microplastics

Article

Mitigating Microfiber Pollution in Laundry Wastewater: Insights from a Filtration System Case Study in Galle, Sri Lanka

Mahagama Gedara Yohan Lasantha Mahagamage [1,*], Sachith Gihan Gamage [1], Rathnayake Mudiyanselage Shehan Kaushalya Rathnayake [1], Premakumara Jagath Dickella Gamaralalage [2,*], Matthew Hengesbugh [2], Thejani Abeynayaka [2], Chathura Welivitiya [3], Lahiru Udumalagala [3], Chathura Rajitha [3] and Supun Suranjith [3]

[1] Centre for Environmental Studies and Sustainable Development (CESSD), The Open University of Sri Lanka, Nawala, Nugegoda 10250, Sri Lanka; sachith08@yahoo.com (S.G.G.)

[2] Institute for Global Environmental Strategies (IGES), Hayama 240-0115, Japan; hengesbaugh@iges.or.jp (M.H.); thejaniabeynayaka@gmail.com (T.A.)

[3] HELP-O, Galle 80000, Sri Lanka; chathura.helpo@yahoo.com (C.W.)

* Correspondence: mgyma@ou.ac.lk (M.G.Y.L.M.); premakumara@iges.or.jp (P.J.D.G.)

Abstract: Synthetic fibers are widely used in daily life due to their durability, elasticity, low cost, and ease of use. The textile industry is the primary source of synthetic microfibers, as these materials are mostly used in production processes. Globally, plastic pollution has been identified as a major environmental threat in this era, since plastics are not degradable but break down into smaller particles such as mesoplastics, microplastics, and microfibers. Synthetic microfiber pollution is a significant issue in aquatic ecosystems, including oceans and rivers, with laundry wastewater being a major source. This problem is particularly pressing in cities like Galle, Sri Lanka, where numerous tourist hotels are located. Despite the urgency, there has been a lack of scientific and systematic analysis to fully understand the extent of the issue. This study addresses this gap by analyzing the generation of microfibers from laundry activities at a selected hotel and evaluating the efficiency of a laundry wastewater filtration system. This study focused on a fully automatic front-loading washing machine (23 kg capacity) with a load of 12 kg of polyester–cotton blend serviettes (black and red). Samples (1 L each) were taken from both treated and untreated wastewater during four wash cycles, with a total of 100 L of water used for the process. The samples were filtered through a 100 μm sieve and catalytic wet oxidation along with density separation were employed to extract the microfibers, which were then collected on a membrane filter paper (0.45 μm). Microfibers were observed and analyzed for shapes, colors and sizes under a stereo microscope. Results revealed that untreated laundry wastewater contained 10,028.7 ± 1420.8 microfibers per liter (n = 4), while treated wastewater samples recorded 191.5 ± 109.4 microfibers per liter (n = 4). Most of the microfibers observed were black and white/transparent colors. Further analysis revealed that 1 kg of polyester–cotton blend fabric can generate 336,833 microfibers per wash, which was reduced to 6367 microfibers after treatment. The filtration unit recorded an impressive efficiency of 98.09%, indicating a remarkably high capacity for removing microfibers from wastewater. These findings highlight the potential of such filtration techniques to significantly reduce microfiber emissions from laundry wastewater, presenting a promising approach to mitigating environmental pollution from microfibers.

Keywords: laundry wastewater; microfibers; mitigating; treatment unit; microplastics

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1. Introduction

Plastic pollution poses a critical threat to ecosystems globally and results in the accumulation of plastic waste in the environment, causing significant harm to wildlife, their habitats, and humans. Global plastic production increased from 2 to 380 million metric tons between 1950 and 2015 [1]. Plastic production is projected to double in the next 20 years at the current growth rate [2]. Plastic pollution can be categorized in several ways, including mega plastic, macroplastic, mesoplastic, and microplastic pollution [3]. Microplastic and microfiber pollution are major anthropogenic problems in this era [4]. Microplastics are divided into two main types, primary and secondary. Primary microplastics are tiny particles used in products like cosmetics and shed from clothing and textiles such as microfibers. On the other hand, secondary microplastics are particles that are formed when larger plastic items break down over time. Microfibers and microplastics are environmental pollutants, plastic sized at less than 5 mm [5], and found in terrestrial [6], aquatic [7], and air [8] ecosystems.

