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Stanton, T. orcid.org/0000-0001-9097-8739, Stanes, E. orcid.org/0000-0002-7120-257X, Gwinnett, C. et al. (14 more authors) (2023) Shedding off-the-grid: The role of garment manufacturing and textile care in global microfibre pollution. Journal of Cleaner Production, 428. 139391. ISSN 0959-6526

https://doi.org/10.1016/j.jclepro.2023.139391

Journal of Cleaner Production 428 (2023) 139391

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Shedding off-the-grid: The role of garment manufacturing and textile care in global microfibre pollution

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ARTICLE INFO

Handling Editor: Giovanni Baiocchi

Keywords:
Textile fibre
Microfibre pollution
Microplastic
Laundry
Hand washing
Global south

ABSTRACT

Textile fibres are abundant anthropogenic pollutants. These fibres enter aquatic, terrestrial, and atmospheric environments, and biota. Textile fibres pose biological and chemical threats to the environments they pollute. Laundry is a primary source of synthetic and natural textile fibres. Fibre shed from laundry performed in electric washing machines is well characterised. However, over 50% of the global population does not have regular access to an electric washing machine. Without regular access to an electric washing machine, people launder ‘off-the-grid’ with locally specific methods. Their variable laundry methods present a significant challenge to quantifying microfibre shed. This study makes an original contribution to studies of fibre shedding. First, it details laundry protocols in a Global South community. Second, it assesses how textile structure influences fibre shedding independent of laundry practices. To do this, we deploy a hand laundry protocol learned during ethnographic fieldwork. We show that hand-washed garments shed fibres in numbers comparable to machine-washed garments. We show how garment construction (knit and weave) influences fibre shedding. We find fibre type (cotton or polyester) does not. People who hand wash clothing cannot change practices contributing to textile fibre pollution. Thus, industry must act to minimise fibreshed from laundry at the global scale. This entails transforming the design, manufacture, and sale of textiles.

1. Introduction

Scientific efforts to understand textile fibre shed focus on microplastic (MP) fibres. MP fibres are the most abundant particle morphology in environmental surveys of MP pollution (Rochman et al., 2019; Athey and Erdle, 2022). It is laundry and the day-to-day wear of textiles which release most MP fibres into the environment (Browne et al., 2011; Mahbub and Shams, 2022). MP fibres also produce greater toxicological effects than MP fragments, films, and spheres (Thornton Hampton et al., 2022), making fibre shed a persistent and widespread source of aquatic pollution. An extensive literature now shows how MP fibres shed from garments washed using electric washing machines. These studies unfortunately assume a laundry infrastructure that is not globally representative. Focussing on standardised machine laundry

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https://doi.org/10.1016/j.jclepro.2023.139391
Received 17 April 2023; Received in revised form 2 October 2023; Accepted 16 October 2023

experiments neglects the variability of real-world laundry. Washing machine fibreshed does not represent real-world laundry protocols for the majority world.

Washing machine effluent is an important source of MP fibres (Browne et al., 2011). In the Global North, the majority of households and industry discharge effluent into public wastewater infrastructure. It then undergoes treatment in wastewater treatment plants (WWTPs) that receive it. Experiments have sought to quantify MP fibres shed into washing machine effluent. Research has assessed the influence of cycle (Periyasamy, 2021); temperature (Yang et al., 2019); detergent (Hernandez et al., 2017); softener (Rathinamoorthy and Raja Balasaraswathi, 2021); loading position (Sudheshna et al., 2022); fibre capture devices (Napper et al., 2020); load mass (Volgare et al., 2021); fibre type and garment construction (Vassilenko et al., 2021); and garment age (Hartline et al., 2016) on the number of fibres shed. This research identifies the behaviour of householders as the key point of intervention. It advocates adopting new technologies. These minimise fibreshed during laundry or reduce the release of fibres into wastewater. But domestic washing machines are not standardised (Tiffin et al., 2022). These studies thus characterise the extent and variability of domestic fibre shedding. A key drawback is that their methods cannot assess the relative propensity of garments to shed textile fibres. This is because experiments cannot reproduce standardised laundry conditions. Studies using purpose-built standardised non-domestic washing machines (e.g., Carney Almroth et al., 2018) address this challenge. But the rigorous results these washing machine studies generate are of limited relevance in the Global South.

Washing machine ownership varies around the world (Pakula and Stamminger, 2010). So, too, does the way people use their washing machines, which depends on regular access to water and electricity. We know approximately 46% of the world's population lack access to 'safely managed sanitation infrastructure.' The WHO defines this as 'facilities that are not shared with other households and where excreta are safely disposed of in-situ or removed and treated offsite' (WHO, 2021). Though this figure is for sanitation, and not laundry, it is indicative. Lack of access to sanitation infrastructure indicates people who likely launder clothes without electricity or wastewater treatment. All these approximately 3.6 billion people may not lack access to an electric washing machine year-round. It is likely that they mainly use hand laundry and/or laundry shops to wash their clothes, though some people use human-powered washing machines that are not plumbed into sanitation infrastructure. Even within the same location, these 'off-the-grid' practices vary significantly (Khalid et al., 2019).

Local cultures and environments shape hand laundry (Retamal and Schandl, 2018.). People may have personal and cultural preferences for hand laundering clothing. Some people may be able to access others' labour to launder by hand. Others may have concerns about garment care, fabric, and fibre types. Sometimes electrified laundry is available seasonally. People then hand launder when water and electricity are unavailable. The periodicity of this is variable and not well-characterised.

