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Cause of microfibers found in the domestic washing process of clothing; focusing on the manufacturing, wearing, and washing processes

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Abstract

To prepare measures for washing synthetic fibers, which cause proliferation of microplastics in the marine ecosystem, a fundamental analysis is required. Therefore, this study established an efficient method for quantitatively analyzing microfibers using artificial neural networks, comparing the amounts of microfibers generated in the manufacturing, wearing, and washing processes of clothing. The proportion of microfiber emitted during the manufacturing process was the largest (49%), followed by that emitted during the washing (28%) and wearing (23%) processes. This suggests that minimizing the amount of microfiber emitted during the manufacturing process is key to solving microfiber issues in the fashion industry. Additionally, during the wearing process, the amount of waterborne microfiber detected in washing was slightly larger than the amount of airborne microfiber. In the washing process, the washing temperature did not significantly affect microfiber emissions. However, when reducing the amount of water used or increasing the number of washings, microfiber emissions increased noticeably due to the greater friction applied to clothes. A common result of all experiments was that the largest proportion of microfibers was released during the first five washing cycles. Therefore, before wearing new items, consumers can minimize microfiber release by pre-washing using a laundry bag that filters microfibers. Furthermore, the most effective way to minimize microfibers is to eliminate them from the manufacturing process before they are distributed to consumers.

Keywords: Microfibers, Polyester, Washing, Manufacturing, Wearing

Introduction

After industrialization, the economy experienced enormous growth over a short period, and plastic, whose commercial mass production began in 1933, was instrumental in this era. Plastic has posed considerable issues in industrial markets worldwide due to its ease of deformation, lightness, and durability. From 1.7 million tons in 1950 to 335 million tons in 2016, plastic production has expanded dramatically (Plastics Europe, 2013, 2017; Sathish et al., 2019). Due to its durability, however, disposal of plastic places a significant burden on the environment. Microplastics are so small that they can be detected in aquatic organisms. If these organisms swallow microplastics, life-threatening substances such as organic pollutants (POP) and endocrine disruptors (EDCs) may impact the food chain (Gallo et al., 2018). However, there has been insufficient research on these dangers (Rochman et al., 2013).

Microplastics are synthetic polymer particles with a size of less than 5 mm, which are classified into primary and secondary microplastics based on their use and features (Lambert et al., 2017; Li et al., 2020; Liu et al., 2019; Zambrano et al., 2021). Primary microplastics (e.g., toothpaste and cosmetics) have specialized uses and account for 35 percent of microplastics discovered in the ocean (Henry et al., 2019; Park et al., 2020). Secondary microplastics are fragments that gradually decompose into smaller pieces through a weathering process because of improper disposal and treatment of synthetic polymer items such as packaging materials and clothing, which pose an even greater threat to the environment (Li et al., 2020; Liu et al., 2019; Park et al., 2020). Secondary microplastics are released into the environment in various forms, including spheres, films, debris, and fibers (Frias et al., 2010; Li et al., 2020; Royer et al., 2018). According to research by the European Commission, the tire sector is the leading source of microplastic intake, followed by the fashion industry (Hann et al., 2018). Due to their small diameter and lengthy morphological properties, microfibers are detected at a frequency of about 0.009 particles/ℓ per hour in wastewater treatment plants (WWTP) (Almroth et al., 2018; Magnusson and Norén., 2014; Magnusson and Wahlberg., 2014). Polyester (PET), nylon, polypropylene (PP), and other materials are commonly observed in the form of microfibers used in clothing (Mishra et al., 2019). After decomposition, microplastics or nano-plastics are so small that they are nearly impossible to remove from the environment. Therefore, there is a need for rigorous studies in the fashion industry, which generates massive amounts of microfibers (Hann et al., 2018; Nguyen et al., 2019; Yang et al., 2019; Zambrano., 2019).

There have been past studies on microfibers generated during the washing process of clothes; however, there have been few studies on which of the manufacturing, wearing, or washing processes of clothing that is the most significant source. Furthermore, the lack of quantitative analysis for reproducibility due to microfibers' small size is another reason for failure to examine their emissions (Gago et al., 2016; Hidalgo-Ruz et al., 2012; Kershaw., 2015). Developing a protocol to standardize and measure microfibers is required. Therefore, this study aimed to devise a method for analyzing amounts of microfibers emitted during the washing process of clothing products and to investigate the reasons for microfiber emissions during this process.

Experimental

Materials

A 100% polyester polar fleece open zip-up (Open zip-up jacket, Hitee, Republic of Korea) with a fabric structure was used because it emits a large quantity of microfibers. Because the filter is white, a navy-colored cloth was selected to facilitate identification. The samples utilized in the manufacturing and washing processes were cut into 10 cm × 10 cm, making five samples in each experiment and repeating three times. To prevent the release of microfibers taken from the edge of the cut sample, four sides of the fabric were overlocked. The sample for the wearing process was cut into 22 cm × 27 cm according to the size of the simulation device. The experiment was repeated three times with one sheet per experiment. The amount of microfiber detection was converted based on 420 g, which corresponds to the weight of one polar fleece jacket because the size of the sample varied depending on the experimental conditions.