Microfibers can be divided into natural fibers and synthetic fibers. Synthetic fibers have a wide range of applications owing to their durability, elasticity, non-wrinkle nature, and cost-effectiveness [9]. Through the laundry process, broken and torn down fiber particles escape into the environment. Therefore, laundry wastewater can be identified as a major source of microfiber pollution in the environment [8]. These kinds of microfibers directly enter freshwater and marine bodies through land-based sources. It is estimated that 4.8 million tons of synthetic microfibers, such as polyester and nylon, have entered water bodies and terrestrial environments since 1950 [10]. The textile industry is a major contributor to microfiber pollution, especially in South Asian regions. Countries such as India, Bangladesh, and Sri Lanka have experienced significant growth in the textile industry [11], which has boosted their economies, but has also led to environmental challenges. In these regions, where textile usage and production are widespread, microfiber pollution is a pressing issue. Synthetic microfibers such as polyester, acrylic, and nylon, are non-biodegradable [12]. When they enter the aquatic environment, they are found everywhere, from rivers to the ocean [13]. Recent studies have revealed that microfibers are found in the digestive systems of many aquatic organisms [14], which then accumulates in food chains, especially in aquatic animals, and are transported to higher levels of consumers [15]. The impact of microfibers on aquatic organisms has not been fully understood yet, but it can cause entanglement and ingestion issues, disturbing their physiological and reproductive activities [15]. Further, microfibers can act as a vector for carrying heavy metals, as they have polarity and can absorb heavy metals such as Pb, As, and Hg to their surface [16]. When combined, these microfibers and heavy metals can form complexes that deposit into both aquatic and terrestrial environments [17]. Most of these complexes tend to deposit into aquatic environments, while microfibers can release toxic chemicals such as plasticizers, which are added during textile manufacturing. Microfibers serve as a final sink for all environmental contaminants, including those from industrial, mining, and anthropogenic sources [9].

The ecological implications of microfibers in the environment, particularly those released from synthetic textiles during washing, are of increasing concern due to their persistence and ability to carry harmful pollutants. When these fibers enter the environment, they act as vectors for various pollutants, including dyes, antibiotics, pathogens, heavy metals, and other toxic substances. Synthetic fibers such as polyester, nylon, and acrylic shed during the laundering process and enter wastewater systems, eventually reaching water bodies if not adequately removed by wastewater treatment plants. However, even some of the advanced wastewater treatment technologies cannot completely eliminate these microfibers, and a considerably large quantity ends up in rivers, lakes, and oceans, where they accumulate in sediments or are ingested by aquatic organisms [18].

One of the most alarming ecological impacts is the potential for bioaccumulation and biomagnification of toxic substances within food chains. For instance, microfibers can interact with hydrophobic organic pollutants (HOPs) through sorption–desorption processes. The ingestion of microfibers by terrestrial and aquatic organisms increases exposure to HOP levels [19]. Dyes and persistent organic pollutants (POPs) can adsorb to the fibers' surfaces, are typically resistant to degradation and are highly toxic. Dyes used across the textile industries such as azo dyes, can break down into carcinogenic compounds. As Chung [20] discussed, cleaved products of azo dye such as benzidine are known to cause human and animal tumors. Moreover, another dye component, p-phenylenediamine, was found to cause contact allergies. Similarly, heavy metals like Cd, Pb, and Hg, which can be found in the environment due to various sources, can be adsorbed onto microfibers and pose serious risks to both aquatic organisms and ecosystems. When ingested by marine organisms, such as zooplankton or fish, microfibers can cause physical blockages in the digestive system, harming metabolic activities. Further, microfibers can disrupt animals' energy transfer processes by acting as pseudofeces [21]. However, the associated pollutants they carry can also disrupt metabolic functions, leading to decreasing energy reserves, reproductive problems, growth reduction, and even death [22]. As most of these organisms belong to lower trophic levels, the pollutants can move up the food chain, accumulating toxic substances and microfibers in higher trophic levels, including in food species consumed by humans [23].

The degradation of ecosystem health is another serious ecological consequence of microfiber pollution. The presence of microfibers in aquatic systems can disrupt the physical and chemical properties of the system. For example, the accumulation of microfibers in sediments may alter the sediment's structure and chemistry, impacting the benthic animals that rely on specific conditions for survival. In addition, microfibers can alter the transport and bioavailability of nutrients, leading to shifts in ecosystem functions and productivity. In terrestrial environments, where microfibers can accumulate through wastewater sludge applications in agriculture, similar negative effects have been observed. Microfibers can reduce soil porosity and water retention capacity, impacting plant growth and microbial activity, which are crucial for soil health [24–26].

Laundry activities have been identified as the most significant source of microfiber generation for the environment. The release of microfibers from the laundry depends on several factors, such as textile characteristics like fabric type, elasticity, and age. As well as detergent properties such as liquid or powder, washing temperature, rpm rate and abrasion during the washing process. The use of detergent, both liquid and powder detergent, can increase microfiber release. Detergents can break down the chemical and physical characteristics of the material, releasing microfibers into the wastewater. The aforementioned reasons suggest there is a high emission of microfibers in laundry wastewater. Due to the lack of a proper system to control or contain the release of microfibers, it has been identified that a large amount of textile microfibers directly enter both aquatic and terrestrial environments during the laundry process. Microfibers are very small and cannot be seen with the naked eye; they require the use of a microscope for detection. This issue has not been thoroughly researched, making it an emerging problem. This study aims to offer insights into the potential large-scale implementation of technologies to address this issue. The findings could help to develop strategies to reduce the environmental impact of microfiber pollution, which is a significant aspect of the broader goal of reducing microplastic contamination in aquatic ecosystems. This research is particularly relevant given the increasing awareness and regulatory interest in microfiber pollution. Through this study, practical and effective measures have been identified that can reduce microfiber emissions from laundry wastewater and aid policymakers and environmental organizations in addressing this growing problem.