Hand laundry usually features scrubbing. This may be with or without a detergent or source of abrasion. Abrasion may come from another garment, a plastic brush, a scrubbing board, a wooden paddle, or a rock. Hand laundry can take place in buckets which people empty onto the ground (KeChi-Okafor et al., 2023) or into water bodies (Gordon et al., 2009). Very few studies have attempted to quantify fibre shed from hand laundry (e.g., Rathinamoorthy and Raja Balasaraswathi, 2021; Wang et al., 2023). These studies are limited by their methods, which do not reflect lived or ethnographic experiences of laundry practices in the Global South.

Machine laundry generates patterns of fabric contact which influence fibre shed. Forensic science experiments on dry textile fibre sheddability show the nature of fabric contact (intensity, pressure, duration, area) influences the dry transfer of fibres from one garment to another (De Wael et al., 2010). Hand laundry does not follow the same patterns of contact found in machine laundry. These same factors - intensity, pressure, duration, and area - may vary even more during hand laundry. People may hand wash garments alone, against each other, or with an extra source of abrasion. Research must assess the propensity of textiles to shed fibres independent of the laundry protocol applied. This will predict how likely different garments are to shed fibres in circumstances where textile care is variable. This is key to identifying priority points of intervention for minimising fibreshed at the global scale. Hand laundry practices likely add significant fibre loads to the environment, representing a major and uncharacterised environmental concern.

There is an important social issue here, too. Washing machine-focussed fibre shed research underpins recommendations for mitigation through householders' behaviours. But people laundering off-the-grid cannot fit filters to washing machines. They cannot buy fibre-catching technologies. They cannot set the precise temperature at which they wash their textiles. Focussing on washing machines distracts from the bigger picture. It is global commodity chains which shape the life cycle of textiles and the fibres they shed. But fibre shed from hand laundry is outside the current scope of textile lifecycle analyses (e.g., van der Velden et al., 2014; Munasinghe et al., 2021). Omitting hand laundry obscures the role of garment design, manufacture, and retail in textile fibre shed at the global scale.

Some of the clothing people launder by hand comes from a global market in second-hand clothes. Consumption of clothing continues to rise across the globe. In the Global North, the market for second-hand clothing has declined. Instead, there has been an increase in second-hand clothing exports (Stanes and Gibson, 2017). Two thirds of donated, used clothing is exported for reuse and resale in Global South markets (Norris, 2015). These exports are often fast fashion items (Minter, 2019). People who buy them second-hand are seeking cheap and hard-wearing clothes for manual labour. Thus, the garments people hand launder are at the end of a global textile commodity chain.

Our paper makes two original contributions to advance debates on fibre shed. First, we highlight the contribution of off-the-grid hand laundry protocols to microfibre shedding. Second, we examine drivers of fibre shedding independent of laundry methods.

We use a hand laundry method learned during ethnographic fieldwork. We conducted field studies with communities in the Cagayan Valley of the Philippines. We then applied the methods we learned from them in the laboratory. We show that hand-washed garments shed fibres in numbers comparable to machine-washed garments. But we cannot extrapolate to quantify fibre shed from all hand laundered garments globally. As we show, fibreshed will be variable and likely specific to each hand laundry protocol. Reliable data thus could only come from further and extensive experiments in situ. We note that reducing such fibre shed would be challenging, despite its significance. Economic privilege underpins people's potential to change their laundry practices and laundry infrastructure.

We then assess the influence of two garment parameters - knit vs. weave and fibre type - on fibre shedding independent of laundry procedures. This lets us suggest how textile design influences fibre shed. The relationship between textile design and fibre shed is crucial. Where people cannot minimise fibre shed from hand laundry, they may be able to choose different garment types. But there are limits to action in off-the-grid settings. We argue that the responsibility for minimising laundry fibre shed at the global scale must fall to those design, make, and sell textiles. We make recommendations to these stakeholders accordingly.

2. Materials and methods

2.1. Hand laundry ethnography

We collected narrative data on laundry protocols during a workshop on plastics in the environment. We held this workshop with residents of three settlements in the Cagayan Valley in the Philippines (24/01/2020-

01/02/2020). Team members then observed hand laundry practices in situ. At the same time, people taught them local protocols for laundering clothes. This is the classic ethnographic method of participant observation.

Workshop participants came from communities in San Mariano, Isabela Province; Cabagan, Isabela Province and Aparri, Cagayan Province. Isabela State University and the Mabuwaya Foundation convened the workshop. The participant observations of hand laundry validated reports shared by workshop participants. The team undertook these observations at Lake Dunoy, San Mariano. We observed washing of garments of three colours in situ. A plastic scrubbing net was used to apply abrasion. In this settlement, no commercial hand laundry was available. No households employed domestic workers. People described how laundry protocols vary by perceptions of sweat, dirt, and cleanliness. These perceptions, in turn, are shaped by the wider socio-cultural environment.

2.2. *Fibre shedding from hand laundry*

We recreated laundry techniques learned in the laboratory in the United Kingdom. We designed our experiment to consider the amount of fibre shedding that could arise from the Cagayan Valley protocol. We chose as our test garment an item representing ‘workwear’: a pair of polyester trousers. This is a garment which people were likely to wash directly into a watercourse. It is a garment with minimal perceived value. It would be subject to most abrasion in the local laundry protocol. These data are, given the caveats set out above, indicative.

Our polyester trousers typify items donated to charity and shipped to the Global South. We purchased five pairs of the trousers from a ‘fast fashion’ chain on the British High Street. We had seen similar garments for sale in Cagayan Valley ’wag-wag’ (secondhand clothing) markets, and had observed these kinds of trousers being worn during agricultural work. Both pre-worn garments and garments that were never sold (overstock) or went unworn enter Global South markets. And some are purchased new in local markets. Recognising this, we applied two protocols. Our first experiment examined fibre shed from garments that had previously been hand washed. Our second examined shedding of fibres from never-washed garments.

