 % recycled cotton). Finally, this research sought to develop new standardisation practices and standard operating procedures (SOPs) to support the evaluation of fibre evidence, though their application in specific interpretative frameworks is beyond the scope of this study.

2. Material and methods

2.1. Donor garments

2.1.1. Donor garments with 100 % virgin cotton

The first set of donor garments selected was identical knitted jumpers made of 100 % virgin cotton, colour red, women's UK size 12 and 16. The stitch density was found to average approximately 63 stitches per cm^2. These garments will be further referred to as the v-cotton donor garments. They were each assigned a unique identification number which was attached to its label.

For the transfer experiments, ten specific contact areas (CAs) measuring 20 cm × 3 cm were identified on every donor garment using a paper template, measuring 27 cm × 46 cm in total, as illustrated in Fig. 1-A. Half of these areas were arranged to run parallel to the garment's knit ribbing (labelled CA1 through CA5), while the other half were positioned perpendicular to the ribbing (labelled CA6 through CA10), with Fig. 1-B highlighting both orientations.

For the shedding experiments, distinct shedding areas (SAs) of 3 cm × 3 cm each (see Fig. 2) were selected on the v-cotton donor garments. A total of 6 shedding areas were arranged on a tape-lift band measuring 24.2 cm × 5 cm. These areas were separate from those allocated for the transfer experiments (see full details in supplementary information – section I). Each area was only used once for the tape lifting procedure, which is further detailed in the shedding experiments section.

Twenty-four v-cotton donor garments were utilised in total: 20 for ongoing washing activities (as detailed in the washing procedure section), one named G-test for conducting impact tests and repeated contact tests (see shedding experiment section), two to conduct hand pressure shedding experiments (i.e., GH1 and GH2), and one retained as a control garment (unused).

2.1.2. Donor garments with 65 % recycled cotton

A yellow fabric containing 65 % cotton of pre-consumer (production) waste from weaving and knitting companies and 35 % virgin cotton was purchased from Ecological Textiles (see Fig. 3-A). The stitch density was found to average approximately 17 stitches per cm^2. This textile of dimension 2 m × 1 m was used as received and will be further referred to as the r-cotton donor garment. As with the v-cotton donor, a piece of the textile (36 cm × 2 m) was kept as a control textile. The textile was folded in half widthwise, and the top of the folded garment was sewn. Five transfer zones of 26 cm × 45 cm were identified on the textile by sewing transparent nylon threads at each corner, see (Fig. 3-C).

As with the v-cotton donor, specific contact areas (CAs) measuring 20 cm × 3 cm each were identified on the r-cotton donor, for a total of 4 CAs per transfer zone, as illustrated in Fig. 3-C. Half of these areas were arranged to run parallel to the garment's knit ribbing (labelled CA1 and CA2), while the other half were positioned perpendicular to the ribbing (labelled CA3 and CA4).

Distinct shedding areas (SAs) each measuring 24.2 cm × 5 cm, separate from those allocated to the transfer experiments, were selected on the r-donor garment (see full details in supplementary information – section I). Each area was only used once for the tape lifting procedure, which is further detailed in the shedding experiment section.

2.2. Receiver garments

The receiver fabric selected was a plain (white) weave fabric, made of light to medium mass 100 % cotton, weighing approximately 111 g/m^2, see Fig. 4 A and B. For the transfer experiments, the receiver textile was cut into 5 cm × 5 cm and attached using double sided sticky tape to side face of a Perspex cuboid presented in Fig. 4-C. To preserve the textile properties such as tensile strength, flexibility and elasticity, each piece of textile was attached to the Perspex cuboids with care to avoid stretching. The receiver swatches were stored in metal boxes to protect against contamination and electrostatic influences. Each receiver swatch was used only once for each transfer experiment.

Positive control swatches were prepared by transferring from the untouched, unwashed v/r-cotton donor garment/textile, applying an 800 g mass over 20 cm (refer to the transfer experiment section for detailed procedures). The negative controls consisted of a Perspex block with the receiver fabric attached but without any transfer procedure conducted. The control samples were stored in the same container to assess the potential for storage-induced cross-contamination; this

Fig. 1. 100 % v-cotton donor garment, with (A) details of the knit, the arrows showing the perpendicular and parallel orientations on the knit and (B) a full garment with the location of 10 contact areas (CA1 to CA10).

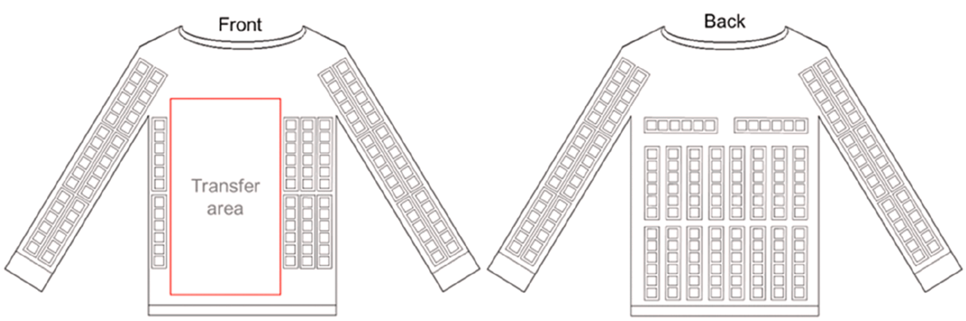

Fig. 2. Shedding areas (SAs) located on the front and the back of the donor garments. Each shedding area measures 3 cm × 3 cm, with 6 shedding areas on a tape-lift band of 24.2 cm × 5 cm. Each area was only used once for the tape-lifting procedure.

investigation did not reveal any significant cross-contamination.

2.3. Washing procedure

The washing machine used for this study was a Montpellier MW7140S with a 7 kg capacity. Specific programmes were employed for the experiments: a 60-minute daily wash cycle at 40 °C and 1200 rpm spin for washing the donor garments, and a 15-minute rapid wash cycle without a spin cycle or set temperature to cleanse the washing machine following each wash. Multiple rinsing cycles, ranging from four to six, were conducted to eliminate any residual fibres from the washing machine post-wash.

The donor garments were simultaneously and repetitively washed under the 60 min - daily wash programme of the machine, 40 °C, 1200 rpm, adhering to the conditions mentioned earlier. Post-washing, the garments were air-dried overnight on a rack, shielded by brown paper to minimise potential contamination.

Six different series of repetitive washing were conducted, as described in Table 1. The washing parameters remained the same across all washing series (i.e., 40 °C, 1200 rpm), however, an Ariel Original Gel detergent and a Comfort Pure fabric conditioner were selected for the second and third washing series (see Table 1). For each series, the wash cycles were repeated until the number of transferred fibres (see Transfer experiment section for more details) between subsequent washes reached a plateau.

2.4. Shedding experiments

2.4.1. Shedding protocol

Two methodologies were employed to evaluate the shedding of the garment. The first method involved a manual pressure application, as described in previous research [7,10,13–15]: a single strip of adhesive tape (J-Lar lifting tape, 24.2 cm long, and 5 cm wide) was placed on top of the garment. Five participants were then instructed to either apply a firm pressure or a gentle pressure along the tape's length, once. Subsequently, the tape was removed from the donor garment and positioned on a transparent acetate sheet, sticky side down. Using a Perspex block, six random shedding areas of 7.84 cm^2 (2.8 × 2.8 cm) were defined on the tape and were subsequently photographed following the protocols described in the photography section. Image analysis was conducted using ImageJ software to determine the shed fibre areas on the tape (see Fibre counting and measurements section). Each participant repeated the procedure three times with two different v-cotton donor garments (i.e., GH1 and GH2), resulting in a total of 18 areas analysed per garment, and 36 areas per participant (n_{total} = 180).

The second methodology introduced the use of a controlled pressure, as described in Fig. 5. A similar piece of tape to that used for the manual pressure experiment was positioned, sticky side down, on the garment. A Perspex block was carefully positioned over the designated shedding area, and a mass was placed atop this block for a duration of 15 seconds. After removing the mass and lifting the tape, it was placed on an acetate sheet. The shedding areas were photographed and analysed following

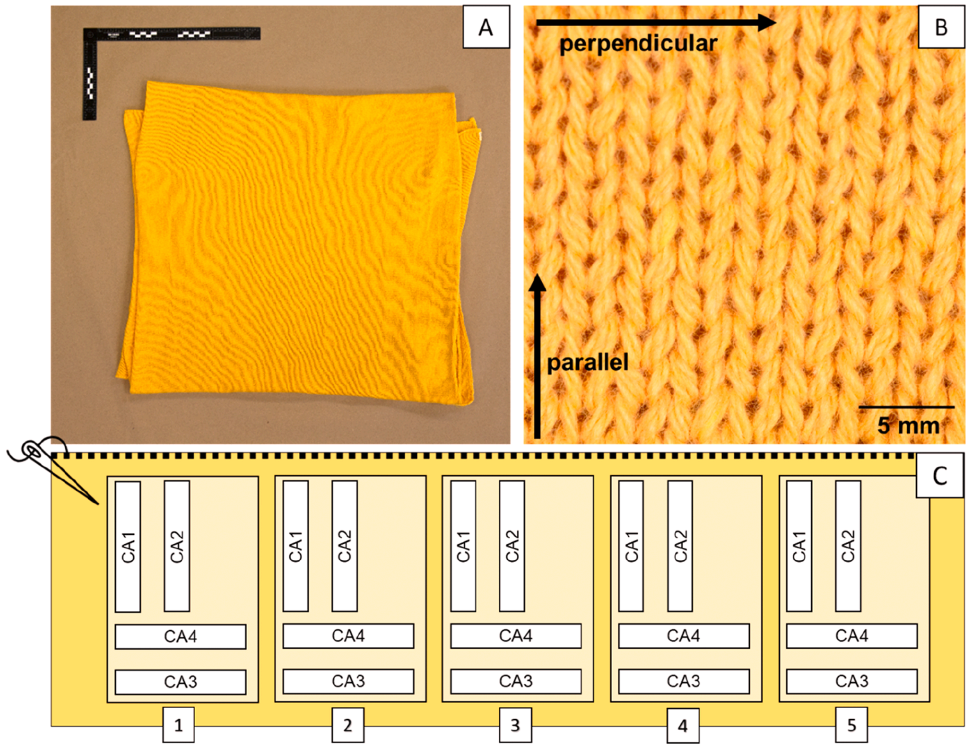

Fig. 3. 65/35 % r-cotton donor garment, with (A) a full textile (B) details of the knit, the arrow showing the perpendicular and parallel orientations on the knit and (C) the location of the transfer zone (1–5) and the contact areas (CA1 to CA4).

the same protocol as the first methodology.