2. Materials and Method

2.1. Study Area and Material

The present study selected the laundry unit attached to a hotel located in Galle, a nearby southern coastline of Sri Lanka. This study used polyester–cotton mixed cloths with a total weight of 12 kg of laundry items, including red (n = 6) and black (n = 100) colors (Figure 1).

Figure 1. Polyester–cotton mixed hotel laundry items, including red (*n* = 6) and black (*n* = 100) colors.

2.2. Washing Process

This study used a high-capacity front-loading washing machine (UniMac, UK) with a 23 kg capacity to simulate laundry conditions (Figure 2). The machine was chosen to represent large-scale laundry processes, such as those found in industrial or commercial laundries in Sri Lanka. The washing machine was loaded with 12 kg of fabric serviettes used in the hotel sector. These materials were selected based on their common use in everyday clothing. The cool washing process followed a standardized cycle, including the following stages:

1. Pre-wash: Initial water intake and agitation to remove loose dirt and debris.
2. Main wash: Incorporation of detergent, agitation, and simulation of regular washing conditions.
3. Rinse cycle: Multiple rinses to remove detergent and loosened fibers.
4. Spin cycle: High-speed spinning to extract excess water from the fabric.

Figure 2. High-capacity front-loading washing machine.

A total of four washing cycles were conducted to ensure the collection of representative samples. A total of 100 L of water were used for all processes, and the process was completed in 45 min.

2.3. The Filtration Unit and Collection of Wastewater Samples

As shown in Figure 3, the microfiber filtration unit contains an inlet where laundry water enters. After flowing through a pre-screen steel filter (2 mm aperture size), the laundry wastewater passes through 10 cartridges having 100 µm pore size nets. Each of these cartridges has the capacity to capture up to 100 g of microfibers. Overall, the entire unit can capture 1 kg of microfibers. During this phase, microfiber filtration occurs and the filtered water exits the unit through the filter outlet. The cartridges must be replaced if the prescreen is free of debris, but water is still overflowing into the bypass. This indicates that the cartridges have reached capacity and need to be replaced. Generally, the unit is capable of handling 180 L of water per minute with a maximum working temperature of 80 °C and under 0.5 bar maximum pressure.

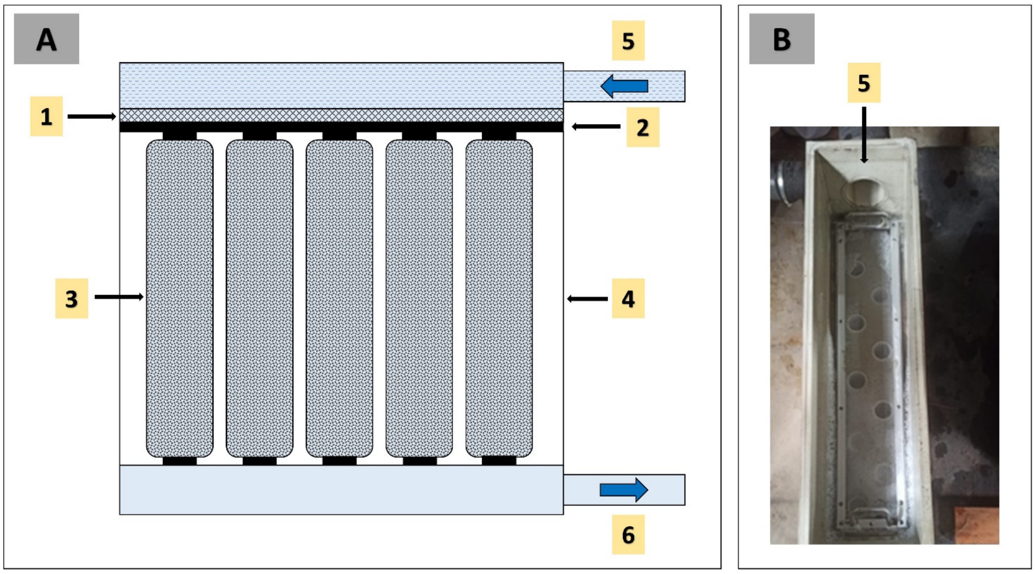

Figure 3. (**A**): Cross section of the filtration system (1—pre-screen cover, 2—cartridge holder, 3—cartridges (10 per unit), 4—filter housing, 5—inlet (drain from the washing machine), 6—filter outlet; (**B**): top view of the filtration unit.