Collection of microfibers produced during the manufacturing–wearing–washing process

An ultrasonic washing machine (WUC-D22H, DAIHAN Scientific Company, Republic of Korea) was employed to analyze the microfibers produced during the manufacturing process before the consumer purchases clothes and does laundry. It can separate the microfibers attached to clothes while minimizing the mechanical force applied to the fabric during pre-washing. It used 12 ℓ of water to wash the clothes at 40 °C for 60 min, which are the same settings for a normal wash cycle with a commercial clothes washer, in order to mimic the consumer conditions.

A simulation device (ASA-7129, ASIA Testing Machines Company, Republic of Korea) capable of adjusting the horizontal operating range of 100 mm, vertical operating range of 210 mm, and rotation speed of 0–60 rpm was manufactured to apply the force of shearing, tension, friction, and pressure generated in the process of wearing clothing. As shown in Fig. 1, tension is represented by vertical motion, shear is represented by right and left motion, and friction and pressure are represented by rotating motion when pressing. One cycle of wearing process includes each vertical motion, right and left motion, and rotation motion while pressing. The wearing simulation device was covered with an impermeable plastic bag to collect microfibers that escaped into the air during the wearing process. Microfibers discovered in water rinsed in an impermeable plastic bag during the wearing process were categorized as airborne, and microfibers detected by ultrasonic washing the fabric after the wearing exercise were categorized as waterborne.

To simulate the washing process, the Launder-O-Meter was utilized. Considering the difficulties of filtering due to bubbles, no detergent was used. One cloth and 10 steel balls (each with a diameter of 6 mm) were placed in each of the five containers (volume of a container; 500 ml), and the rotation speed was set to 50 rpm. The water amount of 1000 ml (40% volume of containers) was determined based on the clothes washer's

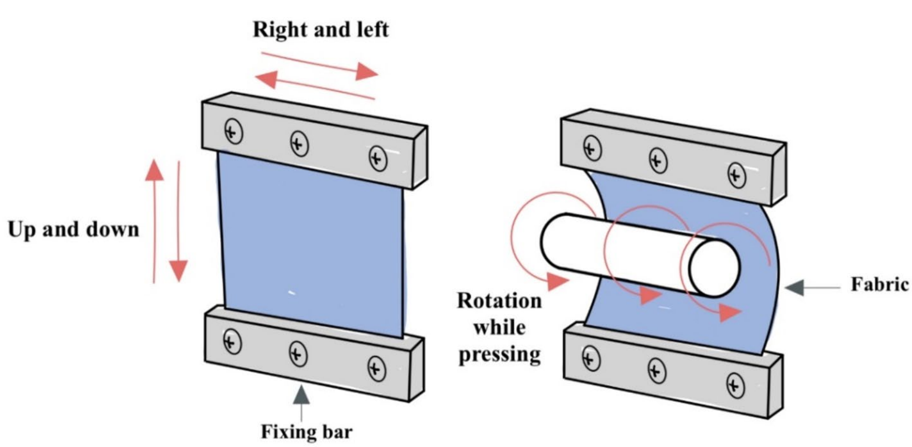


Fig. 1 Simulation of wearing motions

liquor ratio. To analyze the influence of the water amount, it was compared with a water amount of 625 ml, which is 25% of the containers' volume. Temperatures of 40 °C and 20 °C were used to investigate the effect of washing temperatures. Washing time was set to 60 min.

In the washing and wearing simulation processes, the experiment proceeded after ten cycles of ultrasonic washing to remove the influence of microfibers thought to have been introduced from the manufacturing process. Ten cycles of ultrasonic washing were determined by the pretest checking the change in the amount of microfibers detected.