For the donor garments ongoing different washing procedures (see washing protocol section), the second methodology was carried out on varying sections of the tape with different masses: 100 g, 200 g, 400 g, 800 g, 1000 g, and 2000 g. This experiment was conducted five times, resulting in 30 tape-applied contact areas for each garment. For the 1st to the 3rd and the 5th washing series, the shedding properties were evaluated on the donor garments in their as-received condition (before any laundering), following the initial wash, and then after every two washes. Specifically for the 5th series, the shedding was assessed using three donor garments (A to C) from the as-received condition to wash cycle 9, and then using garments D to F from wash cycle 11–15. For the 4th to the 6th washing series, the shedding properties were evaluated on the donor garments before any laundering and at the end of the washing series (i.e., respectively after 51, 41 and 25 washes).

2.4.2. Impact test

Impact tests were conducted on a new and unused donor garment (labelled G-test) to examine the effects of the force exerted by a mass upon its contact with the Perspex block positioned on the tape. Unlike the second method where the mass was gently placed on top of a Perspex block, a 1000 g mass was instead dropped from predetermined heights. The mass fell directly onto the centre of the Perspex cuboid from heights of 5, 10, 15, and 20 mm. This procedure was repeated 10 times for each specified height, yielding a comprehensive dataset covering 40 taped contact areas (see more in supplementary information – section I).

2.4.3. Repeated contact

Shedding experiments were conducted to assess the effect of repeated tape lifting on the same shedding area (SA) on a donor garment (on labelled G-test donor, though on different areas than for the impact test). Five SAs were identified on the donor garment, and a 1000 g mass was applied to each SA following the second shedding methodology, as previously described. The experiment was conducted six times for each SA, yielding a total of 30 samples (six repetitions per SA).

2.5. Transfer experiments

A low-cost Arduino transfer device was used, as fully described in the methodology outlined by Galais et al. [19] providing a robust framework for the current research objectives. The full details regarding the transfer device including a list of components, software codes to read data from the Arduino apparatus and instructions are available in the supplementary information (section II-IV).

For each individual transfer, a receiver swatch was positioned on top of the donor garment (textile on textile), with the pulling frame around the Perspex block. An 800 g mass was applied to the receiver swatch, simulating the pressure of an 80 kg person sitting on a chair. This was based on the assumption that the chair seat measured 30 cm × 30 cm, making the pressure equivalent to 800 g on a 3 cm × 3 cm area. Subsequently, the Arduino interface (IDE) was initiated to log the time and load during the transfer process. Once the data recording commenced, the rocker switch was triggered to initiate the linear motion, which finished after the 3 cm × 3 cm Perspex block traversed the entire 20 cm distance (reaching the linear actuator's end stop at an average velocity of 33 mm/s). Following the transfer, the receiver swatch was carefully detached from the pulling frame and securely repositioned in a metal box (two samples per box).

2.6. Photography

Photographs of the receiver swatches were captured using a Nikon D5600 Digital SLR Camera attached to a macro lens (Nikon 60 mm f2.8 D AF Micro Nikkor Lens). The camera operated on an external power source and was positioned on a Kaiser Copy Stand for stability. Illumination was provided by a LED light unit (Kaiser – 2 × 27 W, 5600 K), ensuring optimal lighting conditions. To eliminate any risk of camera movement during photo capture, a remote shutter release (Nikon MC-DC2) was employed. The camera settings for capturing all images were set to ISO 100, an aperture of f/16, and a shutter speed of 1/80 s.

For the transfer experiments, a classic nano ColorChecker®

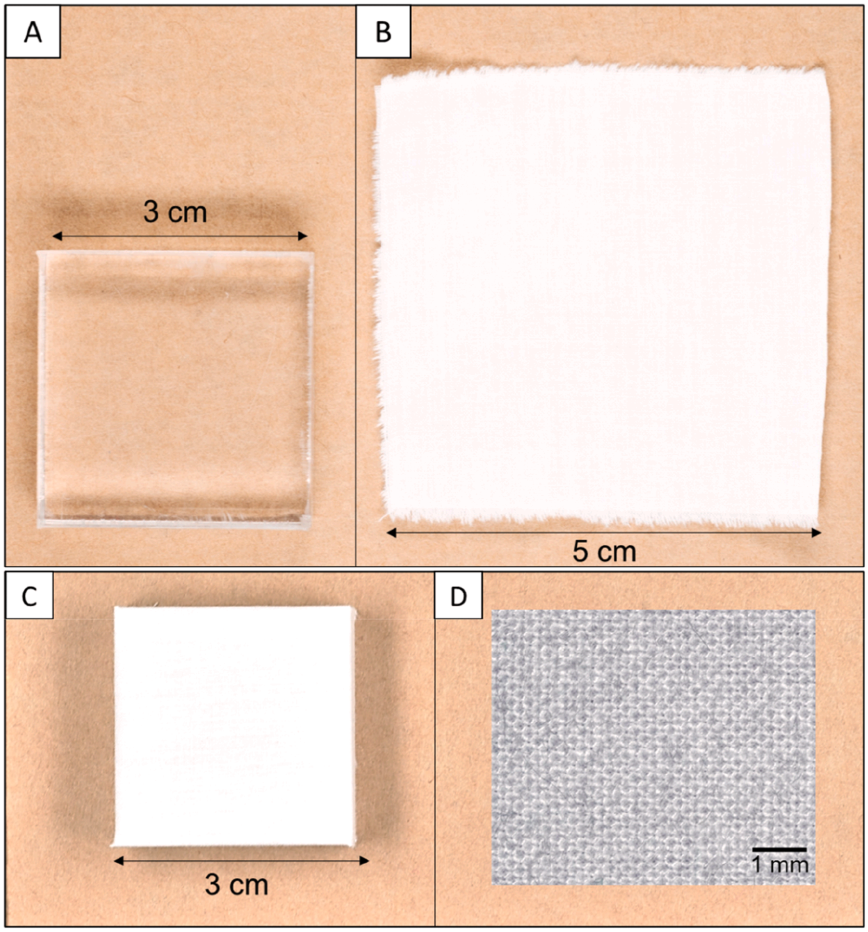

Fig. 4. Receiver textile, in (A) 3 cm × 3 cm Perspex block without receiver textile, (B) 5 cm × 5 cm piece of receiver garment, (C) Receiver swatches: Perspex block with a piece of receiver garment on top, (D) details of the weave with digital enhancement for improved visualisation.

Table 1
Overview of the six series of repetitive washing with controlled parameters (i.e., 40 °C, 1200 rpm), varied detergent and softener usage, and load size.

Series	Donor garment	Label	Size	Mass (g)	Load size	Detergent	Conditioner
1	1 v-cotton	G1	16	343	Small	none	none
2	1 v-cotton	G2	16	353	Small	3 mL	none
3	1 v-cotton	G3	16	347	Small	3 mL	3 mL
4	5 v-cotton	G5 (A to E)	16	1543	medium	none	none
5	12 v-cotton	G12 (A to L)	12	3075	normal	none	none
6	r-cotton	GR	/	800	medium	none	none

(featuring a 24-colour patch, dimensions 24 × 40 mm) was photographed before taking a sequence of images of receiver swatches (background levels and post-transfer). In addition, both a negative control swatch (a receiver swatch with no known transferred fibres) and a positive control swatch (a receiver containing a known quantity of transferred fibres) were photographed to assess the photo acquisition conditions and to further verify the analytical methodology.

For the shedding experiments, the previously described photography protocol and camera settings were employed. Before capturing the photographs (including the ColorChecker®), a sheet of matte photography paper featuring a 3 × 3 cm canvas was placed and secured beneath the camera. The acetate sheets, with the shedding area (SA) on the canvas, were then arranged on this paper to guarantee consistent positioning for image analysis.

2.7. Fibre counting and area measurements

Fibre counting was performed by analysing the photographs of the receiver swatches using the ImageJ software after calibration with a nano ColorChecker® and the Adobe Bridge software. A script was written to automatically crop the photographs, define a colour threshold, and measure the surface area of the fibres (See supplementary information, section V). The L*a*b* colour space was chosen for the analysis, and Fig. 6 shows an example of a receiver swatch (transfer experiment) and an acetate sheet (shedding experiment) before and after being processed in ImageJ.

For the transfer experiments, all receiver swatches were photographed prior to the transfer experiments and after the transfer was performed. The area of fibres was determined by subtracting the area of fibres detected with ImageJ on the images before transfer from the area of fibres detected on the images after the transfer. For the shedding experiment, the area of fibres retrieved on the tape lift was directly used for the analysis.

Data processing was carried out using R (version 4.3.1) and RStudio (Version 2023.06.2), the code is available via: https://doi.org/10.5281/zenodo.13907730 a persistent identifier.

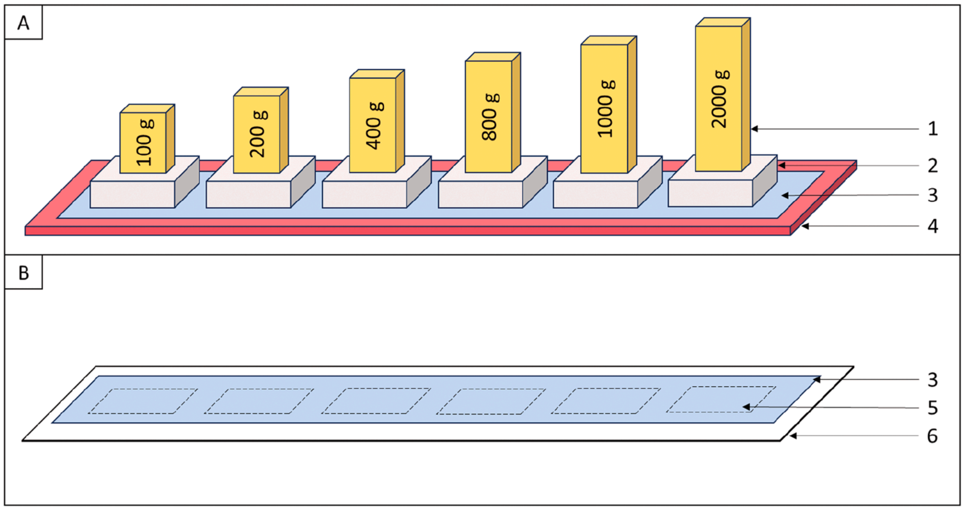

Fig. 5. Shedding assessment protocol with in (A) application of the tape lift on the donor with Perspex cuboids and mass on top and (B) the tape lift placed on top of an acetate sheet after being lifted away, following the 15 s contact between the tape and the donor. 1) Mass applied for the shedding test, 2) 3 × 3 cm Perspex cuboid, 3) lifting tape, 4) donor garment, 5) shedding area delimited after tape lifting, 6) acetate sheet.