Wastewater samples were collected from both the untreated and treated water outlets of the washing machine. The untreated water samples (n = 4) were collected before entering the filtration unit (Figure 3), while treated samples (n = 4) were collected after passing through the filtration system. A one liter sample of wastewater was collected into precleaned sterilized glass bottles for each washing cycle at four stages including pre-washing, after pre-wash, during the main wash, and after the rinse cycle. This method of sampling was designed to capture variations in microfiber release at different stages of the washing process. Since the inlet water source for the washing machine was the municipal tap water line, microplastic quantification was performed to ensure that there was no significant contamination from the inlet water source. Based on this analysis, microplastic presence in the tap water was found to be negligible. Furthermore, to ensure all the microfibers had been removed from the internal surface of the washing machine and the drain pipe once the washing process was concluded, the machine was flushed several times with water and cleaned thoroughly before the next test.

2.4. Microfibers Extraction from Wastewater

Once the fiber-containing laundry water was collected, microfibers were extracted from the wastewater by filtering the sample through a 100 µm mesh size sieve. Microfibers trapped on the mesh were then washed with microplastic-free water and collected into another sterilized glass bottle for further analysis to ensure that no microfibers bypassed the initial filtration step.

2.5. Catalytic Wet Peroxide Oxidation

Following the initial filtration, catalytic wet peroxide oxidation was performed to remove organic matter and isolate the microfibers. 20 mL of 30% H_2O_2 and 5 mL of catalyst

($FeSO_4$) (Fenton reagent) were added [27]. The samples were allowed to react at room temperature for 30–45 min.

2.6. Density Separation

A saturated solution of sodium chloride (1.2 g/mL) was used to separate microfibers from other particles, such as non-degradable materials, based on their buoyancy. The samples were then stored for 24 h to allow for sufficient density separation, causing synthetic microfibers to float, while denser particles settled. Subsequently, density-separated samples were filtered onto 0.45 µm membrane filter papers and dried in a controlled environment to prevent contamination and were prepared for subsequent analysis under a stereo microscope.

2.7. Color and Morphological Analysis

The dried samples were observed using a stereo microscope (×40). Microfibers were categorized into color groups (black, white, transparent, red, and blue) and sizes to determine the dominant types released during the washing process.

3. Results and Discussion

3.1. Sample Observations

Figure 4 shows some of the microfibers present in the treated (n = 4) and untreated (n = 4) laundry water samples. While many of the observed fibers were presented as individual strings, in some instances, the fibers were entangled together. An example is shown in Figure 4, namely, the UT-2 plate. In such cases, for ease of calculation, the entangled strings were counted as one microfiber. Based on these observations, the abundance, color, and size of the microfibers were recorded for further analysis.

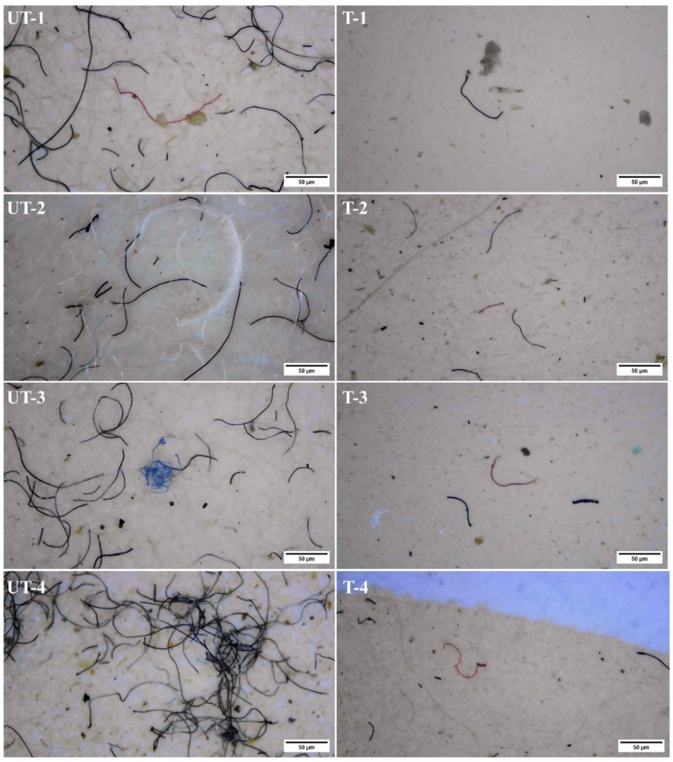

Figure 4. Morphological observations of microfibers present in untreated (UT) (n = 4) and treated (T) (n = 4) laundry effluent.

3.2. Quantification of Microfibers

On the basis of the stereo microscopic observations of the 0.45 µm membrane filter papers, the number of microfibers per liter of untreated and treated laundry effluent was calculated. Considering the untreated samples, UT-1, UT-2, UT-3 and UT-4 contained 10,416, 8482, 11,898 and 9625 pieces of microfibers, respectively. Once the effluent underwent the treatment process, the abundance of microfibers decreased drastically (Figure 5). Consequently, the treated samples of T-1, T-2, T-3 and T-4 contained only 47, 215, 192 and 312 microfibers, respectively.

