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Letter

Microfibers Released into the Air from a Household Tumble Dryer

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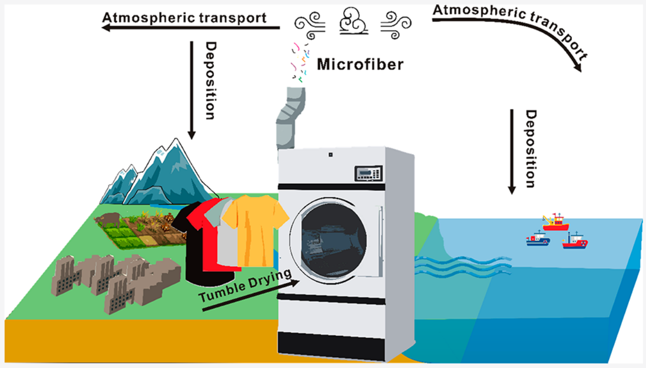
ABSTRACT: Microfibers of polyester and cotton might be significant for the transport and fate of chemical pollutants in the air due to the amounts emitted, as well as their capacities to sorb inorganic and organic compounds. It was hypothesized that household tumble driers could be atmospheric sources of these microfibers. This study quantified the number of the two most common textile fibers discharged from a household vented tumble dryer to ambient air. The results suggest that driers of this type are a potential source of air contamination by microfibers, releasing 433,128−561,810 microfibers during 15 min of use. Microfibers can be generated from both polyester and cotton textiles. The abundances of microfibers of polyester produced were directly proportional to the masses of clothing loaded into a dryer, but such a relationship was not apparent for cotton textiles. On the basis of the results presented here and other relevant data, it was estimated that the average Canadian household can annually release from 9×10^7 to 12×10^7 microfibers from a single dryer. To minimize the release of these microfibers into the air, an appropriate engineered filtration system should be developed and adopted as an effective control measure for individual household driers.



■ INTRODUCTION

Synthetic textile fibers, such as linear polymers, are widely used in the manufacturing of clothing.[1] Materials used in synthetic textile fibers include polyester, nylon, acrylic, and polypropylene.[2] Global consumption of these synthetic fibers has increased.[3] For example, the use of polyester fibers reached 76.66 million tons per year and accounted for 55% of the global clothing market.[4] During laundering, synthetic textiles can release microfibers, which are a common group of microplastics released into aquatic environments.[5−9] Microplastics are a growing threat to aquatic organisms and their ecosystems.[10,11] Apart from marine[12,13] and freshwater environments,[14−17] microfibers have been found in air[18] and terrestrial ecosystems,[19−21] where they are relatively persistent.[22]

The occurrence of microfibers in air has attracted increasing attention.[18,23] For human exposure, the intake of microplastics via inhalation by air was much greater than that via other exposure routes.[18] While airborne microplastics can be directly inhaled by humans, deposited microplastics can be ingested by hand-to-mouth contact, especially for children.[24,25] Microplastics have been found in human stools as direct evidence of common exposure.[26] Exposure to airborne microplastics has been linked to adverse effects on the health of humans, including chronic obstructive pulmonary disease (COPD).[27]

To date, most published research has focused on the generation of microfibers from washing machines.[28,29] For instance, one pair of jeans can release 56,000 ± 4100 microfibers per wash.[5] One hundred percent polyester knitted fabrics could release large microfibers under various operative washing conditions.[30] During washing, T-shirts made of polyester and polyamide can produce more microfibers than other tested textiles.[31] Cotton textiles can also release microfibers. The numbers of microfibers released from polyester or cotton textiles ranged from 2.1×10^5 to 1.3×10^7 fibers per wash.[7] A report by the Ellen MacArthur Foundation (2017) estimated that by 2050 the number of microfibers released into the environment by washing textiles might increase to 70,000 tons per year, which is equivalent to dumping 400 million polyester T-shirts into the sea.[32] Fortunately, since most laundry water is treated by sewage treatment plants, such large quantities of microfibers would be unlikely to be discharged into aquatic environments,[33−35] but they might enter other environments associated with biosolids.[36,37] Recent research (2021) confirmed microfiber contamination in the atmosphere, even in the Arctic.[38−40] However, the release of textile-associated microfibers into the

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atmosphere has been less studied.[41,42] Household tumble dryers can be an important mechanism for releasing textile microfibers to the ambient atmosphere. Because vented air is usually not treated, microfibers are emitted directly through a ventilation pipe connected to the dryer to ambient air, either indoor or outdoor.[41,43,44] When textiles are rotated in a forced-air dryer, microfibers might be shed from the textiles, especially at higher temperatures.[43] The releases of microfibers from large-scale commercial dryers are unknown but could also be significant and not negligible. In addition, if dryers are not connected to a ventilation system, the released microfibers could be inhaled directly from the indoor air by humans. Microplastics have been reported in indoor and outdoor air worldwide.[18] It has been estimated, based on a normal exposure scenario, that more than 900 microplastic particles might be ingested by a child per year through dust (200 mg day^{-1}).[45]

Given that the release of microfibers from driers remains largely unknown, the goals of this study were to (1) test the hypothesis that household driers are significant atmospheric sources of polyester and cotton microfibers, (2) evaluate the potential release of these microfibers from clothing containing the two textiles, (3) evaluate the annual emission of microfibers from a dryer, and (4) evaluate the contribution of household tumble driers to microplastic air pollution in Canada.