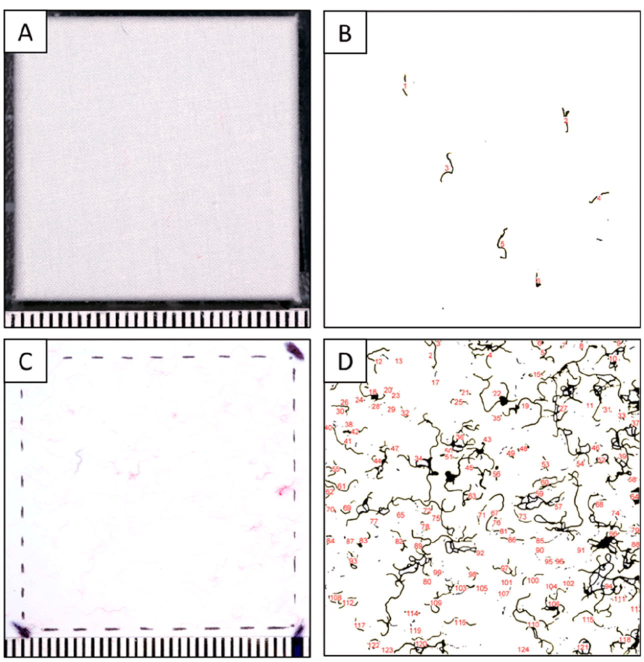

Fig. 6. Fibre counting with ImageJ. In A) a photo of the receiver sample after a transfer with a v-cotton donor and in B) the same sample after being processed in ImageJ. In C) a photo of the acetate sheet after tape-lifting (shedding experiments) with the v-cotton donor and in D) the same sample after being processed in ImageJ. Image adapted from Galais et al. [19].

3. Results

3.1. Shedding experiments

3.1.1. Hand pressure

Fig. 7 shows the comparison of the area of shed fibres (mm^2) obtained from different operators using two manual pressure applications on adhesive tape, "gentle" (Fig. 7-A) and "firm" (Fig. 7-B). Four operators were initially asked to apply either a gentle pressure (Operators 1 and 4) or a firm pressure (Operators 2 and 3) on a single strip of adhesive tape. Following the analysis of the results from these operators, experiments with Operator 5 were conducted to investigate the differences in the firm and gentle pressure applications by the same individual.

The average area of shed fibres obtained using a gentle pressure was 10.81 ± 5.66 mm^2 (mean ± standard deviation), with all garments, repeats, and operators combined. In comparison, an average area of shed fibres of 37.59 ± 27.07 mm^2 was retrieved when a firm pressure was applied. For the results obtained with gentle manual pressure, Operator 1 maintains a relatively consistent and low fibre area across all three repetitions, with 9.94 ± 4.62 mm^2 shed fibre area. Operator 4 displays a slightly higher fibre area of 14.78 ± 6.27 mm^2, with moderate consistency, and Operator 5 presents the most consistent results with the lowest variability (7.70 ± 3.21 mm^2). For the results obtained with firm manual pressure, the results remain consistent for Operator 2, however with a low area of shed fibres (11.13 ± 6.13 mm^2). Operator 3 and Operator 5 show a significantly higher shed fibre area with the largest variability among the operators, with respectively 55.39 ± 28.70 mm^2 and 46.26 ± 15.99 mm^2.

A Kruskal-Wallis test was performed to compare differences between the group of operators applying gentle pressure and the group of operators applying firm pressure on the shed fibre area (see full details in supplementary information – section VI). For both pressure levels applied (Fig. 7), the results of the Kruskal-Wallis test showed significant differences between the Operators applying gentle pressure and between Operators applying firm pressure (p-value < 0.001). In addition, no statistical differences between the two donor garments used were observed (p-value > 0.05), see full details in supplementary information – section VII.

3.1.2. Impact test

Initial tests were conducted to determine whether the force exerted by a mass added onto the tape lift could impact the shedding of fibres, measured as the total area of fibres retrieved on the tape lift. Different impact heights (i.e., 5 mm, 10 mm, 15 mm, and 20 mm) between a 1000 g mass and the tape lift were defined and the mass was dropped on the tape lift. The results are presented in Fig. 8. The average area of shed fibres across 10 repeats per height was found as follows: 52.8 ± 9.6 mm^2 at 5 mm, 64.9 ± 24.3 mm^2 at 10 mm, 53.8 ± 7.9 mm^2 at 15 mm, and 62.1 ± 12.5 mm^2 at 20 mm. To assess the impact of these different heights on the shed fibre areas, an ANOVA test was conducted. The heights were subsequently compared in pairs and the analysis revealed no significant difference between groups (p-values > 0.05).

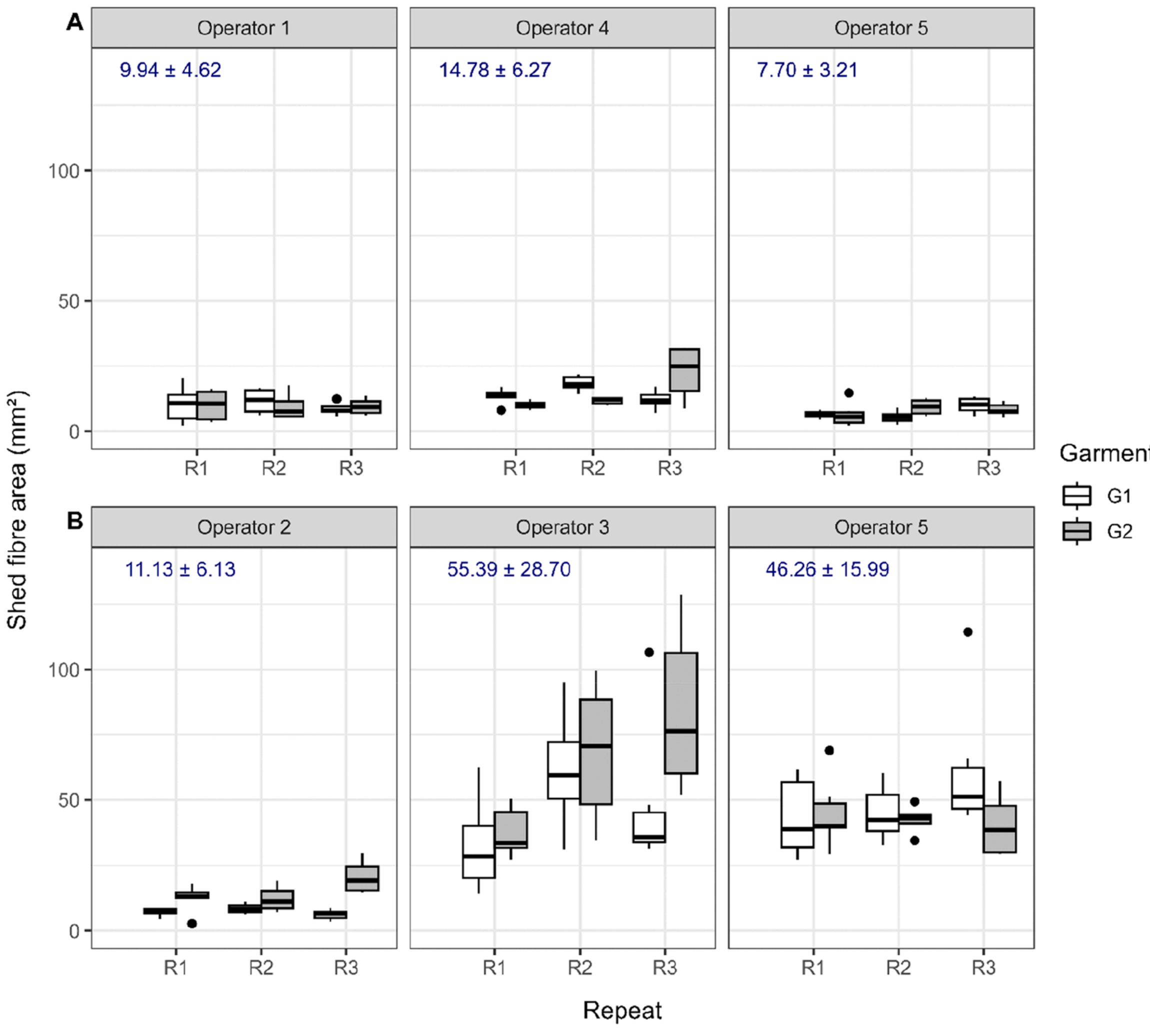

Fig. 7. Shed fibre area (mm^2) as a function of the hand pressure applied by different operators, with A) gentle pressure and B) firm pressure. The mean and standard deviation for each Operator are labelled in blue (Mean ± SD).

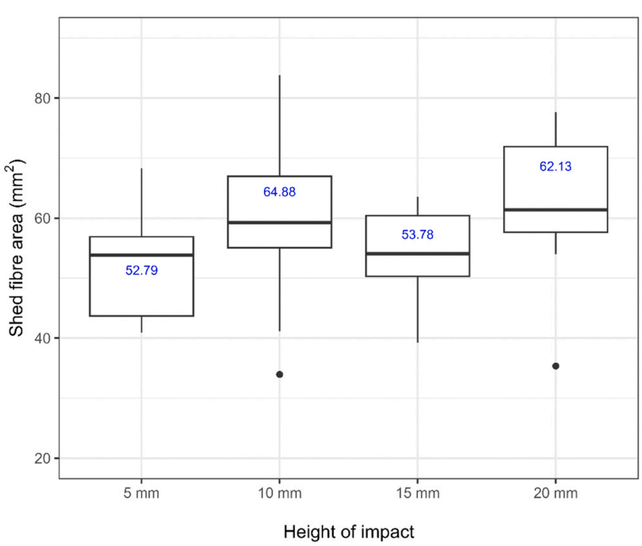

Fig. 8. Relationship between the impact heights of a 1000 g mass dropped on top of the tape lifts on the donor garment and the area of shed fibres (mm^2). The median values are indicated by the whiskers through the centre of the boxes, and the mean for each set is marked in blue.