2.2.1. *Textile sourcing and preparation*

All five pairs of trousers were labelled 100% polyester. They were black, with thin stripes of yellow, red, blue, and white (Fig. S1). All five pairs were labelled as the same size. We noted that the exact measurements of each garment varied by < 5 mm in each direction. The trousers had a tight, closed weave with low elasticity.

Treatment one assessed the shedding of fibres from garments previously washed by hand. This treatment involved washing the garments three times (as outlined below) and air drying between each wash. Treatment two assessed the shedding of fibres from garments that had not been pre-washed.

2.2.2. *Fibre shedding*

We washed all five pairs of trousers individually in 12 L of filtered water (wash and rinse combined). This occurred in a clean large clear polypropylene plastic container. We applied scrubbing with a nylon-bristle/polypropylene block plastic scrub brush (Fig. S2). We used two teaspoons powdered detergent purchased from a UK supermarket (Persil). We dissolved this in the first 6 L of wash water. We washed each pair of trousers for 3 min, with 1 min of scrubbing applied. We then wrung out the trousers by twisting them into a loose tube-shape. We then rinsed the trousers in 6 L of clear water.

Duration of washing and scrubbing and the amount of water used replicated conditions we had observed in situ in the Philippines. We washed the whole garment, but the location and intensity of our scrubbing with the plastic brush varied, as would be the case in-situ. We directed scrubbing to areas that attract most dirt in agricultural work: knees, seat, and lower legs/hems.

The time expended and volume of water standardise observations between garments and treatments. We selected these parameters to fall close to observed real-world practices. We were unable to quantify exact parameters of time and water for ‘normal hand laundry’ during field observations. This was because methods in the Cagayan Valley laundry protocol were highly variable.

We filtered all 12 L of wash water from each separate hand wash under vacuum, using a ceramic Büchner funnel and a Whatman 3 cellulose filter paper (WHA 1003070). The filter papers were then tape lifted using either Easylift® tape, available from Staffordshire University, as described in Gwinnett et al. (2021) or J-Lar fingerprint tape (Jones et al., 2019), available from Scenesafe, catalogue number B20610. This occurred whilst the filter papers were still wet to retrieve the fibres for later counting. Easylift® taped samples were secured onto clean glass microscope slides. J-Lar tape was secured onto clean CSI equipment acetate sheets, catalogue number 96134B, ready for searching.

2.2.3. *Fibre quantification*

We conducted fibre quantification for the unwashed and pre-washed garments using the same method, similar to Stanton et al. (2019). A Nikon C lens model microscope with a magnification of 35× was used to observe samples. We used a grid searching method with a cell counter to count the total fibre numbers. We did not count white fibres to minimise the potential contribution of cross-contamination from protective clothing (see QA/QC).

2.3. *Laundry-independent fibre shedding*

Our method here builds on Cai et al. (2020). Their design assesses MP fibres in garments at distinct stages of the garment manufacturing process. They apply a standardised gentle agitation procedure (standardised sonication of a standardised surface area of fabric) to demonstrate presence (not shedding) of MPs. Here, we conducted a mechanistic assessment of fibre shedding from a standardised fabric area (3.14 cm2). We exposed this area to a standardised agitation procedure. This enabled us to assess the propensity of fibre shedding from seven textile types, each in isolation. We used four knitted (polyester, acrylic, cotton, wool) and three woven (polyester, cotton, wool) fabric types. All acrylic and polyester textiles were constructed from continuous filaments.

2.3.1. *Textile sourcing and preparation*

We used pre-worn garments as the source of our textile samples. These comprised polyester (knitted shorts, woven trousers), acrylic (knitted jumper), cotton (knitted t-shirt and woven denim jeans) and wool (knitted jumper and woven trousers).

We cut five circular swatches of fabric from distinct locations on each garment. This accounts for variations in fibre shedding within each garment. We weighed each swatch, approximately 23 mm in diameter, using a 3 decimal place balance (Ohaus Explorer). This ensures consistency between swatches from the same garment (Table S1). We then inserted each swatch into a DGT passive sampler housing unit (Fig. S3). These passive sampling devices have a 20 mm diameter circular window (area = 314 mm2). They expose a standardised surface area of a membrane to aquatic environments for the passive sampling of chemical pollutants. The design of the DGT passive samplers means that the edges of the swatches are not exposed when fibre shedding is assessed (Fig. S3).

2.3.2. *Fibre shedding*

For standardised agitation we placed an inverted DGT sampler in a beaker of 300 ml of deionised water with a stirring bean in a 400 ml glass beaker. The beaker was placed on a mixing plate for 15 min at 300 rpm (hereafter a ‘run’). Our preliminary experiments identified 300 rpm as the ideal spin speed. Higher rates of rotation overcame the floatation of the DGT samplers. We used an initial conditioning run of 30 min. This run removed any fibres that might have loosened during the cutting and handling of swatches, and ensured the entire fabric swatch was saturated with water. Saturation is an important consideration. The tensile strength of natural fibres depends on whether the fibre is wet or dry (Hearle, 2002). Any fibres released into this water after 30 min were not counted.

We then conducted five sequential 15-min experimental runs per swatch. This assessed the consistency of fibre shedding over a 75-min period (n = 175 runs). After each run, we removed the passive sampler and stirring bean. We filtered the 300 ml of water on to 0.45 μm mixed cellulose ester gridded filter papers (Whatman ME 25/41). We rinsed the 400 ml glass beaker three times with deionised water over the vacuum filtration apparatus. We then rinsed the vacuum filtration apparatus thoroughly before the filter paper was removed and stored in a sealed petri dish for analysis. Due to the importance of maintaining swatch saturation, each 15-min agitation run immediately followed the previous. This ensured the swatches would not dry out between runs. Each swatch thus underwent 75 min of agitation. Once filtered, the samples were transferred into labelled petri dishes and sealed using electrical tape.