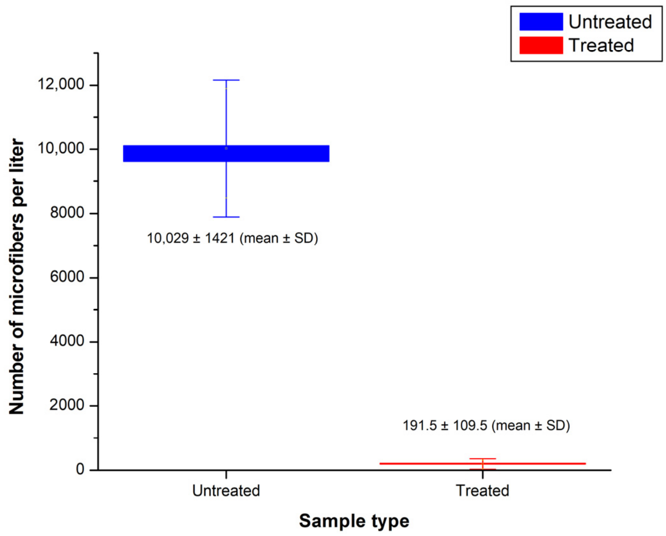

Figure 5. Boxplot of the abundance of microfibers per liter in untreated and treated samples.

3.3. Color Distribution

The colors of the microfibers ranged from blue, black, white or transparent and red. Since the laundry used for this experiment was made up of black and maroon color cloths, these findings were expected. In the untreated laundry water samples, blue, red, white or transparent and black microfibers were found in quantities of 1936, 34, 16,003 and 22,447, respectively. After treatment, the blue, red, white/transparent and black microfibers were 72, 6, 311 and 375, respectively. Figure 6 shows the differences in the colors of the microfibers in the untreated and treated samples. In both scenarios, the abundance of colors followed the order black > white/transparent > blue > red arrangement. Similarly, such results have been reported in a number of studies. From Haque et al. [28], industrial laundry effluent in Bangladesh had the highest proportion of fibers colored black (33.3%), followed by white (16.7%) and blue (14.5%). On the other hand, the majority of colorless microfibers were found in textile effluent in China, followed by black and blue microfibers. Thus, the prevalence of the three colors is indicated. Nevertheless, understanding that the colors of microfibers are dependent mainly on the colors of the source materials is essential. Additionally, chemicals, dyes and organisms adsorbed by the microfibers may alter the color, while degradation of the material could also affect the specific color. These studies suggest that the photoaging process of synthetic materials could be influenced by the color of the garment. When the color of the garment is darker, it has a stronger light absorbance ability and a greater potential for photodegradation and fragmentation. Therefore, the color of the fibers in the laundry effluent could vary across scenarios [29,30].

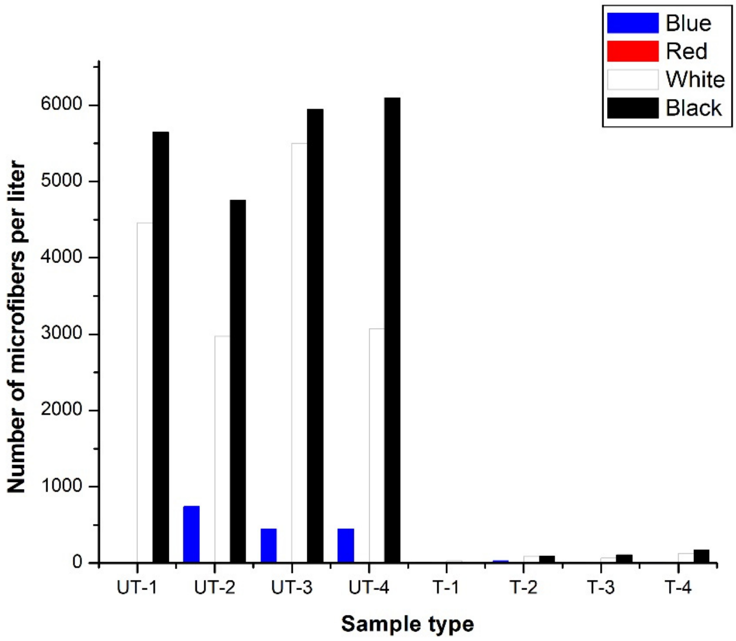

Figure 6. Colors of microfibers available in untreated and treated samples.