Detection and analysis of microfibers

Using each container, water collected after ultrasonic washing in the manufacturing process, after ultrasonic washing or rinsing an impermeable plastic bag in the wearing process, and after washing through the Launder-O-Meter during the washing process was separated. Stainless-steel sieves (ISO Tokyo test save, Sanpo, Japan) with pore diameters of 500 μm and 40 μm served as filtering devices. After each experiment, the microfibers were filtered by passing the collected water through a stainless-steel sieve. Because of microfiber' small diameter and lengthy shape, it was determined that they could not be filtered completely by passing them through each sieve only once. Therefore, several sieves of the same size were used by stacking, and the number of which was determined through experiments. Each sieve was rinsed with running water, collecting and individually filtering microfibers using a vacuum filtration system with a glass fiber filter paper (pore size: 1 μm). As illustrated in Fig. 2a, the vacuum filtration system consisted of a vacuum pump, glass fiber filter paper, glass funnel, spring clamp, vacuum base cap, and filtering flask. A microscope with an image capture program (Kyowa BIOLUZ-12 Japan) was used after the microfibers dried in the shade for 24 h with filter paper. To uniformly observe a glass fiber filter larger than the microscopic observation area, it was divided into nine areas per filter and repeated five times. Figure 2b illustrates the filtering and microscopic observation processes. Subsequently, the number of fibers, mean fiber length, and total fiber length were derived from microfiber images using a self-developed software based on artificial neural networks. The results from the software were compared to the results manually counted by a researcher to determine the software's accuracy, assessing statistical significance through a t-test using SPSS (IBM SPSS program 26, International Business Machines Corporation, USA).

Results and discussion

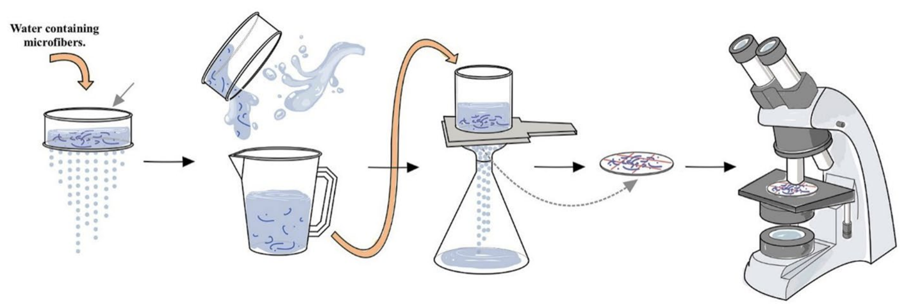
Devising a method of analyzing microfibers

Microfiber analysis using artificial neural networks

A software using an artificial neural network (ANN) was developed to analyze the microfibers identified by the filter. The first process was to train the artificial neural networks. After opening microscopic image files of microfibers on filter paper with a size of 1280 mm × 720 mm in the program (Fig. 3a), it was converted to grayscale (Fig. 3b). Next, ANN was made to categorize fibers and backgrounds in the image with a volume of 100–150 dots (Fig. 3c). Then, an artificial neural network was created for microfiber recognition by repeating this process with photos and storing the training data. The ANN trained to subdivide fibers was utilized to analyze the microfibers. The "segment

No.	Component	Specification
1	Vacuum dry pump	45 ℓ/min
2	Micro glass fiber filter	Ø 90 ㎜㎜, pore size 1 ㎛
3	Glass funnel	1000 ㎖
4	Spring Clamp	90 ㎜
5	Vacuum Base Cap	90 ㎜
6	Filtering Flask	2000 ㎖

(a)



(b)

Fig. 2 A system for filtering microfibers. **a** Configuration and specifications of the filtering system. **b** Schematic diagram of the method for collecting and analyzing microfibers

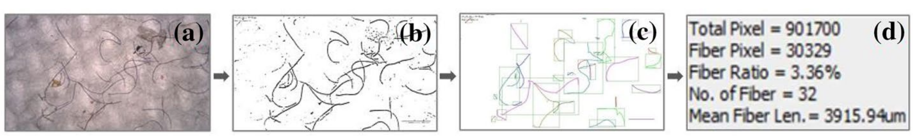


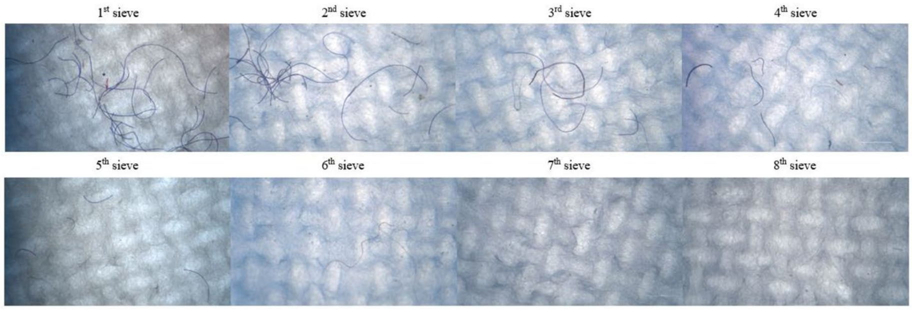
Fig. 3 Method of analyzing microfiber images through ANN. **a** Microscopic images of microfiber after filtering; **b** microfiber images that have been converted to grayscale; **c** process of recognizing microfiber as pixels; **d** final output. To check the accuracy of the software developed using ANN, a t-test compared the results obtained using ANN and the results manually counted by the researcher. The significance probability (p) value was greater than 0.05, indicating that the difference between the two was not statistically significant, as shown in Table 2. In other words, the ANN-based software created for microfiber analysis was as accurate as manual counting

fibers" function was then used to recognize fibers in the images in pixel units. Finally, actual dimensions such as the number of fibers, fiber ratio, mean fiber length, and total fiber length were represented through unit conversion when the scale bar included in the image was dragged through the program (Fig. 3d).