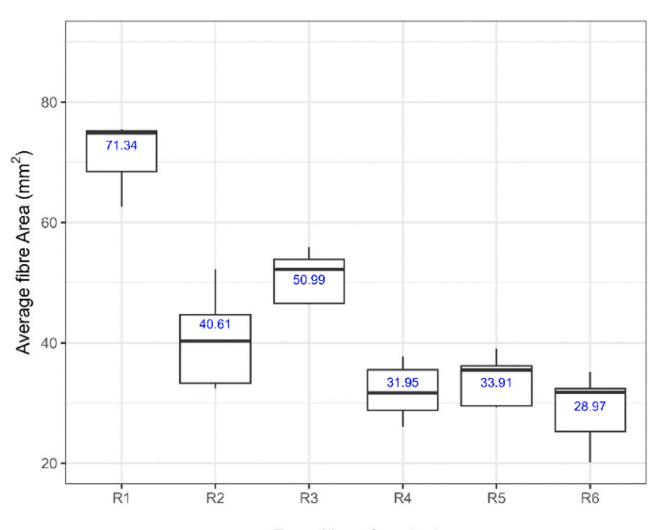

Fig. 9. Relationship between the number of repeated contacts of the tape lifts with the shedding area on the donor garment and the area of shed fibres (in mm^2) recovered on the tape lifts. The whiskers through the boxes represent the medians and the mean for each box is labelled in blue.

3.1.3. Repeated contact test

This experiment was conducted to investigate whether the use of the same shedding area repeatedly has an impact on the shedding. Fig. 9 displays the variation in the area of shed fibres (mm^2) retrieved on tape lifts across six repeated contacts (labelled R1 through R6) between the tape lift and a v-cotton donor garment (i.e., G-test), on 5 different shedding areas (SAs). The mean values showed a downward trend in the total fibre area with increasing contact frequency, with 71.3 ± 5.7 mm^2 after the first repeat to 29.0 ± 6.11 mm^2 after the sixth repeat, corresponding to a percentage decrease of 59.3 %. To assess the impact of the repeated contacts on the fibre area, an ANOVA test followed by Tukey's post-hoc analysis was conducted. The repeats were subsequently compared in pairs and the analysis revealed significant differences between the first repeat and all other repeats (p-values < 0.001). Full details are available in the supplementary information (section VIII).

3.1.4. Washing activities – Influence of washing conditions

Fig. 10 shows the output image of a tape-lift with shed fibres, after the first shedding experiment performed on top of the v-cotton garment from the 1st wash series (i.e., no detergent, no softener), before the first wash cycle (W000). Displayed is the first replication from five conducted tape lifts for each sample mass (i.e., 100 g, 200 g, 400 g, 800 g, 1000 g and 2000 g). This figure shows a heterogeneous fibre distribution for each mass, with certain areas displaying a dense accumulation of fibres, while others are significantly less filled. The purpose of this visualisation was to show the variability in the shed fibre area as a function of the mass used in the shedding experiments. A full presentation of the results is referred to in to Fig. 11 and Fig. 12.

The shedding experiments performed with the *v*-cotton donor garments from the first three series of repetitive washing (i.e., 1st to 3rd) are presented in Fig. 11. The experiments were conducted to assess the influence of different mass (i.e., 100 g, 200 g, 400 g, 800 g, 1000 g and 2000 g) and washing conditions (i.e., with or without detergent and with or without conditioner) on the total shed fibre areas (mm^2) retrieved on the tape lifts, following the protocol described in the methodology section. Across all three washing series, the area of shed fibres increased with the applied mass on top of the donor garments, with the 2000 g mass condition showing higher levels of shedding. The shed fibre areas increase following the initial wash across all masses and washing conditions, reaching its peak in subsequent instances for most cases. An exception occurs in the 3rd series (i.e., detergent and conditioner), specifically for the masses of 100 g, 200 g, and 800 g, where the largest area of shed fibres is observed after the third wash. Afterward, the shed fibre areas then decreased with the number of washes.

A Friedman test (non-parametric test) was conducted to evaluate the differences in shedding across multiple washes conditions for the three series (i.e., 1st to 3rd), under the different weight conditions. The results indicated no significant differences in the shedding across washes for all three series and weights (p-values > 0.05), the full details of the analysis are available in the supplementary information (Section IX).

3.1.5. Washing activities – Load size and textile type

Fig. 12 shows the shed fibre areas (mm^2) from the shedding experiments performed with the donor garments from the last three series of repetitive washing (i.e., 4th to 6th). For the 4th and 5th series, the largest average area of fibres was recovered from the washed garment (i.e., W051 or W041) when subjected to the heaviest mass (i.e., 2000 g), yielding 86.28 ± 31.05 mm^2 for the 4th series (5 v-cotton garments washed together) and 135.29 ± 33.28 mm^2 for the 5th series. Conversely, for the 6th series, the largest average area of fibres was recovered from the unwashed garment (i.e., W000) when subjected to the heaviest mass (i.e., 2000 g), yielding 280.51 ± 47.20 mm^2.

In the 4th series, the highest ratio (calculated as |unwashed / washed|) in the area of fibres between the unwashed and the washed garments occurred with a 100 g mass, reaching 5.52 while the lowest was 1.02 with a 2000 g mass. In the 5th series, the highest ratio in the area of fibres between the unwashed and washed garments occurred with a 400 g mass, reaching 2.52, while the lowest was 1.1 with a 1000 g mass. For the 6th series, the highest area of fibres retrieval ratio was 52.03 with a 100 g mass, and the lowest was 11.26 with a 800 g mass, which is notably higher than any ratio seen with the v-cotton garments (4th and 5th series).

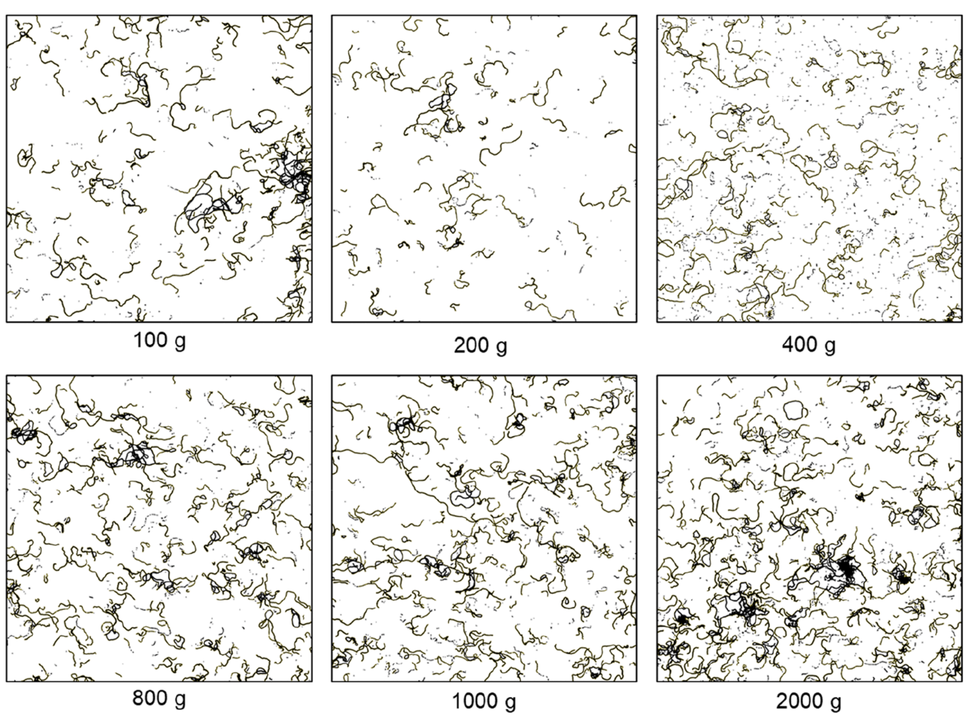

Fig. 10. Visual analysis depicting the tape-lift with shed fibres after the first shedding experiment performed on top of the v-cotton garment from the 1st wash series (i.e., no detergent, no softener), before the first wash cycle (W000).The images displayed show the ImageJ output obtained from the photograph of the first repetition (R1) of the tape lifting.