All fabric swatches remained in the DGT samplers throughout the experimental procedure, except for woven polyester. Woven polyester swatches were the lightest of all swatches (Table S1). The swatches would not remain in the DGT samplers during the experimental procedure on their own. We therefore secured woven polyester swatches in the DGT samplers using Blue Tack® on the underside of the swatch. This placement ensured the Blue Tack® did not interfere with the shedding surface.

2.3.3. *Fibre quantification*

Fibres were counted using a dissecting microscope with a magnification range of 6.5-50X (Zeiss Stemi, 2000). We used a grid counting method. This prevented repeated scanning of the same filter paper area. Only fibres that were the same colour and material as the test swatch were counted.

2.4. *QA/QC*

Our QA/QC procedures did not need to account for other fibre types in the same manner as pollution-based microfibre studies. This is because the assessment of fibre shedding from both hand laundry and the laundry-independent method was targeting only known fibres (from the test garments themselves). Our methods thus only counted those fibres. Nonetheless it was important not to contaminate the equipment and samples with other fibres that would appear the same as the target fibres under the illumination conditions used for counting. We achieved this by two methods for both the laundry and shedding propensity samples:

1. We used anti-contamination protocols during sampling and processing as described in Woodall et al. (2015) and Gwinnett and Miller (2021). These protocols include: triple cleaning of all equipment with filtered (hand laundry) or deionised (shedding propensity) water before and between uses; keeping water samples covered with clean aluminium sheets; and using ambient controls and sampling/monitoring of any other textiles present during experimentation.
2. The taking of control samples from the target garment. These samples were then observed under the same illumination and magnification conditions as samples being searched. We observed these fibres for their colour, cross-sectional shape, and relative thickness. This allowed for comparison to fibres counted from the experimental samples. This is the standard protocol used for the searching for target fibres in forensic science.

For the hand laundry study, we excluded white fibres from the count. This minimised any cross-contamination from white polyester laboratory coats/jumpsuits and hair covers.

For the laundry independent fibre shedding samples, we included a series of ‘no spin’ runs in the experimental design. These runs followed the same experimental procedure except samples were not placed on the stirring plate. This meant they did not undergo the experimental agitation. This ensured that the loss of fibres during experimental runs result from the agitation to which each run exposed the sample. We carried out three of these ’no spin’ runs per fabric type. Each was performed after a different experimental run. These runs accounted for any potential variation in fibre shedding throughout the series. The order of experimental and no spin runs is shown in Table S2. We assumed that any fibres lost during a no spin run would have been lost during the run that followed them. These were thus added to the totals of the experimental runs that followed them.

2.5. *Statistical analysis*

Statistical analysis of laundry-independent shedding was performed using SPSS Version 27 (IBM Corp, 2020). P values < 0.05 were considered significant for all analyses.

Following log10(x+1) transformation, the number of fibres shed met the assumptions required for repeated measures ANOVA (Mauchly’s test of sphericity, $P > 0.05$). We thus used a repeated measures ANOVA (with the number of fibres shed in the five sequential runs (log10(x+1) transformed) inputted as repeated measures, and the garment type [acrylic knit, polyester woven, polyester knit, cotton woven, cotton knit, wool woven, wool knit] inputted as factors) to identify if fibre shedding differed between garments and between runs. Pairwise comparisons were examined using Bonferroni correction for differences in sequential runs (repeated measures variable), and Tukey’s HSD test for differences in garment type.

We then explored the drivers of differences observed between the fibre shedding of garment types. The log10(x+1) data met the assumptions required for a general linear model (Levene’s test, $P > 0.05$), with the fibres shed during the first experimental run as the dependent variable, and the fabric material (acrylic, polyester, cotton, wool) and the fabric construction (knitted or woven) inputted as fixed variables. We examined the first run data due to its independence of other experimental runs.

3. Results

3.1. *Microfibre shedding in the Global South*

3.1.1. *An ethnography of laundry in the Philippines*

Workshop participants impressed on the team the variability of laundry protocols. Approximately 46.5% of Filipino households own a washing machine. Ownership rates are 46.9% in the Cagayan Valley (PSA, 2019). But washing machines ownership does not mean that people do all their laundry in the machine. Electric washing machines here are rarely plumbed into a mains water supply. This is true even in urban centres. People must fill these machines, by hand, making them awkward to use (Retamal and Schandl, 2018). Thus, where and when available, people tend to use washing machines for larger items like sheets, but not clothing. And people do not always perceive washing machines as an effective method to clean clothing (Retamal and Schandl, 2018). They often prefer hand laundry.

In the rural and peri-urban Cagayan Valley, electricity is irregular and seasonal. Where people run a washing machine, wastewater is rarely plumbed into sanitation infrastructure. People hand wash laundry for most of the year instead. They wash on concrete, stone, or dirt washing ‘decks’ which drain onto the soil and then into a nearby waterway. Or they may wash their clothes at the edge of a water body. Here, they empty buckets of wastewater into the watercourse, or launder in the watercourse itself (Fig. 1.)

Their hand laundry protocols involve strong abrasion. People scrub garments against other garments and/or with a scouring pad or plastic brush. Sometimes they use an improvised scrubber – e.g., a plastic soap wrapper or piece of plastic netting (Fig. 1). For exceptionally soiled items, they use a wooden paddle (called palu-palo) to remove dirt.