Determining the number of sieves used for filtering

Even after filtering once using a sieve, microfibers of the target size were still found in the water because the microfibers are thin and lengthy. As a result, the microfibers were detected by filtering with the same-sized sieve repeatedly, and we determined how many times to filter with the same-size sieve. Although the sieve pores were 500 μm, the actual

Table 1 Comparison of detected microfibers by repeated filtration using a series of sieves with size of 500 μm



length of the filtered microfibers was noticeably shorter due to their morphological characteristics. Nevertheless, because the pore size of the glass fiber filter used in the final filtering was 1 μm, we judged that this did not significantly affect the final results. As shown in Fig. 4 and Table 1, all the sieves utilized in this study demonstrated a consistent decrease in the amount of microfibers up to five filters, and there was no discernible variation after six filters. Consequently, the number of stainless-steel sieves required for each size was determined to be five. After the fifth filtering, water was filtered in the next step using a device with smaller pores.

Table 2 Differences between manual counting method and fiber counter program

		N	Mean	Standard deviation	*t* (*p*)
No. of fibers	Manual counting method	45	8.29	4.230	−1.636 (0.109)*
	Fiber counter program	45	8.6	4.649	

Detection of microfibers introduced during the manufacturing process

Considering the situation before consumers purchase and use clothes, the amount of microfibers introduced during the manufacturing process was measured using an ultrasonic washing machine. Because microfibers can also form via physical force from a conventional washing machine, we used an ultrasonic washing machine to remove only microfibers created on the fabric's surface due to the manufacturing process. Figures 5–7 show the outcomes of number of microfibers, mean fiber length, and total length of microfibers, respectively, with washing cycles of 1–6 times, eight times, and ten times. In the first cycle, the number of microfibers was the highest at 2463, as shown in Fig. 5. The microfiber size range of 40–500 μm appeared most frequently, while the size range of 1–40 μm appeared least frequently. As shown in Fig. 6, the average length of the microfibers found in the polar fleece fabric was 47.4–70.0 μm in each cycle, and the average length did not noticeably differ depending on the number of ultrasonic washing cycles. When checking the total fiber length (Fig. 7), nearly 18.0 cm of microfiber was observed after one wash, and the amount decreased to about 5.8 cm after 10 cycles. Because the large microfibers on the fabric surface had mostly been eliminated by the fifth cycle,