While the colors of microfibers do not necessarily reflect the associated environmental problems, global scientific studies have illustrated some of the environmental consequences linked with certain colored microfibers. Chen, Li and Li [31] reported that zooplanktons such as *Daphnia magna* are unable to distinguish between colored microplastics and algae, ultimately feeding on microplastics, whereas white microplastics inhibit *Scenedesmus obliquus* algal growth. Since microplastics can affect both primary producers and consumers, the environmental and eco-toxicological effects associated with this process are highly significant. They further reported that the color of plastics had an effect on microbial colonization (e.g., biofilms colonizing blue-colored microplastics have greater functional diversity than yellow-colored microplastics), and the adsorption, release and degradation of different pollutants (e.g., cadmium (Cd)-colored microplastics may release Cd due to sunlight). The ingestion of microfibers by marine and freshwater organisms has been observed numerous times, and certain colors are more commonly ingested. For example, microfibers were predominantly (68.3%) found in the gastrointestinal tract of dermal and pelagic fish in the English Channel, United Kingdom, and the majority of the fibers were black (45.4%) in color [32]. As discussed earlier, darker-colored plastics have a greater energy absorption potential due to solar infrared absorption, potentially altering the temperature of the surrounding water. A rising water temperature increases the metabolic activities of organisms, resulting in competition for survival, the spread of diseases, and disruption of the seasonal succession of phytoplankton (primary producers) communities, which can alter food web dynamics and element cycling [33,34]. On the basis of this evidence, the danger of emitting untreated laundry water containing microfibers is very clear.

3.4. Size Distribution

To understand the size distribution of the microfibers in the two samples, 100 fibers were randomly chosen from the untreated and treated categories, which represented all the replicates. The sizes of the fibers were measured via ImageJ software (version 4.5.g), and the overall trend is shown in Figure 7. Considering that more than 80% of the fibers in the untreated samples were between 50 and 150 µm, 16% were found to be 150–250 µm long. These results correlate with most of the literature, as shown in Table 1. However, in the treated samples, the majority (more than 90%) were in the range of 50–100 µm. As shown in Figure 7, the treatment process drastically decreases the number of microfibers exceeding lengths of >100 µm.

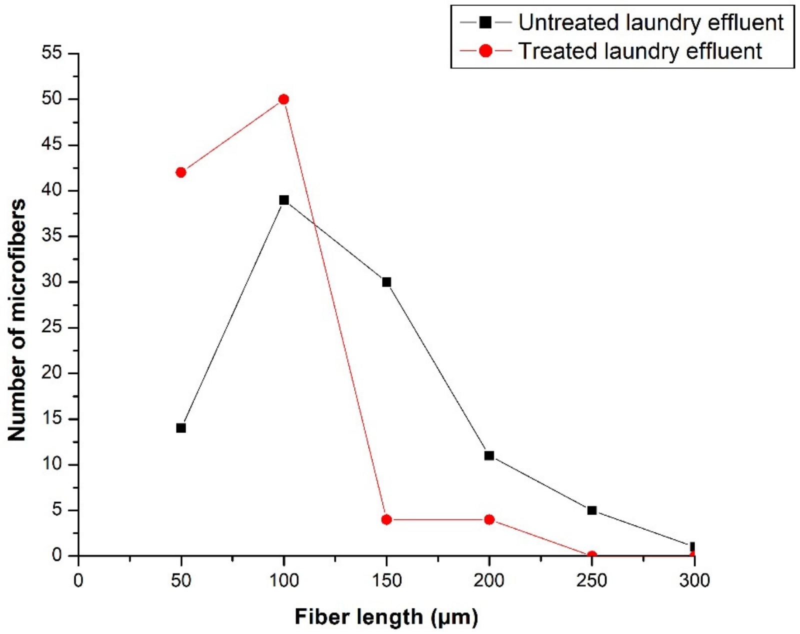

Figure 7. Size distribution of microfibers (*n* = 100) in the untreated and treated samples.

Table 1. Loss of microfibers during washing, as discussed in the global literature (NS = not stated).

Emission Rate	Fiber Sizes	Reference
3,000,000 MF/kg (synthetic fibers)	Microfiber sizes: 5–100 μm (53%), 100–500 μm (40%) and >500 μm (7%)	[35]
In front-loading washing machines: 202,237 MF/kg and 233,558 MF/kg In top-loading washing machines: 290,218 MF/kg and 232,567 MF/kg (synthetic fibers)	Majority of the fibers (mixed) were in the ≤5 μm (48.64%) size range, and least amount of fibers were in the >500 μm range (11.49%).	[36]
Polyester–cotton blend: 22,992 MF/kg, polyester: 82,671 MF/kg, and acrylic: 121,465 MF/kg	Polyester–cotton blend: 17.74 μm in diameter and 4.99 mm length, polyester: diameter 11.91 μm and length 7.79 mm, acrylic: diameter 14.05 μm and 5.44 mm length.	[37]
Polyester: 1,200,000 MF/kg	Plain weave polyester: 340 ± 292 μm in length and 14 ± 3 μm in diameter, double knit jersey polyester: 478 ± 408 μm in length and 20 ± 6 μm in diameter, plain weave polypropylene: 339 ± 247 μm in length and 19 ± 6 μm in diameter.	[38]
Polyester: up to 23,094 ± 1812 items/m^2, polyamide fabrics: up to 69,723 ± 40,773 items/m^2, and acetate fabric: 74,816 ± 10,656 items/m^2	Polyester fabrics diameter: 13.25 ± 4.24 μm, polyamide fibers diameter: 16.61 ± 5.96 μm, acetate fabrics diameter: 15.17 ± 5.88 μm.	[39]
From hand washing and machine washing: 37.84 mg fiber/kg of textile and 222.84 mg fiber/kg of textile, respectively.	Fiber lengths of hand washing and machine washing: 258 μm and 155 μm.	[40]