People describe their hand laundry protocols as targeted to lifting visible dirt and perspiration. This is mud or agricultural waste, which has accumulated on their garments. They target scrubbing to visible stains in the areas of seat, knees, hems and to underarm seams. Their laundry efforts are not applied consistently across the garment. They explain that they reserve clothing purchased in new or 'as new' condition for best. People buy garments worn for agricultural work, cleaning, home repairs etc. from wag-wag dealers. Because best garments do not become heavily soiled, people launder them more gently. Work clothes they scrub, twist, and slap on rocks. Our participants reported that their work clothes do not last long. They attributed this to the abrasion they apply in hand laundering them. Once garments were beyond use, people repurposed some as rags. People reported that they burned most of their discarded garments. Burning required using added accelerant and occurred in what they euphemistically called 'compost pits'.

Our ethnographic findings represent only some of the hand laundry practices of Global South communities. They are not representative of all off-the-grid laundry practices. Yet these findings highlight the variability of approaches used to launder even the same type of clothing, depending on its condition. Moreover, they show why quantifying fibre shed from hand laundry would be a huge challenge. But we cannot disregard hand laundry as a source of microfibre pollution. And hand laundry will remain important because it is increasingly unlikely to be electrified. Our participants reported sporadic, seasonal access to electricity. Their access to electricity relies on output from hydropower facilities. This output is becoming unreliable because of the impacts of climate change. The Cagayan Valley experiences drought-induced low flow conditions and increasingly intense storms. Both render hydropower facilities unable to generate power for significant periods of the year. During periods of low flow, those who launder off-the-grid travel further to access water. This concentrates their laundry activity. This means textile fibres and detergent residue are released in more localised receiving waters. Our findings thus suggest climate change will see hand laundry become a more important source of water pollution for the Global South.

Fig. 1. Photograph of member of the Cagayan Valley community washing clothing in a river showing a laundry soap bar (A) and blue plastic netting (b) used as a source of abrasion. Photograph taken with participant's consent. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.1.2. *Shedding off-the-grid*

Research on machine-washed garments has found the number of textile fibres shed to be highly variable. Hazlehurst et al. (2023) summarise fibre shedding from 37 studies which use a variety of electric laundry methods and reporting units. They report fibre shedding ranging from thousands to millions of fibres per wash. In our experiments, the per garment fibre shed from pre-washed garments was lower than that from the unwashed garments. We report 6499 fibres shed from one pre-washed garment, and 9282 fibres from the other. The numbers of fibres shed from each unwashed garment were 25 640, 33 382, and 64 350 (Fig. 2). When combined with our ethnographic observations, our results show fibre shed from hand laundry depends on protocol, culture, and geography. Our data demonstrate the potential magnitude of fibre shedding from hand laundering protocols. A full assessment would need a global and comprehensive study.

3.2. *Laundry-independent fibre shedding propensity*

Fibre shedding under the standardised experimental conditions ranged from 0 to 164 fibres per 15 min run. Total fibre loss ranged from 9 to 279 fibres per swatch over the 75 min of swatch agitation. Across all garments, this equates to a loss of 0.287–8.885 fibres per cm^2. Shedding differed significantly between sequential experimental runs across all fabric types (Repeated measures ANOVA, $F(4, 112) = 22.883$, $p < 0.001$). Pairwise comparisons indicated that shedding typically decreased during the experimental procedure. The first runs shed significantly more fibres than runs 2, 3, 4 and 5 ($p < 0.001$ for all cases; Fig. 4). This difference suggests that there is a higher propensity for fibres to be shed during the initial stages of laundering.

Differences in total fibre shedding were also observed between each fabric type (Fig. 3). Across the seven fabric types, total fibre shedding throughout the experimental procedure decreased in the order: Polyester knit>Cotton knit>Acrylic knit>Wool knit>Polyester weave>Cotton weave>Wool weave (Table S3). The repeated measures ANOVA found the differences between fabric types to be significant ($p < 0.001$). Tukey's HSD post-hoc tests identified that woven fabrics shed significantly fewer fibres than knitted fabrics in eight of the 12 pairwise comparisons. Woven wool shed significantly fewer fibres than knitted fabrics in all cases. No significant differences were found between pairwise comparisons of garments sharing the same fabric construction (knitted or woven) (Table S4).

To consider the influence of fibre material and fabric construction on fibre shedding, a general linear model was performed on the number of

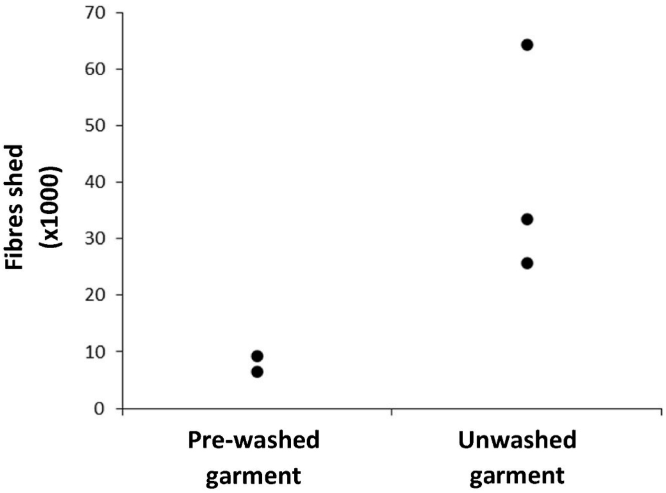

Fig. 2. Microfibres shed from two prewashed garments and three unwashed garments following the hand laundering protocol learned from Cagayan Valley communities.