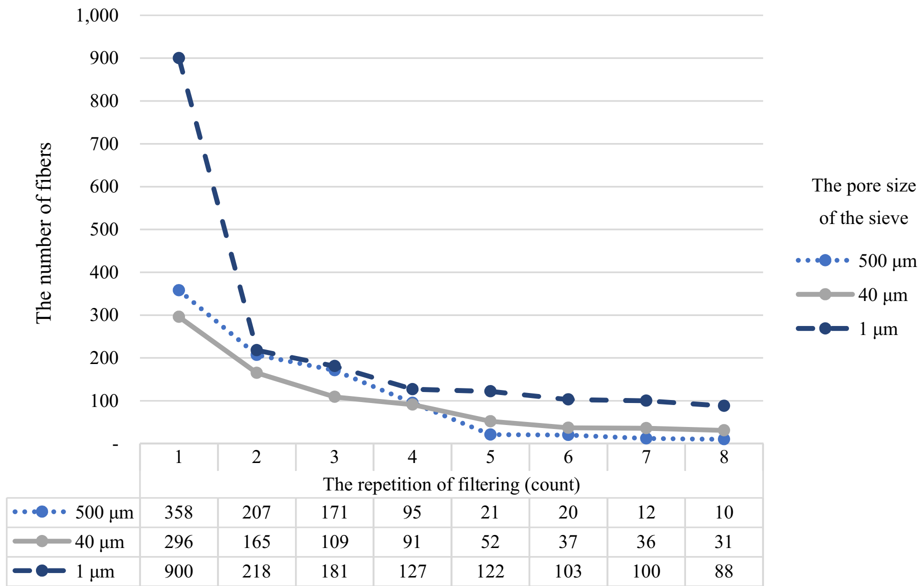


Fig. 4 Amount of detected microfibers in repetitive filtering using each sieve

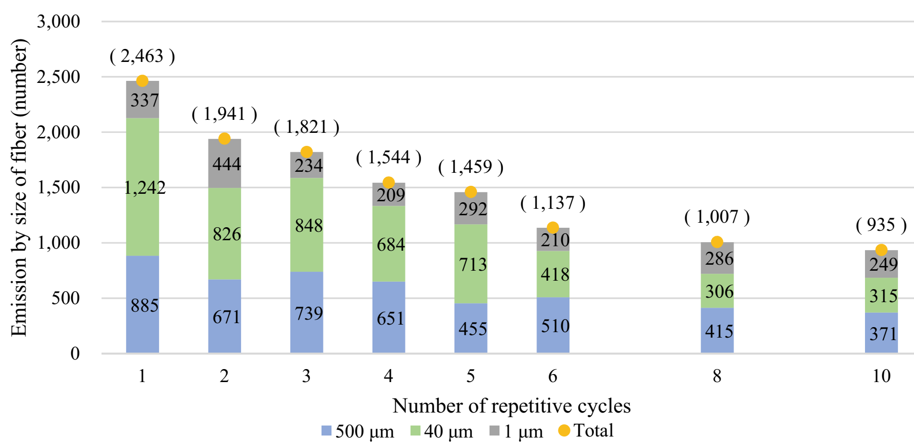


Fig. 5 Number of microfibers from the manufacturing process (values in parentheses indicate totals)

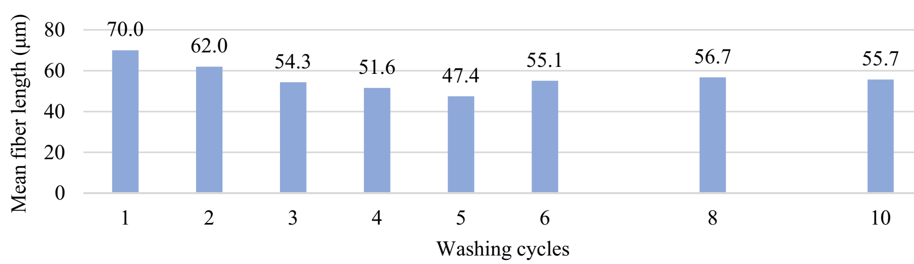


Fig. 6 Mean fiber length of microfibers from the manufacturing process

there were no subsequent significant changes, which is consistent with earlier research demonstrating that most microfibers appear within the first five cycles (Belzagui et al., 2019; Napper and Thompson., 2016; Pirc et al., 2016). Under this study's experimental

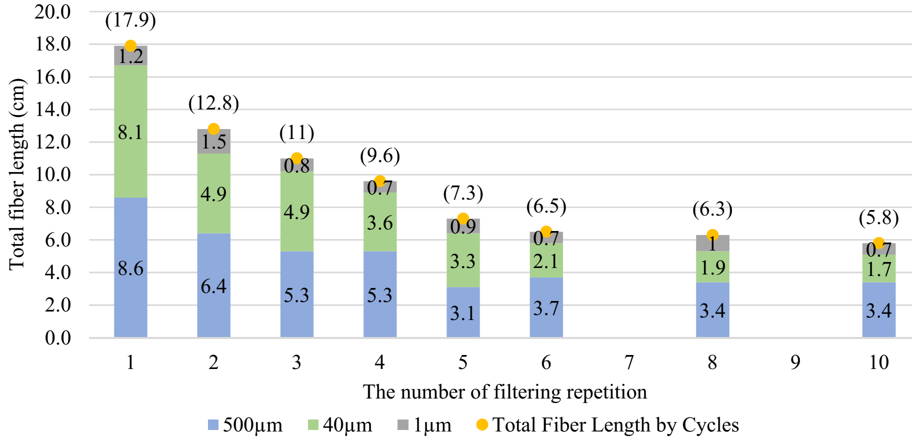


Fig. 7 Total length of microfibers from the manufacturing process (values in parentheses indicate totals)