Table 1. *Cont.*

Emission Rate	Fiber Sizes	Reference
22,600 MF/kg or 12 mg of fibers	Majority of the fragments in the range of 20–200 μm followed by few long fibers (approximately 700 μm)	[41]
Polyester fleece fabrics: 7360 fibers/m^{-2}/L^{-1} and polyester fabrics: 87 fibers/m^{-2}/L^{-1}	Microfiber sizes ranges from 0.025 mm to >3 mm.	[42]
114 ± 66.8 mg microfiber (mixed fibers) per kg of fabric	NS	[43]
During delicate handwashing microfiber emission: 17.33 MF/cm^2, harsh hand washing (e.g., washing followed by beating and brushing processes): 23.7 MF/cm^2, and machine washing: 18.06 MF/cm^2.	NS	[44]

3.5. Efficiency of the Treatment Process

The analyzed 23 kg front-loading washing machine released 40,420 microfibers per liter of wastewater during the washing of 12 kg of cloth. Overall, the machine requires around 100 L of water per wash and therefore releases 4,042,000 microfibers for a wash or 336,833 microfibers per kilogram of laundry. After filtration, the microfiber quantity was decreased to 742 microfibers per liter. On the basis of the test parameters applied in this experiment, the microfiber removal efficiency (*MRE*) of the treatment process could be calculated as follows.

$$MRE = \left(\frac{Decreased\ microfiber\ quantity\ after\ the\ treatment}{Original\ qunatity\ of\ microfibers} \right) \times 100 \quad (1)$$

Accordingly, the *MRE* of the treatment process was 98.08%. Compared with findings from the literature, the findings of the present study vary, especially with respect to microfiber emission from direct laundry water. Table 1 summarizes some of the emission rates reported by different researchers.

Table 2 summarizes some of the microfiber removal methods available in the present market.

Table 2. Currently available microfiber treatment methods [45,46].

Removal Method	Efficiency
Laundry bags: The garment can be inserted into these bags and the washing process can be continued.	54 ± 14%
Cora ball: designed to place inside the laundry drum and mimics the nature of corals. The water flows through the Cora ball (containing nylon filament with 50 μm pore size) and captures the microfibers. However, with continued usage, the efficiency of the fiber capture will increase.	31 ± 8% 100% (polyester), 100% (acrylic)
PlanetCare filters: Fibers are electronically charged and the filtration technique is based on membrane nanotechnology (200 μm). After 20 filtrations, the filter has to be changed.	29 ± 15%
XFiltra: This filter has the finest pore size (60 μm) compared to other filtration techniques. The filter can be placed at the end of the wastewater pipe.	78 ± 5%

Table 2. *Cont.*

Removal Method	Efficiency
LUV-R lint filters: Equipped with metal mesh filters (285 µm and 175 µm), this filter is more successful in capturing longer fibers compared to shorter fibers.	29 ± 15%
Filtrol 160: The filtration takes place in a canister comprising filter bags made out of 100 reusable micron meshes. However, the usage of fabric softener and excessive detergent could clog up the filter.	30–60%
The fourth element washing bag:	21 ± 9%

Microfiber emission during the washing process depends on some factors. While some of the factors discussed below affect the efficiency of the treatment process, it is important to test newly developed treatment processes using a range of parameters to understand their strengths and weaknesses. As a result, compared with the methods discussed in Table 2, the microfiber removal rate of the present study was significantly higher (98%).

Top-loading vs. *front-loading washing machines:* As previous research has indicated, top-loading washing machines tend to shed more microfibers than front-loading washing machines. Compared with the rotating drum of the front-loading washing machine, the central agitator of the top-loading washing machine, which rotates the garments vigorously, is the main reason for this difference [47]. As discussed by Ramasamy and Subramanian [46], top-loading machines generate seven times more fibers than their counterparts do. In this study, a front-loading washing machine was used, and in future research, the experiment should be redone with a top-loading machine to analyze the fiber emissions and the success of the filter.

Water temperature: High temperatures tend to shed larger amounts of microfibers, as shown by [39]. In their experiment, at 60 °C the water released more polyester and acetate fibers. In contrast, Lim et al. [48] argued that there is no correlation between the water temperature and fiber generation. The present experiment analyzed only the effects of low-temperature water on the washing process. Thus, in future studies, microfiber release could be maximized by increasing the temperature, which should be used to validate the removal efficiency of the presented method.

Washing cycle: Once the number of wash cycles is moderate and short with a low water volume, the microfiber quantity tends to decrease [46]. Increased times and greater agitation loosen the fiber structure and fragments the loosely bound fibers in the garments. However, some studies have revealed that during the first five wash cycles, a greater number of microfibers are released. However, after the fifth cycle, this decreases. As a result, many researchers recommend the use of laundry bags to control fiber emissions during the first five cycles [48]. This experiment implemented only a single wash cycle to check the filtration success and fiber release. In the future, with respect to the number of wash cycles, the volume of water and rotation, RPMs should be considered to develop further outcomes.