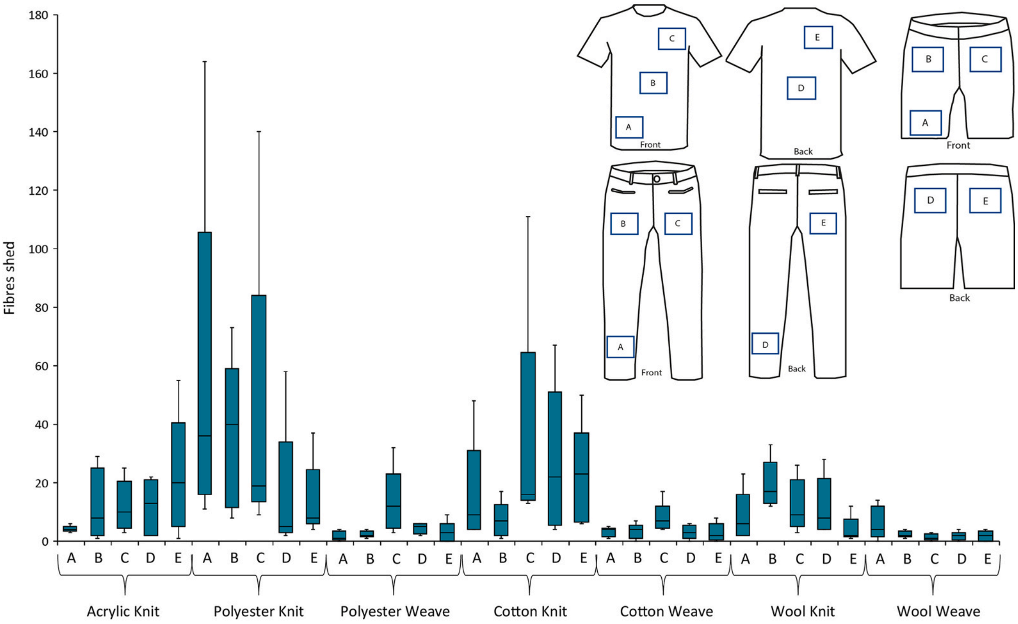

Fig. 3. Box plots showing the fibres shed (total count) from each swatch (A–E) for each test fabric. Each boxplot represents the shedding of fibres from each swatch across 5 runs. The approximate location that swatches were cut from each garment are shown in the inset diagrams for garments that were tops (Acrylic knit, Cotton knit, Wool knit), trousers (Polyester weave, Cotton weave, Wool weave), and shorts (polyester knit).

fibres shed during the first run. Number of fibres shed in the first run (log10 (x+1)) was the dependent variable, and fibre material and fabric construction were fixed factors. The model was significant ($F_{6, 34} = 9.498$, $P < 0.001$). There was no difference in the fibres shed between fabric types ($p = 0.080$). Knitted fabrics, however, shed significantly more fibres than woven fabrics ($p < 0.001$). There was no significant interaction between fibre material and fabric construction ($p = 0.241$). This indicates that the influence of fabric construction on fibre shedding was consistent across all fabric types.

4. Discussion

Our data show off-the-grid laundry protocols can introduce thousands of textile fibres into the environment per garment. The contribution is comparable to that of machine-laundered garments (Hazlehurst et al., 2023). This lack of research on hand laundry in situ is thus a discipline-limiting knowledge gap. Without addressing the contribution of hand laundry, research on textile fibre shed is constrained to the Global North.

We find that garment structure significantly influences fibre shedding (as reported in machine laundry research, e.g., Vassilenko et al., 2021). Woven garments shed significantly fewer fibres than knitted garments. But our assessment of fibre shedding independent of laundry practices found textile type does not have a significant influence on the propensity of fabrics to shed fibres. This is a novel and important finding. Previous work considering fibre shedding from hand laundry (e.g. Wang et al., 2023) has not considered multiple fibre types, or ethnographically-informed hand laundry protocols. Though our assessment here highlights the role of garment manufacturing in the propensity of textiles to shed fibres, our experimentation was not able to consider all parameters found to influence shedding during machine washing. This would include fabric weight, staple vs filament yarns, and chemical/mechanical finishing (Liu et al., 2021). Here we also highlight how ethnographic research can ensure future work in this field is informed by, and sensitive to, in-situ hand laundry protocols. These will be key areas for future exploration of fibre shed during hand laundry.

Our findings have important implications for narratives of 'greener' fashion, care, and consumption. Innovations to minimise fibre shed include washing machine filters, fibre-collecting balls, and fibre-catching bags. All rely on electrification, mains sewerage, and waste disposal infrastructure. Each anticipates a householder who will be able to invest money and time to minimise fibre shed. This requires householders with economic privilege. This is not appropriate for the Global South. Future development here is unlikely to extend infrastructure to remote, rural areas. These innovations are thus not the answer. Minimising fibre shed requires greater recognition of the role of textile design and manufacturing instead (De Falco et al., 2020). To design low-shed textiles requires understanding how garment structure influences fibre shed beyond machine laundry.

Minimising textile fibre shed is a vital global environmental challenge. While research has focussed on MP fibres, there is growing evidence that natural textile fibres are also problematic. Natural fibres, particularly cotton, dominate environmental samples (Stanton et al., 2019; Suaria et al., 2020; Le Guen et al., 2020; Liu et al., 2022; KeChi-Okafor et al., 2023). Natural fibres also persist in the environment (Chen and Jakes, 2001). And they elicit comparable ecotoxicological effects to their plastic analogues (Kim et al., 2021). Cotton is the standard fibre of denim jeans, the world's single most popular garment (Athey et al., 2020). Cotton is mercerised to improve dye uptake and fibre strength. Mercerisation converts naturally occurring cellulose I to cellulose II. Cellulose II is a product of anthropogenic processes – it is not a natural polymer.