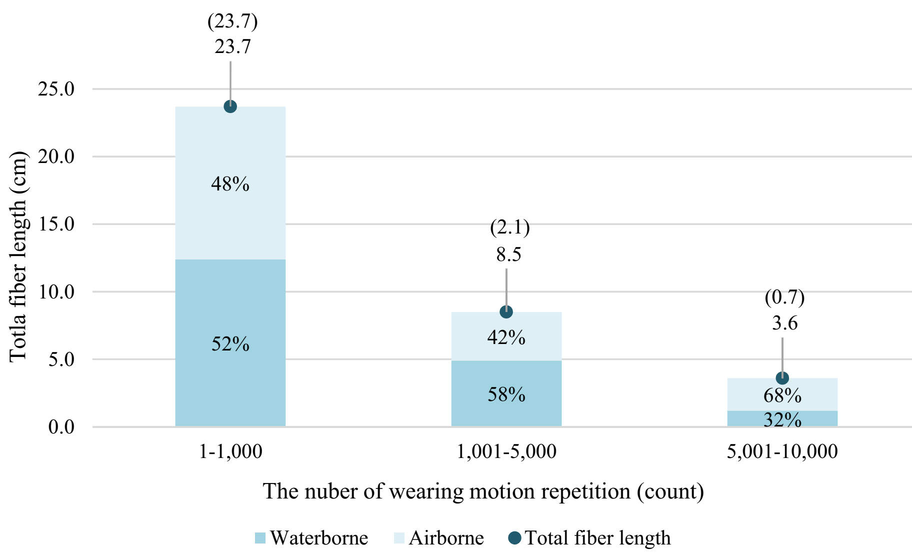


Fig. 8 Total length of microfibers from the wearing process up to 10,000 cycles (values in parentheses are total fiber length emitted per 1000 cycles)

conditions, most microfibers detached after five cycles of ultrasonic washing, and it was assumed that there was no difference in the number of microfibers that detached subsequently because the washer continued to apply an identical amount of force.

It was thought to be valuable to investigate further why the amount of microfiber formed throughout the manufacturing process was significant. The presence of many microfibers in newly manufactured clothing is because microfibers are created in large quantities during the manufacturing process. Studies on pneumoconiosis in clothing factory workers are constantly published, with several pathological studies presenting a risk of pneumothorax, bronchitis, and "flock workers' lung" (FWL), which is a chronic interstitial lung disease, among textile factory workers (Ghio et al., 2006; Lougheed et al., 1995; Pimentel et al., 1975). According to a 2002 analysis, fiber dust formed in the workplace in the cotton, silk, and synthetic fiber sectors enters the body through inhalation, and the mortality rate from digestive cancer continues to rise dramatically (Mastrangelo et al., 2002). Therefore, removing microfibers, which are synthetic fiber dust formed during the clothing manufacturing process, is critical not only for factory workers but also for consumers in minimizing the number of microfibers released after washing.

Detection of microfibers generated from the wearing process

A wearing simulator was used to measure the total length of microfibers released after 10,000 cycles. It was divided into ranges of 1–1000 cycles, 1001–5000 cycles, and 5001–10,000 cycles to study the number of microfibers accumulated due to wearing clothing. Figure 8 presents the results, including the amount normalized by the number of microfibers per 1000 cycles. The total length of microfibers per 1000 cycles was 23.7 cm, that for 1001–5000 cycles was 8.5 cm, and that for 5001–10,000 cycles was 3.6 cm. Although the quantity per 1000 cycles decreased significantly, additional microfibers were still released as the cycle of wearing increased. The wearing simulator applied tensile, bending, shear, friction, and pressure to the fabric, with these forces likely releasing microfibers. When normalizing with 1,000 cycles in each area, the difference became much more noticeable. This was likely because most of the microfibers, which could have been released due to repeated mechanical forces, detaching during initial wear, and the amount of microfibers generated thereafter was relatively small.

The amount of microfiber release from the wearing process was assessed in two conditions (waterborne and airborne) based on research showing that synthetic fibers are the main source of microplastic released in the air (Dris et al., 2016). The airborne microfibers floating in the air during the wearing simulation process were compared and evaluated to the waterborne microfibers found during the washing process after the wearing exercise. Waterborne microfibers accounted for a larger proportion up to 5000 cycles, but airborne microfibers accounted for a larger proportion after 5000 cycles. This could be because the pilling on the fabric's surface fell into the air after 5000 cycles. However, this could be explained as a result of our ultrasonic washing machine's insufficient power in detecting waterborne microfibers, so the ratio of the two could change throughout the actual domestic washing process. Nonetheless, because past studies have revealed that both waterborne and airborne microfibers impact oceans, a thorough investigation of both types of microfibers is essential.

Detection of microfibers generated from the washing process

Number of wash cycles' effect on microfiber generation

Fabrics were washed 20 times using a Launder-O-Meter to identify the microfibers formed by the mechanical action of the washing process. Figure 9 shows the amount of microfibers released. Most microfibers appeared within the first five washes; as the number of washings increased, the number of microfibers declined. After more than five washings, however, the difference in the results was negligible. Other research has also reported that most microfiber generation occurs within the first five cycles, with no significant changes after this (Belzagui et al., 2019; Napper et al., 2016; Pirc et al., 2016). The Launder-O-Meter, which exerts considerably stronger force than ultrasonic washing machines, was able to remove microfibers that could not be removed by ultrasonic