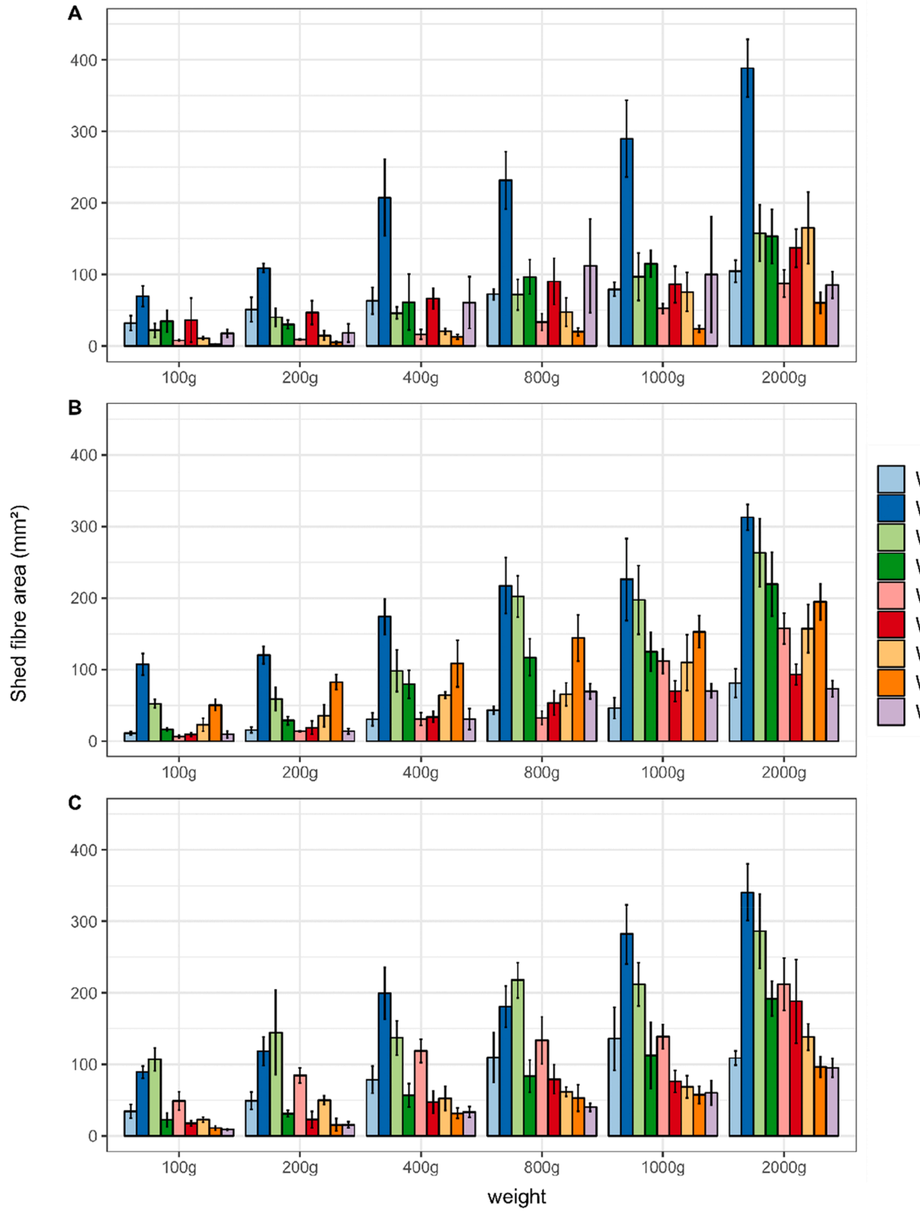

Fig. 11. Total shed fibre areas (mm^2) retrieved as a function of the mass added on top of the tape lift with A) the first series with one garment washed alone, no detergent, no conditioner, B) the second series with one garment washed alone, with detergent, no conditioner, and C) the third series with one garment washed alone, with detergent and conditioner. The tape lifting was performed before any wash (W000), after the first wash (W001), and after every other wash that followed the first wash. The whiskers represent the standard deviation.

The analysis of variance (ANOVA) and Kruskal-Wallis tests were also conducted to evaluate the differences in shedding areas (Area.mm^2) across the donor garments. The shedding areas from the donor garments were analysed from the 1st to the 5th series, before any washing (W000). The choice of the statistical test was based on the data distribution: ANOVA for parametric data and Kruskal-Wallis for non-parametric data (full details available in supplementary information – section X). The results indicated that there are statistically significant differences in the shedding areas across the five donor garments, independently of the weight used.

3.2. Transfer experiments

3.2.1. Washing activities - conditions

Experiments were conducted to investigate the transfer of fibres between donor garments and recipient fabric swatches using a specific device as detailed in the methodology section. The data for the 1st, 4th and 5th series were sourced from Galais et al. [27]. Fig. 13 illustrates the average area of transferred fibres (mm^2) from v-cotton donor garments to recipient swatches across the 1st, 2nd, and 3rd washing series. The average aeras were calculated by including all garments and averaging the number of contact areas per wash series. The variation in the fibre area on the swatches - calculated as the post-transfer area minus the pre-transfer area - was determined by analysing images with ImageJ software.

In the first wash series (a single garment with no detergent or softener) the area of transferred fibres increased from 0.19 ± 0.09 mm^2 before washing (W000) to 0.21 ± 0.1 mm^2 after washing (W001). This increase was followed by a gradual decrease to a stable level after several washes. A similar pattern was observed in the 2nd series (one garment washed with detergent but without conditioner), peaking at 0.3 ± 0.12 mm^2, and in the 3rd series (one garment washed with both

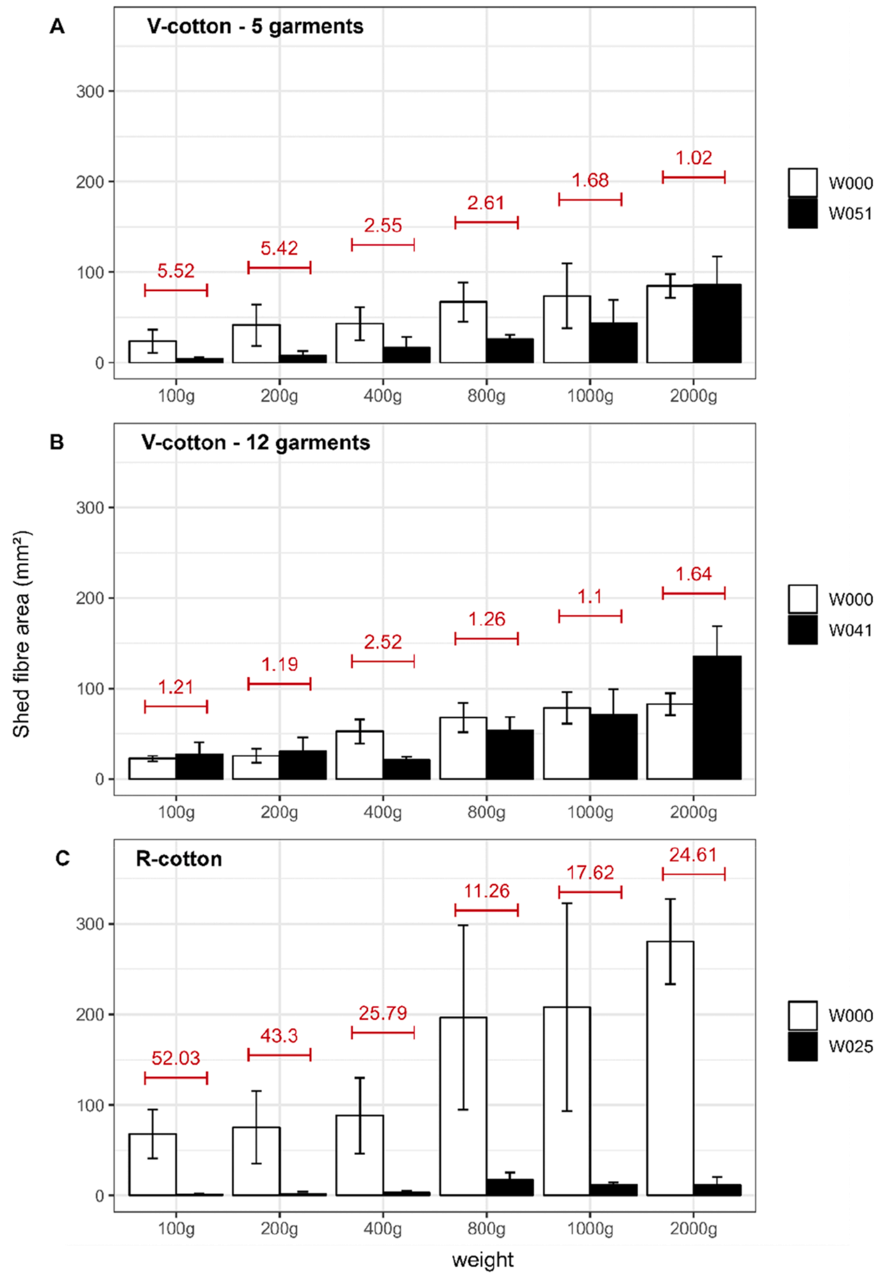

Fig. 12. Total shed fibre areas (mm2) retrieved as a function of the mass added on top of the tape lift with A) the fourth series with five v-cotton garments washed together, no detergent, no conditioner, B) the fifth series with twelve v-cotton garments washed together, no detergent, no conditioner and C) the sixth series with the r-cotton textile washed alone, no detergent, no conditioner. The ratio between the unwashed (W000) and washed garment (either W015, W025 or W051), was calculated as |unwashed / washed|.

detergent and conditioner), peaking at 0.23 ± 0.07 mm^2. A Friedman test was conducted to assess the differences in the transfer of fibres between the wash series (1st to 3rd series), and the results indicated significant differences in the transfer of fibres across washes for all three series (p-values < 0.05). Details of the analysis are available in the supplementary information (Section IX).

3.2.2. *Washing activities – Load size and textile type*

The analysis now proceeds to wash series 4 (5 v-cotton donor garments washed together), 5 (12 v-cotton donor garments washed together), and 6 (one r-cotton donor textile washed alone). These wash series were conducted in the absence of detergent or softener. Fig. 14 illustrates the average area of fibres transferred from donor garments to the recipient swatch across the 4th, 5th and 6th wash series, The average aeras were calculated by including all garments and averaging the number of contact areas per wash series. As previously, the variation in fibre area on the swatches - calculated as the post-transfer area minus the pre-transfer area - was determined by analysing images with ImageJ software.