Detergent and fabric softeners: The use of washing detergent promotes fiber shedding for several reasons. For example, some detergents contain surfactants, which can promote damage to fibers. Chemical damage caused by detergent or fabric softeners coupled with mechanical damage greatly influences fiber release. Furthermore, research indicates that commercial detergent usage could create 124–308 mg of microfibers per kg of laundry. On the other hand, the excessive usage of detergent can clog lint filters and external filters, decreasing the efficiency of such filter mechanisms. By using mild or biobased detergents and avoiding fabric softeners, microfiber generation can be significantly reduced [39,46].

Fabric type: Compared with synthetic fibers, natural fibers shed larger quantities of microfibers during different processes. However, because of the biodegradability of natural fibers, their importance in the natural environment is limited. On the other hand, semisynthetic fibers have a greater impact. Many experiments have demonstrated that fabric types such as acrylic, polyester and acetate shed larger quantities of fibers. Furthermore, the manufacturing process of such fabrics or threads has a significant effect on the shedding potential. For example, many researchers argue that a tighter fabric structure leads to less microfiber emissions, but this opinion is highly controversial. Moreover, factors such as fabric finishing and abrasion resistance characteristics also play vital roles [46]. To test the range of the presented treatment techniques, more fabrics with different origins (both natural and synthetic) should be tested in the future.

Garment age: Older garments (15–31 years) release twice as many fibers as newer garments do (1–10 years), and morphological observations of these garments reveal several types of mechanical damage, such as fiber splitting and peeling [49]. Heartline et al. [47] analyzed the effects of aging on microfiber recovery and reported that aging resulted in the recovery of 25% more microfibers. They further reported that the aging process has a significant effect on the release of larger fibers. Therefore, it is essential to include older clothes and newer clothes in future studies to test the efficiency of this method.

3.6. Limitations and Future Research Directions

Since this is a preliminary case study to assess the suitability of microfiber filtration units for coastal hotels, the present study contains several limitations. As discussed in the earlier section, the suitability and the success of the filtration unit depends on a number of factors. However, due to financial and technical constraints, long-term observations and performance analyses were not possible. Due to the importance of such factors, the present study recommends comprehensive long-term performance analyses including chemical characterization to understand the performance of the system based on the type of microfiber. By doing so, the efficiency of the present system can be compared to other systems and based on that information new improvements can be implemented. Another important consideration is the financial feasibility and the sound management of collected microfibers. When considering waste generation, the current practice for dealing with the collected microfibers is to recycle or reuse them. As a solution, more sustainable waste management methods should be investigated (e.g., ecobrick manufacturing) to efficiently discard the collected microfibers. As mentioned earlier, the cartridges can be replaced once the maximum retention capacity has been reached and the factors influencing this may vary. By identifying the other potential drivers that can cause increased replacement frequencies, necessary solutions can be developed. One potential method is to incorporate hybrid filtration techniques to increase the efficiency and the replacement frequency of the cartridge.

4. Conclusions

The present study aimed to quantify microfiber emission during the laundry process and calculate the removal efficiency of the installed filtration unit. This study used polyester–cotton blend serviettes (12 kg) and measured the microplastic generation. Results revealed that untreated laundry wastewater contained 10,028.7 ± 1420.8 microfibers per liter, while treated wastewater samples recorded 191.5 ± 109.4 microfibers per liter. Most of the microfibers observed were black and white/transparent colors. Further analysis revealed that 1 kg of polyester–cotton blend fabric can generate 336,833 microfibers per wash, which was reduced to 6367 microfibers after treatment. The filtration unit recorded an impressive efficiency of 98.09%, indicating a remarkably high capacity for removing microfibers from wastewater. These findings underscore the significant impact of laundry processes on microfiber pollution and highlight the effectiveness of filtration systems in mitigating this environmental threat. Implementing such filtration technologies could play a crucial role in reducing microfiber emissions and protecting ecosystems.

However, several limitations should be acknowledged. This study focused on a single type of washing machine and a specific polyester–cotton blend fabric, which may not represent all laundry scenarios. The filtration system's effectiveness was evaluated under controlled conditions, and its performance in real-world settings, where variables such as detergent type, fabric composition, and washing temperature vary, remains to be tested. Additionally, this study did not explore the long-term durability and maintenance requirements of the filtration system, which could impact its practicality and cost-effectiveness in widespread applications.

Future research should consider a broader range of washing conditions, including different types of fabrics, washing machines, and detergents, to better understand the variability in microfiber emissions. Studies should also investigate the cumulative effects of repeated wash cycles and explore innovative filtration technologies or methods that could further enhance microfiber removal. Moreover, examining the potential ecological impact of residual microfibers that escape filtration will be essential for developing comprehensive environmentally friendly strategies to address microfiber pollution.

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