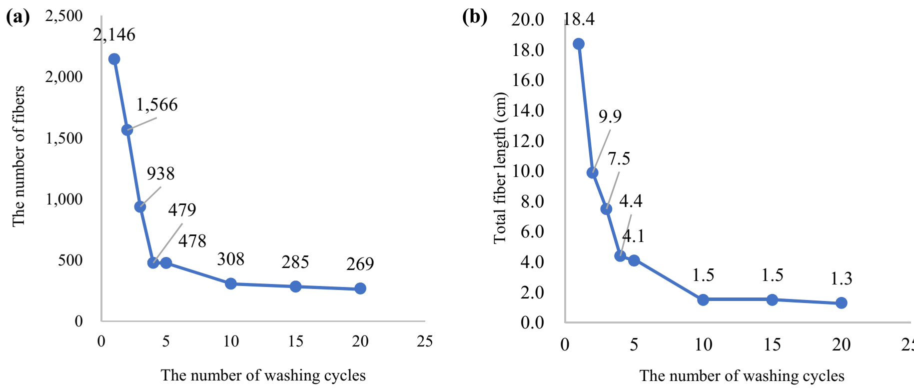


Fig. 9 Analysis of microfibers after repeated wash cycles; **a** Number of fibers, **b** Total fiber length

washing. Therefore, this result may be interpreted as microfibers from the manufacturing process, and it is thought that a further study using methods other than the ultrasonic washing machine are necessary for the manufacturing process.

Effect of washing temperature and water amount on microfiber release

Washing was repeated five times with varying temperatures and water amounts to determine the effect of washing conditions on microfiber generation (Fig. 10). The amount of microfibers released at 20 °C during the first cycle was somewhat higher than at 40 °C, but there was no significant difference after 2–5 cycles. The differences in the amount of microfibers due to temperature differences was not significant. Given that the results of the first cycle were influenced by the difference in the mechanical forces between the ultrasonic washing machine used for the pretreatment and the Launder-O-Meter used for the washing process, it was concluded that washing temperature had little effect on microfiber generation. Because no detergent was used in this study, even if washing utilized different temperatures for the same duration, the mechanical force applied to the fabric would not differ; hence, the number of microfibers generated was similar. One study found that more microfibers were detected when detergent was applied at a higher temperature (Zambrano et al., 2019). This result might be because the detergent, which separates particles such as microfibers from clothes and disperses them stably in the washing solution, might be more active at higher temperatures, making it easier to detect microfibers rather than actually creating more microfibers (Yang et al., 2019). Therefore, the effect of washing temperature may vary depending on the use of detergent.

The effect of water amount on microfiber generation was investigated using water amounts of 40% (1000 ml) and 25% (625 ml) of the capacity of the Launder-O-Meter's container. It was confirmed that with less water, more microfibers formed during the first three wash cycles. It was thought that with less water, there were more opportunities for the fabric to rub against the steel balls or the container's wall, resulting in the release of many microfibers (Tiffin et al., 2021).

Causes of microfiber generation during domestic washing

We compared the amounts of microfibers in the simulated manufacturing, wearing, and washing processes to investigate the causes of microfiber detected when washing