In the 6th wash series (r-cotton textile washed alone), the area of transferred fibres decreases from 0.26 ± 0.17 mm^2 before the first wash, to 0.2 ± 0.16 mm^2 after the first wash. This is followed by a rapid decline in subsequent data points with a plateau reached after wash 5 (0.02 ± 0.02 mm^2). For the 4th wash series (5 v-cotton donor garments washed together), the area of transferred fibres increases from 0.24 ± 0.14 mm^2 before the first wash to 0.58 ± 0.22 mm^2 after the 4th wash. Subsequent data points show an exponential decay before reaching a plateau after the 30th wash (0.03 ± 0.03 mm^2). In the 5th

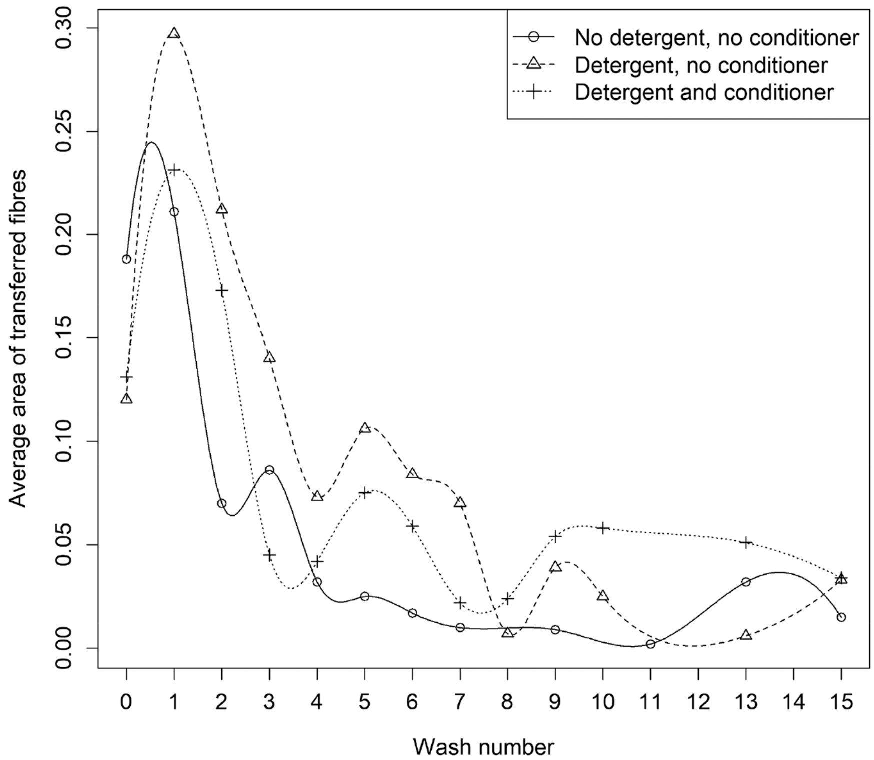

Fig. 13. Average transferred fibre areas from donor garments across the first three washing series. Each point corresponds to measured data, the lines represent the spline curve, a smooth, continuous line that provides an interpolated fit through the data points, for visualisation purposes only.

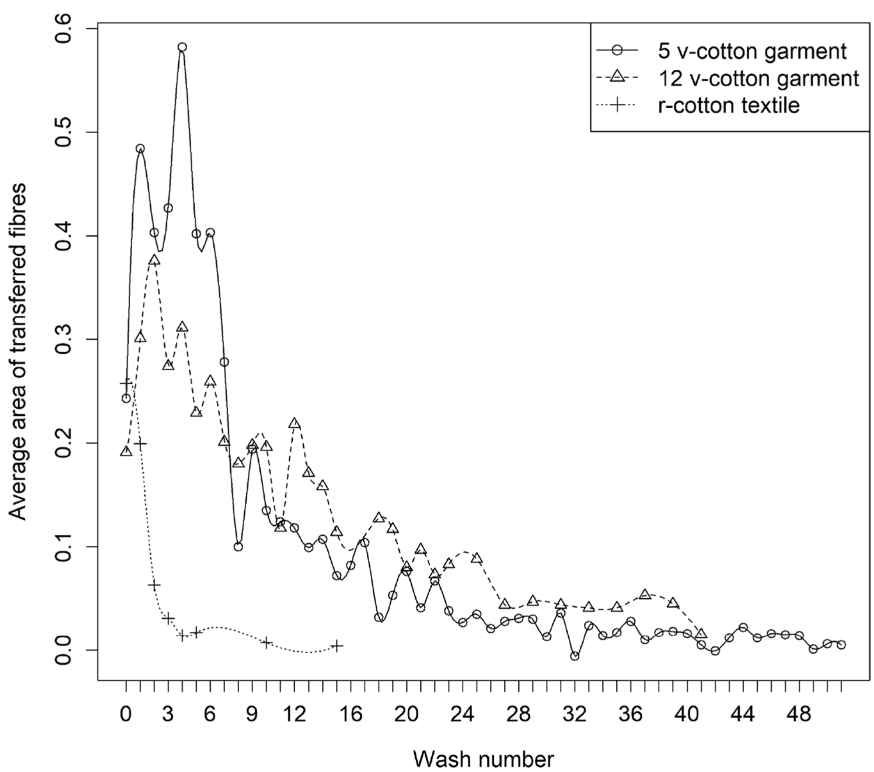

Fig. 14. Average transferred fibre areas from donor garments across the last three wash series (4th, 5th and 6th). Each point corresponds to measured data, the lines represent the spline curve, a smooth, continuous line that provides an interpolated fit through the data points, for visualisation purposes only.

wash series with 12 v-cotton garments washed together, an increase in the number of fibres transferred was observed, from 0.19 ± 0.14 mm^2 before the first wash to a peak at 0.38 ± 0.16 mm^2 after the second wash. This was then followed by a slow decline before reaching a plateau after the 27th wash (0.04 ± 0.04 mm^2).

3.3. Transfer VS Shedding

Table 2 shows the average fibre area retrieved from the shedding experiments and transfer experiments obtained with an 800 g mass, at the corresponding wash: W000, W001, W003, W005, W007, W009, W011 * , W013, W015 (W011 not included in the 2nd and 3rd series as no transfer was performed after the 11th wash). The shedding experiments resulted in a larger average fibre area than the transfer experiments, from a minimum ratio of 358.26 (2nd series, W000) to a maximum of 23950.91 (2nd series, W013). Generally, the results presented in Table 2 shows that all the ratios are above 1, with particularly high values, and there are variations across different washes and series.

Pearson correlation coefficients were calculated to assess the strength of the linear association between the average fibre area retrieved from the shedding experiments and transfer experiments. For the first three wash series, the Pearson correlation indicated a moderate (1st series, r = 0.62; 2nd series, r = 0.62) to weak positive correlation (3rd series, r = 0.38). However, the p-values for all experiments exceeded the 0.05 threshold (0.074, 0.094 and 0.38, respectively for the 1st, 2nd and 3rd series), indicating that the correlations observed do not reach statistical significance.

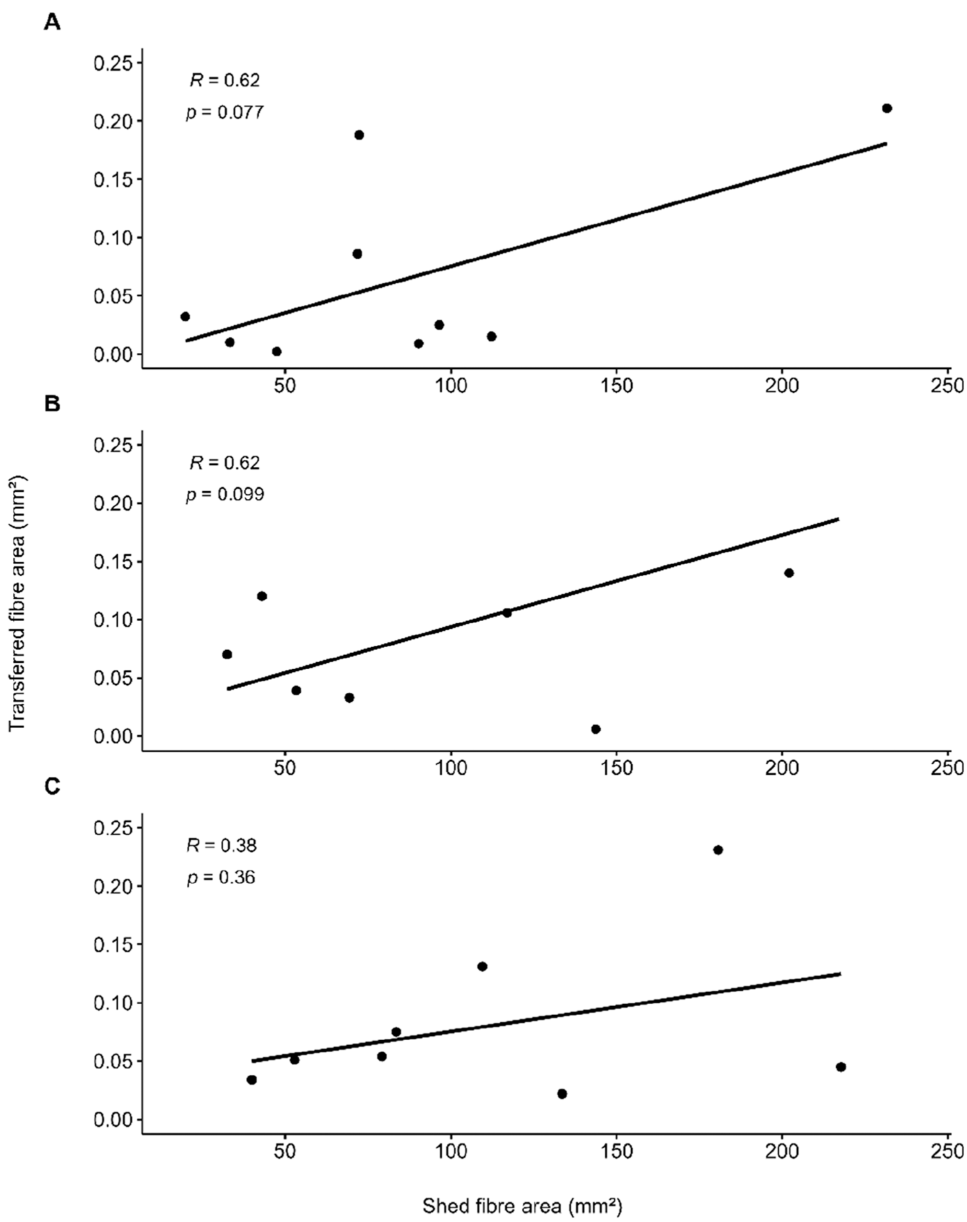

Fig. 15. Comparison between the average fibre area retrieved from the shedding experiments and transfer experiments, performed with an 800 g mass, at the corresponding wash (W000, W001, W003, W005, W007, W009, W011 *, W013, W015). A) 1st series, one garment, no detergent, no conditioner. B) 2nd series, one garment, detergent, no conditioner. C) 3rd series, one garment, detergent and conditioner. The black line represents the regression line. *W011 was not included in the 2nd and 3rd series as no transfer was performed after the 11th wash.

Table 2
average fibre area retrieved from the shedding experiments and transfer experiments obtained with an 800 g mass, across the wash series. W011 was not included in the 2nd and 3rd series as no transfer was performed after the 11th wash. *T = Transfer experiments. * *S: Shedding experiments. * **Ratio = Shedding/Transfer.