Cellulose II is the most thermodynamically stable cellulose polymorph (Gubitosi et al., 2017), making mercerised cotton more resistant to biodegradation than raw cotton. Both cotton and wool textiles have also been found to contain higher concentrations of toxic additives (e.g., bisphenols) than their plastic analogues (Freire et al., 2019; Sait et al., 2021). Textiles made from natural fibres are currently underrepresented in efforts to quantify microfibre shedding. When assessed, natural fibre garments have been found to shed comparable fibre loads to those of similarly structured plastic-fibred garments when laundered using washing machines (Zambrano et al., 2019, 2021; De Felice et al., 2022). Our findings suggest natural fibre textiles will also shed significant amounts of fibres when laundered off-the-grid. Sustainable textile futures need research on the fate and impacts of natural textile fibres as compared to plastic fibres. Recognising the prevalence, persistence, and

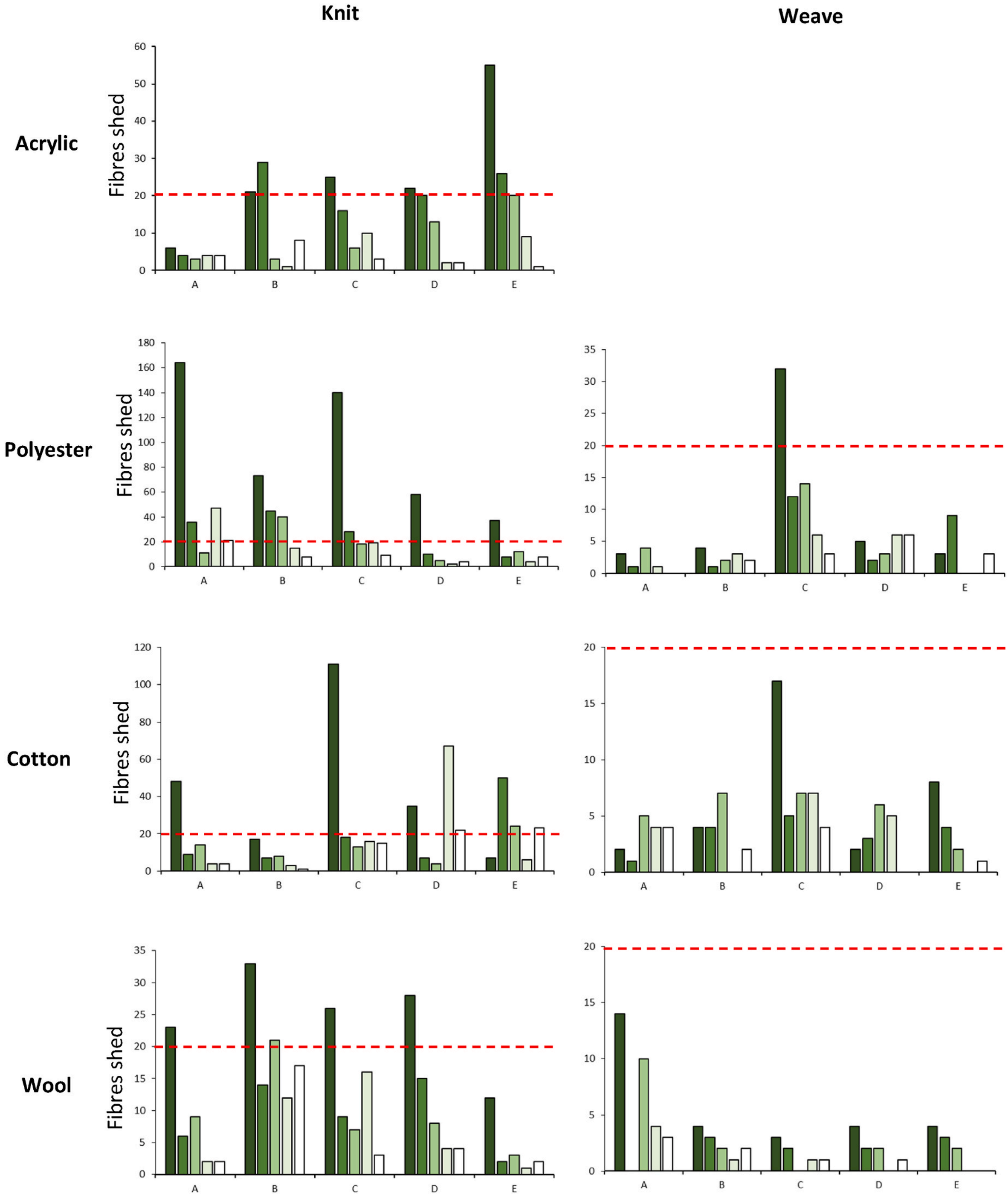

Fig. 4. Bar graphs showing fibre shedding (total count) for each of the five sequential shedding runs by swatch (A–E), fibre type, and garment construction. Runs are ordered left to right for each swatch from first run (darkest green) to fifth run (lightest green). Red hashed lines indicate 20 fibres shed on all graphs to aid comparison between different magnitudes of shedding. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

impacts of natural fibre production, use, and pollution is vital. Otherwise, the fashion and textiles industry may substitute plastic fibres with equally problematic 'natural' ones.

Minimising environmental impacts from textile fibres requires reducing textile consumption (Munasinghe et al., 2021). Low-shed, low-toxicant and biodegradable materials should replace the current suite of fibres. Industry must extend current life cycle analysis approaches (Munasinghe et al., 2021; van der Velden et al., 2014) to textile end-of-life. This change requires expanding the scope of life cycle research to incorporate the Global South, and identifying contributions from local practices for care and disposal of garments. Life cycle studies need to represent the varied real-world conditions of household laundering.