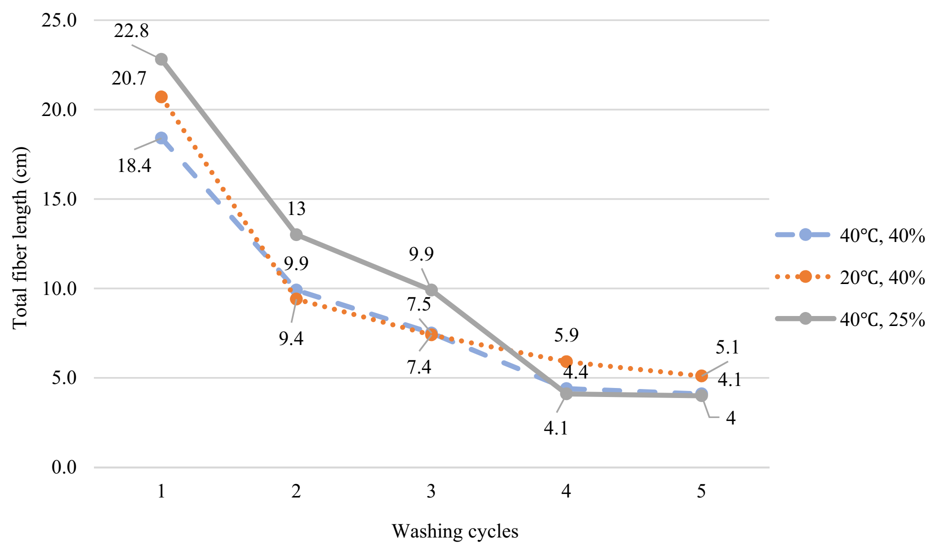


Fig. 10 Effect of washing temperature and water amount on microfiber generation

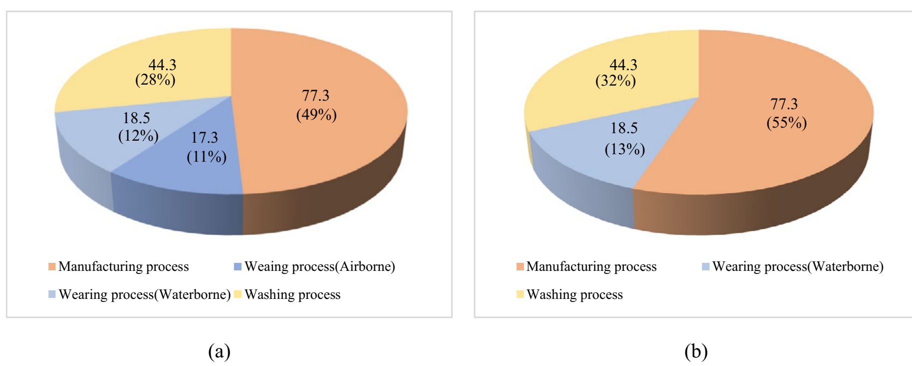


Fig. 11 Total fiber length(cm) of microfibers released in simulated conditions (manufacturing process with an ultrasonic washing machine, wearing process with a custom-built setup, and washing process with a Launder-O-Meter). **a** Including airborne microfibers of wearing process. **b** Excluding airborne microfibers of wearing process

clothes in actual consumer use. The manufacturing process was based on a cumulative 10 cycles of ultrasonic washing. The wearing process using a custom-built setup was based on 10,000 cycles for both waterborne and airborne microfibers, and the washing process using a Launder-O-Meter was based on five cycles at 40 °C and 40% water. Figure 11 shows the ratio of each process to the overall amount of microfibers. Microfibers were found in 49% of the total amount during the manufacturing process, 28% during the washing process, and 23% during the wearing process. However, because airborne microfibers were not identified by a clothes washer during the wearing process, the proportion of the manufacturing process increased to 55%, as illustrated in Fig. 11b. Accordingly, it was concluded that in the case of microfibers detected in consumers' washing processes, those originating from the manufacturing process have a significant impact and that modifying the manufacturing approach would be effective in reducing microfibers found in the domestic washing process.

Conclusions

Researchers have highlighted the fashion industry as one of the main causes of microfibers found in oceans, and microfibers are generally known to leak into the environment during domestic washing of synthetic fibers. However, it is difficult to devise precise countermeasures because few studies have examined whether microfibers detected in the clothes washer were generated during the washing process or were originated from the manufacturing or wearing processes. Therefore, this study devised a method for determining the number of microfibers using an artificial neural network then compared the number of microfibers formed in the simulated manufacturing, wearing, and washing processes using ultrasonic washing machine, custom-built setup, and Launder-O-Meter.

The total length of microfibers released during the manufacturing process was 77.3 cm with 10 cycles of ultrasonic washing. The largest amount (18.0 cm) was released in the first cycle, and declined to 5.8 cm by the 10^{th} cycle. In the simulated wearing process, the total length of microfibers after 10,000 cycles was 35.8 cm, with waterborne microfibers comprising 18.5 cm and airborne microfibers comprising 17.3 cm. Approximately 66% of microfibers were released during the first 1000 wearing cycles, whereas the rate was 24% at 1001–5000 cycles and 10% at 5001–10000 cycles, indicating that a large proportion of microfibers were released early in the wearing process. The total length of microfibers detected after five washing cycles was 44.3 cm, according to the analysis using a Launder-O-Meter. Microfibers showed an increase when the water amount was reduced and more friction was generated by increasing the number of washings, even though there was no significant difference across washing temperatures. When analyzing the average values for each of the different processes mentioned above, the number of microfibers originating from the manufacturing process accounted for the highest proportion, followed by the washing process and then the wearing process. Therefore, it is expected that if an in-depth investigation can identify a means to remove microfibers originating from the manufacturing process before they are distributed to consumers, overall microfibers generation could be reduced efficiently.

The amount of microfibers was slightly large during the initial experiment of the wearing and washing process because the ultrasonic washing machine did not sufficiently eliminate microfibers originating from the manufacturing process. This study also has the limitation in that it didn't accurately reflect the real situation in the field, as it relied on an ultrasonic washing machine for the manufacturing process, a simulator for the wearing process, and a Launder-O-meter for the washing process. Nevertheless, this study is meaningful in that it provides essential data for developing countermeasures by analyzing the causes of microfibers released in domestic washing and proposing an artificial neural network-based method for analyzing microfibers.

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Author contributions
JL conceived the ideas, experimental design, performed the experiments, collected the data, interpretation of the results, and drafted the manuscript of the analysis. JC and AW performed the experiments and collected the data. MK gave continuous support to perform the experiment successfully. SK gave support to the development of artificial neural network programs used in the experiment.CY supervised on the experimental design, experimental results, and manuscript preparation. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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