Wash	1st Series			2nd Series			3rd Series		
	Average fibre area (mm^2)		Ratio* **	Average fibre area (mm^2)		Ratio	Average fibre area (mm^2)		Ratio
	T*	S**		T	S		T	S	
W000	0.188	72.38	385	0.12	42.99	358.25	0.131	109.55	836.26
W001	0.211	231.63	1097.77	0.297	217.16	731.18	0.231	180.71	782.29
W003	0.086	71.86	835.58	0.14	202.11	1443.64	0.045	217.78	4839.56
W005	0.025	96.54	3861.6	0.106	117.01	1103.87	0.075	83.51	1113.47
W007	0.01	33.4	3340	0.07	32.49	464.14	0.022	133.59	6072.27
W009	0.009	90.29	10032.22	0.039	53.37	1368.46	0.054	79.24	1467.41
W011	0.002	47.49	23745						
W013	0.032	19.91	622.19	0.006	143.71	23951.67	0.051	52.84	1036.08
W015	0.015	112.25	7483.33	0.033	69.4	2103.03	0.034	39.95	1175

4. Discussion

In this study, the results of the experiments involving manual pressure application showed significant differences in the shed fibre area between operators, irrespective of whether they applied firm or gentle pressure. For instance, gentle pressure applied by Operators 1, 4, and 5 resulted in an average shed fibre area of 10.81 ± 5.66 mm^2, while firm pressure applied by Operators 2, 3, and 5 led to a higher average of 37.59 ± 27.07 mm^2. Notably, the results from Operator 3 demonstrated particular sensitivity to the amount of pressure, with a gentle pressure result of 11.13 ± 6.13 mm^2, underscoring the variability depending on the operator. These findings suggest that the manual pressure method lacks reproducibility. When comparing these results with those from previous studies, Sheridan et al. [13] and Lau et al. [15], who also used firm pressure, reported significantly lower shed fibre areas than those observed in the current work. When adjusted to a taped area of 7.84 cm^2, as used in the current study, the shed fibre area reported by Sheridan et al. was estimated based on an average fibre length of 1.2 mm [13] and the most common range of cotton fibre diameters (6 – 13 µm [28]). The estimated shed fibre area ranged from 8.41 ± 3.84 mm^2 for fibres with a 6 µm diameter to 18.22 ± 8.32 mm^2 for fibres with a 13 µm diameter. Lau et al. reported even lower values, ranging from 1.86 ± 0.45 mm^2 (6 µm diameter) to 4.04 ± 0.98 mm^2 (13 µm diameter). These values are lower than both firm and gentle pressure results obtained in the current study. This discrepancy may be attributed to differences in the knitted cotton garments used (such as fibre length or knit size) or the differences in measurement units (fibres/cm^2 versus fibre area/cm^2). Nonetheless, the significant variation among operators in this study highlights the challenge of achieving consistent results using manual pressure.

The second approach involved using standard weights to apply controlled pressure during shedding assessments. For the wash series with virgin cotton donor garments, the first shedding assessment was conducted before any washing, allowing for direct comparison across all series. Using six standard weights ranging from 100 g to 2000 g, the shed fibre areas from the unwashed garments varied as follows: 32.06 ± 10.58 mm^2 to 104.33 ± 15.45 mm^2 in the 1st series, 10.73 ± 2.26 mm^2 to 80.94 ± 15.45 mm^2 in the 2nd series, 34.26 ± 9.78 mm^2 to 135.8 ± 44.11 mm^2 in the 3rd series, 23.56 ± 12.88 mm^2 to 84.61 ± 13.04 mm^2 in the 4th series, and 22.43 ± 3.17 mm^2 to 82.61 ± 11.88 mm^2 in the 5th series. Although the findings of Sheridan et al. [13] fall within the range observed in the current study, their reported values are only comparable to those observed when the lowest masses were used, specifically in a few wash series: 10.73 ± 2.26 mm^2 (100 g, 2nd series), 15.38 ± 4.2 mm^2 (200 g, 2nd series), 23.56 ± 12.88 mm^2 (100 g, 4th series), and 22.43 ± 3.17 mm^2 (100 g, 5th series). Sheridan et al. [13] and Lau et al. [15] noted that significant hand pressure was applied to the tape, suggesting the use of greater pressure than that exerted by 100–200 g masses in the current study. Therefore, the overall fibre area retrieved in the current study was expected to be much lower when using the lowest masses (i.e., 100 g and 200 g) compared to the numbers reported in previous studies [13,15].

The intra-operator variability, as shown by the standard deviation for operators applying manual pressure, varied from 2.31 (Operator 5) to 6.27 (Operator 4) with the gentle pressure application, whereas it ranged from 6.13 (Operator 2) to 28.70 (Operator 3) for those using firm pressure. This shows that the intra-operator variability tends to increase with the pressure, suggesting that applying more force may lead to less predictability in the shed fibre area collected on the tape lift. The variations between operators using a firm hand pressure (SD_{total} = 27.07) fall within the range of variation observed with the controlled pressure experiments with weights 400 g and an 800 g (respectively 22.45 and 29.03). However, the variations between operators using a gentle hand pressure (SD_{total} = 5.66) were found to be lower than the variation observed with the controlled pressure experiments with the smallest weight (100 g; SD = 11.71). Surprisingly, when the highest mass was used in the controlled pressure experiments (2000 g), the variability decreased to 17.94, comparable to the lowest weight (i.e. 100 g and 200 g). Sheridan et al. [13] and Lau et al. [15], who used a manual firm pressure, reported lower variabilities, respectively between 3.84 and 8.32 [13], and between 0.45 and 0.98 [15], with a much lower sample size (n = 5). In comparison, the current study collected 36 samples per operator with the manual pressure approach (n_{total} = 216) and 30 samples per v-cotton garment (W000) following the controlled pressure method (n_{total} = 150). While the use of controlled masses generally led to higher variabilities compared to the hand pressure, this method reflects a more accurate measure of how differing amounts of pressure can affect the shedding. Using controlled masses provides a standardised method that can be consistently replicated across different studies and settings, which is crucial for scientific research. This consistency is less achievable with manual pressure due to the subjective nature of how much pressure an individual operator may apply. This study revealed significant differences among operators when using a manual pressure application, but not between the two donor garments used for this experiment. This suggested that human factors, such as individual technique and pressure application, introduced the variability. Conversely, with the use of standard weights, significant differences among the donor garments were found, suggesting inconsistencies either in weight application or post-application measurements. However, the application of the weight was controlled and consistent, and all tapes were analysed using a controlled photography-automated protocol, ensuring the repeatability of the analysis. One reason to explain the variability observed with the standard weights could be the process of pulling off the tape, for example, the force and angle of tape removal which could introduce variability. This study did not aim to examine this specific variable; however, this should be considered and standardised for future research.

Regarding the washing activities with the v-cotton donor garments washed alone (1st to 3rd series), an increase in the shed fibre areas was observed after the first wash (W001). The percentage increase ranged from 165 % (800 g, 3rd series) to a maximum of 999 % (100 g, 2nd series), with average increases of 303 %, 623 %, and 240 % for the first, second, and third series, respectively. This was followed by a decay in the following washes, until reaching, in 72 % of the experiments (all three wash series and masses combined) a lower fibre area after the last wash (n = 13) than before the first wash (n = 5). This study revealed fluctuations in the shed fibre area as a function of the number of washes a garment has undergone, underscoring the significance of understanding the history of the garment when evaluating its shedding capacity. This study also demonstrated that there was no significant difference in the shedding across the first three series, indicating that the use of detergent or detergent plus conditioner does not impact the shedding. While this study controlled for variables such as water temperature, spin speed and washing machine type, the load size of the 1st to the 3rd wash series were small, which might not accurately reflect typical real-life scenarios. Further studies incorporating variations in detergent and conditioner formulations, washing machine models and a broader range of garments are necessary to provide a more comprehensive understanding of shedding behaviour.

Examining the medium load size, it was observed that the v-cotton donor garments in the 4th series (5 v-cotton donors) produced a higher shed fibre area before being washed (55.56 ± 20.8) than after 51 repetitive washes (30.76 ± 13.27), when all weights were combined. With the normal load size (5th series, 12 v-cotton donors) however, the results were more heterogeneous, with sometimes a higher shed fibre area before being washed than after 41 repetitive washes (100 g, 200 g and 2000 g). These findings suggested that both the number of washes and the load size affect the shedding of fibres. While one could argue that the v-cotton garments did not undergo the same number of washes (i.e., n = 51 or n = 41), the transfer experiments indicated that both load sizes had reached a plateau in terms of transferred fibres. The r-cotton garments in the 6th wash series followed a similar trend to the 4th wash series, with a higher shed fibre area before being washed than after the repetitive washes (W000 = 152.76 ± 62.05; W025 = 7.85 ± 4.13). In general, the shed fibre areas retrieved from the unwashed r-cotton donor garment were higher than the unwashed v-cotton donor garment (4th and 5th series), for all the standard masses used for the tape lifts. This result suggested that, before washing, the r-cotton donor garment was a better shedder than the v-cotton donor garment. Conversely, after a full set of washes, the average shed fibre area retrieved from the r-cotton donor garment was generally lower than the -cotton donor garment. This highlights the importance of considering a garment's history and number of washes when evaluating activity levels if it is found long after a crime was committed. Changes in shedding levels over time may influence the accuracy of the assessment and should therefore be factored into the evaluation.

Using the transfer device, the average transferred fibre area retrieved from the v-cotton and r-cotton donors was found to be similar before washing, with respectively 243×10^{-3} mm^2 (4th series), 191×10^{-3} mm^2 (5th series) and 257×10^{-3} mm^2 (6th series). After washing, similar results were obtained after a plateau in the average transferred fibre area was reached: 5×10^{-3} mm^2 (4th series, n = 51), 15×10^{-3} mm^2 (5th series, n = 41) and 4×10^{-3} mm^2 (6th series, n = 15). However, this initial similarity between the v-cotton and the r-cotton donor garments was not observed in the shedding assessment using tape lifts. Differences in shedding were evident both before the garment first washing (i.e. new and used as received after purchase) and after completing a full set of washes.