Our work identifies a significant knowledge gap for future research. Addressing this gap will generate microfibre research with the rigour needed to address it as a global problem. This work will need substantial funding. While, in the Global North, surveys have identified variation in laundering practices between countries and among different demographics (Laitala et al., 2020), this has not been replicated for the Global South. Thus, this new body of research should engage with wardrobe studies (DeLong and Bang, 2021) and laundry surveys (Laitala et al., 2012), or assess fibre shedding from laundry loads sourced from households (e.g., Lant et al., 2020). Those leading it should be sensitive to local knowledges, culture, and economies.

Garments hand laundered in the Global South may not reflect local choices. These garments may be at the end of an international supply chain. Their design and manufacture may meet the needs of consumers in the Global North (Minter, 2019). Likewise, their design will expect that infrastructure of clothing care as 'normal'. Anticipating hand laundry protocols in textile design requires shifting dynamics in the industry. These dynamics obstruct efforts to minimise pre-consumer textile fibre pollution (Forum for the Future, 2023). But regulations requiring filters, balls and bags for fibre capture will be impossible to put in place off-the-grid. These interventions have a place, however, rather than focussing interventions on post-consumer microfibre release, industry needs to transform materials and production methods to address fibre shedding from laundry at the global scale.

Future research requires improved life cycle analysis (LCA) of textiles' environmental footprints. LCA identifies electric clothes washing and drying as a major contributor to the energy and carbon footprints of a garment during its use phase (van der Velden et al., 2014; Munasinghe et al., 2021). But garment footprints vary by geography. Energy consumption of in-home hand laundering textiles represents just 7.3% of the energy footprint of a cotton T-shirt in China, compared to >70% in Germany and the United States of America (Zhang et al., 2015). Life cycle assessments need to recognise geographic and cultural variations in laundry practices to inform decision making and policy. They must incorporate potential environmental impacts from post-consumer use following export to the Global South. This would incorporate post-donation transport, fibre shed and energy consumption from hand laundry, and final disposal by burning. Recognising these processes as part of the lifecycle of garments purchased in the Global North would be a timely advance. The impacts of hand laundry protocols for new garments bought in the Global South should likewise be factored in. Life cycle analysis will remain essential to informing sustainable fashion futures. But the industry must recognise that environmental footprints as currently quantified are limited and specific.

5. Conclusion

We have presented a detailed assessment of the role of off-the-grid laundry practices in microfibre shedding. This is only one metric of fashion's environmental footprint. Our findings indicate significant fibre shed from hand laundry and that garment construction is more important for fibre shed than fibre type. These findings motivated us to consider the context of clothing care. We outlined how people in the Global South acquire, use, and care for clothes where they lack access to electricity and mains sewerage. These elements of infrastructure are nonetheless assumed at the point of textile design. This kind of thinking globally about laundry is vital to sustainable fashion discourses. Minimising global fibre shedding from laundry will thus need a global research effort. Industry must make changes informed by multi-stakeholder dialogue. Thus far, it has been the study of fibre loss from machine laundry that has informed recommendations for change. This has directed research towards laundry practices limited to the Global North. Textile design continues to assume an infrastructure for fibre interception which is not found around the world. The flaw is in the design, not the off-the-grid laundry practices. As we show here, the focus on washing machines and textile material type obscures more important factors. The power to change this lies with those who design and manufacture the garments driving global microfibre pollution.

CRediT authorship contribution statement

Thomas Stanton: Conceptualization, Investigation, Formal analysis, Writing – original draft. **Elyse Stanes:** Conceptualization, Investigation, Formal analysis, Writing – review & editing. **Claire Gwinnett:** Conceptualization, Investigation, Writing – review & editing. **Xiaoyu Lei:** Conceptualization, Writing – review & editing. **Myrna Cauilan-Cureg:** Conceptualization, Writing – review & editing. **Myrna Ramos:** Conceptualization, Writing – review & editing. **J. Brett Sallach:** Conceptualization, Writing – review & editing. **Eleanor Harrison:** Conceptualization, Investigation, Writing – review & editing. **Amy Osborne:** Conceptualization, Investigation, Writing – review & editing. **Catherine H. Sanders:** Formal analysis, Writing – review & editing. **Edwin Baynes:** Conceptualization, Writing – review & editing. **Antonia Law:** Writing – review & editing. **Matthew Johnson:** Writing – review & editing. **David B. Ryves:** Conceptualization, Writing – review & editing. **Kelly J. Sheridan:** Writing – review & editing. **Richard S. Blackburn:** Writing – review & editing. **Deirdre McKay:** Conceptualization, Investigation, Formal analysis, Writing – original draft.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Thomas Stanton reports financial support was provided by AXA Research Fund.

Data availability

All data are available in the manuscript or supplementary materials (tables S1, S3, and S4)

Acknowledgements

The authors would like to thank the members of the Cagayan Valley community for their participation in the ethnographic research that contributed to this manuscript. The research was facilitated by Isabela State University and the Mabuwaya Foundation. Observational data collection was enabled through a participatory community workshop held with ISU's established community partners and organised by the ISU Development Communications Department, led by Dr Myrna Cureg. Further observations in a rural field site were facilitated by ISU Cabagan and their partners, the Mabuwaya Foundation, under Dr Cureg's leadership and with a field trip led by Myrna Ramos.

Funding for the Philippines workshop and laboratory work on hand laundry came from Keele University (DM) and from an Association of Commonwealth Universities Blue Charter Fellowship (ES). TS is funded by the AXA Research Fund Fellowship programme.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.139391.

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