While this study focused on developing and validating reliable methods rather than investigating fibre mechanisms, the results revealed complex shedding patterns influenced by factors such as the fibre type, garment structure, and the washing history. The differences in shedding between the v-cotton and r-cotton donors may be explained by their fibre composition and knit structure, with the v-cotton donors having longer fibres and a denser knit, while the r-cotton donor blends shorter recycled fibres with a looser knit. Washing further impacts these differences, as the v-cotton donor sheds more fibres over time, whereas the r-cotton donor sheds more fibres initially but less with repeated washes. Future research is needed to explore these trends further; however, such work can only be accomplished using a repeatable method, as demonstrated in this study. The results of this study corroborated the findings of Coxon et al. [5] and Skokan et al. [11], confirming that the use of tape lifts can significantly overestimate a garment's shedding capacity. In addition, the tape lift method of assessing shedding capacity produced differences among identical unwashed donor garments from series 1–5. The transfer method did not produce differences among the garments either before their first wash or after undergoing washing cycles. This was further highlighted by the Pearson correlation analysis, which showed no significant correlation between the average fibre area retrieved from the shedding experiments (with standard weights) and the transfer experiments. Due to the limited number of studies available on this topic, the current study highlights the critical need for reporting comprehensive data and detailed methodologies. This work aims to fill this gap by providing extensive data that future research can build upon, enhancing the understanding of the variables impacting fibre shedding. These findings are particularly important due to the varied results observed between manual and controlled pressure methods, highlighting the importance of standardised approaches that enable reliable comparisons across different settings. The findings also emphasise the need to explore alternative methods to tape lifts, such as using a transfer device, as demonstrated in this study, for more precise and standardised measurements and assessments.

5. Conclusion

This study investigated the shedding capacity assessment in relation to washing activities using tape lift methods and a transfer method for simulated contact. With the experiments performed with different operators, a gentle pressure manually applied generally resulted in lower shed fibre areas. This study showed significant differences among operators, highlighting the need to standardise and control the pressure when using tape-lift methods to assess the shedding capacity of a garment.

The approach using standard weights to apply controlled pressure application on the tape lifts demonstrated that variability could occur even with controlled masses. However, this method offered a more precise and standardised measure of how different pressure levels affected shedding, providing a standardised method that could be consistently replicated across different studies and settings. This consistency is crucial for scientific research, which is less achievable with manual pressure due to the subjective nature of how much pressure an individual operator might apply.

The results also showed that the use of tape lifts significantly overestimated the shedding capacity of the donor garments. The experiments with controlled pressure on the tape lifts produced inconsistent shedding capacities across different series (especially the 4th and 5th), while the average transferred fibre area during the simulated contact using the transfer method, closer to practical scenarios, remained similar before and after repeated washes. These findings highlighted the critical need to adopt alternative methods to tape lifts for more precise and standardised shedding assessments, such as the transfer device used in this study.

While this research aimed to establish a consistent method to assess the shedability, it is important to acknowledge that the actual contact conditions in forensic cases may vary widely, from gentle to firm pressure, as mentioned in the ENFSI Best Practice Manuals. The proposed method may be more relevant for scenarios involving direct textile contact, such as during physical altercations, but may not fully capture fibre behaviour in other contexts, such as cases involving tape bindings or stabbing incidents. Therefore, the objective of this method is not to replicate specific contact conditions but to provide a reliable, comparable framework for assessing the shedding capacity, that limits intra- and inter-operator variation.

Regarding the washing activities, the study highlighted that the shedding capacity of the donor garments was influenced by the number of washes. However, different washing conditions, such as the use of detergent type and fabric conditioner, did not impact the shedding capacity of garments. Furthermore, the study found that virgin cotton garments tended to shed more fibres after repeated washes compared to recycled cotton garments. This suggested that, in addition to the washing history of the garment, the type of fibres also impacts shedding.

The results from this study contributed to the existing body of knowledge by providing a controlled approach to investigate the transfer of fibres encountered in forensic science, focusing on 100 % virgin cotton and 65 % / 35 % recycled cotton garments. This research lays the groundwork for future studies and emphasises the importance of engaging with practitioners to develop standardised practices and standard operating procedures (SOPs) for fibre evidence evaluation. Consistent, reliable shedding capacity assessments are crucial for the evaluation of evidence, particularly when estimating outcomes based on specific activities. Forensic casework could benefit from more focused examination strategies and more reliable interpretations of evidential findings by improving the consistency of shedding assessments. Future research should include various fibre types and mesh structures to broaden the scope and enhance the robustness of the findings. By doing so, the forensic community could improve the accuracy and reliability of forensic fibre analysis, ultimately strengthening the link between research and forensic casework.

Funding

This research was funded by the Leverhulme Trust RC-2015-011.

CRediT authorship contribution statement

Virginie Galais: Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Stephanie Wilson:** Writing – original draft, Investigation. **Patricia Dugard:** Writing – original draft, Formal analysis. **Chris Gannicliffe:** Writing – review & editing. **Bronagh Murphy:** Supervision. **Niamh Nic Daéid:** Writing – review & editing, Funding acquisition. **Hervé Ménard:** Writing – review & editing, Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors would like to express their gratitude to members of the Leverhulme Research Centre for Forensic Science for their invaluable assistance.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.forsciint.2025.112369.

References

[1] J. Robertson, C. Roux, K.G. Wiggins. Forensic Examination of Fibres, *3rd ed.)*., Taylor and Francis, 2017.
[2] E.J. Mitchell, D. Holland, An Unusual Case of Identification of Transferred Fibres, J. Forensic Sci. Soc. 19 (1) (1979) 23–26.
[3] A.E. Parybyk, R.J. Lokan, A Study of the Numerical Distribution of Fibres Transferred From Blended Fabrics, J. Forensic Sci. Soc. 26 (1) (1986) 61–68.
[4] M.T. Salter, R. Cook, A.R. Jackson, Differential shedding from blended fabrics, Forensic Sci. Int. 33 (3) (1987) 155–164.
[5] A. Coxon, M.C. Grieve, J. Dunlop, A method of assessing the fibre shedding potential of fabrics, J. Forensic Sci. Soc. 32 (1992) 151–158.
[6] Hellwig, J. *The effect of textile construction on the shedding capacity of knitwear*. in *Proceedings of the 5th Meeting of the European Fibres Group* (*pp. 102–106*). 1997. Berlin.
[7] K. De Wael, et al., Evaluation of the shedding potential of textile materials, Sci. Justice 50 (4) (2010) 192–194.
[8] J. Robertson, C. Roux, From Crime Scene to Laboratory, in: C. J.R. Robertson, K. G. Wiggins (Eds.), Forensic Examination of Fibres, CRC Press, Boca Raton, 2017, pp. 99–143.
[9] S. Charles, M. Lannoy, N. Geusens, Influence of the type of fabric on the collection efficiency of gunshot residues, Forensic Sci. Int. 228 (1) (2013) 42–46.
[10] M. Schnegg, et al., A preliminary investigation of textile fibers in smothering scenarios and alternative legitimate activities, Forensic Sci. Int 279 (2017) 165–176.
[11] L. Skokan, A. Tremblay, C. Muehlethaler, Differential shedding: A study of the fiber transfer mechanisms of blended cotton and polyester textiles, Forensic Sci. Int 308 (2020) 110181.
[12] N. Glauser, et al., Fibres in the nasal cavity: A pilot study of the recovery, background, and transfer in smothering scenarios, Forensic Sci. Int. 354 (2024) 111890.
[13] K.J. Sheridan, et al., A study on contactless airborne transfer of textile fibres between different garments in small compact semi-enclosed spaces, Forensic Sci. Int. 315 (2020) 110432.
[14] K.J. Sheridan, et al., A quantitative assessment of the extent and distribution of textile fibre transfer to persons involved in physical assault, Sci. Justice 63 (4) (2023) 509–516.
[15] V. Lau, X. Spindler, C. Roux, The transfer of fibres between garments in a choreographed assault scenario, Forensic Sci. Int. 349 (2023).
[16] C.A. Pounds, K.W. Smalldon, The Transfer of Fibres Between Clothing Materials During Simulated Contacts and their Persistence During Wear: Part I—Fibre Transference, J. Forensic Sci. Soc. 15 (1) (1975) 17–27.
[17] C. Roux, J. Chable, P. Margot, Fibre transfer experiments onto car seats, Sci. Justice 36 (3) (1996) 143–151.
[18] R. Palmer, The retention and recovery of transferred fibers following the washing of recipient clothing, J. Forensic Sci. 43 (1998) 502–504.
[19] V. Galais, et al., Exploring the influence of washing activities on the transfer and persistence of fibres in forensic science, Forensic Sci. Int. 361 (2024) 112078.
[20] J. Robertson, D. Olaniyan, Effect of Garment Cleaning on the Recovery and Redistribution of Transferred Fibers, J. Forensic Sci. 31 (1986) 73–78.
[21] M.C. Grieve, J. Dunlop, P.S. Haddock, Transfer experiments with acrylic fibres, Forensic Sci. Int. 40 (3) (1989) 267–277.
[22] R.R. Bresee, P.A. Annis, Fiber transfer and the influence of fabric softener, J. Forensic Sci. 36 (6) (1991) 1699–1713.
[23] R. Szewcow, J. Robertson, C.P. Roux, The influence of front-loading and top-loading washing machines on the persistence, redistribution and secondary transfer of textile fibres during laundering, Aust. J. Forensic Sci. 43 (4) (2011) 263–273.
[24] *Best Practice Manual for the Forensic Examination of Fibres*. 2022, ENFSI: Wiesbaden, Germany. p. 156.
[25] R. Cook, et al., A model for case assessment and interpretation, Sci. Justice 38 (3) (1998) 151–156.
[26] ENFSI Guidel. Eval. Report. Forensic Sci. (2015).
[27] Galais, V., et al. *LRCFS/Fibre-Evidence_Transfer_washing-activities: Complete release*. 2024; Available from: https://doi.org/10.5281/zenodo.11387110.
[28] S. Macarthur, F.J. Hemmings, in: C. J.R. Robertson, K.G. Wiggins (Eds.), *Fibres, Yarns and Fabrics: An Introduction to Production, Structure and Properties*, in *Forensic Examination of Fibres*, CRC Press, Boca Raton, 2017, p. 30.