■ MATERIALS AND METHODS

Materials. Two types of textiles (polyester and cotton) were selected for this study (Table S1, Supporting Information (SI)), including 12 polyester items of clothing and 10 cotton items of clothing. The textiles were dried in a household, electric vented tumble dryer, Electrolux Wascator TT200, and the technical specifications of this dryer are shown in Table S2 in the SI. A high-volume, total suspended particle air sampler (Sibata, Japan) was placed at the end of the ducting to collect all airborne particles independent of size. The volume of air sampled was measured by a TSI Mass Flowmeter Calibration Analyzer 4043, which was placed at the outlet of the dryer. The pump was started when the drying process began. The targeted substance in the air was filtered onto Whatman GF/C glass fiber filters (1.2 μm pore size). After sampling, the glass fiber filter was carefully transferred to a Petri dish with stainless steel tweezers and sealed with parafilm. The microfibers collected on the filter were subjected to examination through standard procedures (see Text S1 and Characterization and Enumeration of Microfibers section).

Drying Trials. The details of the method for collecting microfibers are shown in Text S1 and Figure 1. The effects of the drying duration on the release of microfibers were tested using the same number of polyester textiles for 10, 20, 30, 40, or 50 min. There was no significant difference in the number of microfibers released among the different drying durations (One-way analysis of variance (ANOVA): $F_{4,10} = 1.751$, $p = 0.215$, Figure S2). On the basis of this finding, the drying duration for all subsequent experiments was set to 15 min, which could effectively reduce the experiment time. Trials were replicated six times for each type of textile: (i) No. 1−4, (ii) No. 1−8, (iii) No. 1−12, (iv) No. 13−16, (v) No. 13−19, and (vi) No. 13−22 (see Table S1 for details). Cycles for (i), (ii), and (iii) were performed with 100% polyester clothes, while the other cycles were carried out for pure cotton clothes. To account for variations among runs, the cycles were repeated three times. The air evacuation rate of the dryer was large, and the air vacuum pump could only absorb part of the gas. Equation 1 was employed to obtain the amount of the released microfibers. Given that the practical air evacuation rate was 525 m^3/h, the total number of released microfibers was calculated using the following equation

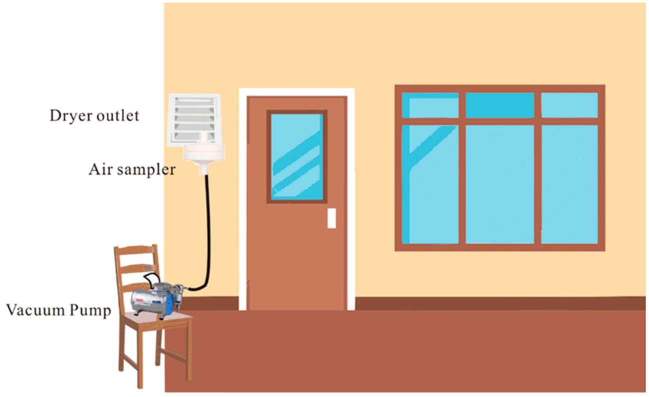

Figure 1. Experimental setup.

$$N = (r/v) \times n \quad (1)$$

where N is the microfiber number per drying cycle, r the air evacuation rate of the dryer, v the flow velocity of the pump sampler, and n the counted microfiber number released from the textiles in our study.

Characterization and Enumeration of Microfibers. The individual microfibers on the filters were identified based primarily on shape, surface texture, and color and were counted under a stereomicroscope at up to 40× magnification. Further confirmation was achieved by picking out microfibers and examining them by micro-Fourier transform infrared spectroscopy (μ-FTIR) (Thermo Nicolet iS10 with Continuμm/iN5, Thermo Fisher Scientific, USA). The spectral range was set from 4000 to 550 cm^{-1}, and 16 scans were performed for each measurement. The spectra acquired were compared with standard spectra from open-access databases (Aldrich Polymers, Sprouse Polymer by ATR, and Hummel Polymer Sample Library), and the chemical compositions were identified according to the presence of characteristic peaks and similarities (at least with a match score >70%) with matched spectra. Nitrile gloves and a laboratory coat were worn to avoid contaminating the samples during sample analysis.

Quality Assurance and Quality Control (QA/QC). Three field blank samples were collected from the ambient environment when the dryer was not in use. Three process blank samples were collected when the dryer was in operation without textiles. The duration of the collection was 15 min. We collected three control samples to evaluate the potential carryover effect from a prior load. According to our evaluation, such carryover contamination was negligible and may be due to the short length of the venting pipe. The dryer was installed in a room approximately 15 m^3 with a vent line, and the room was at the residence building of the Swire Institute of Marine Science located at the Cape D'Aguilar Marine Reserve in Shek O, Hong Kong. As Cape D'Aguilar is in a rural area on the southern edge of Hong Kong Island with a low ambient level of microfibers in the atmosphere, we selected this location to conduct the experiment (Figure S1).

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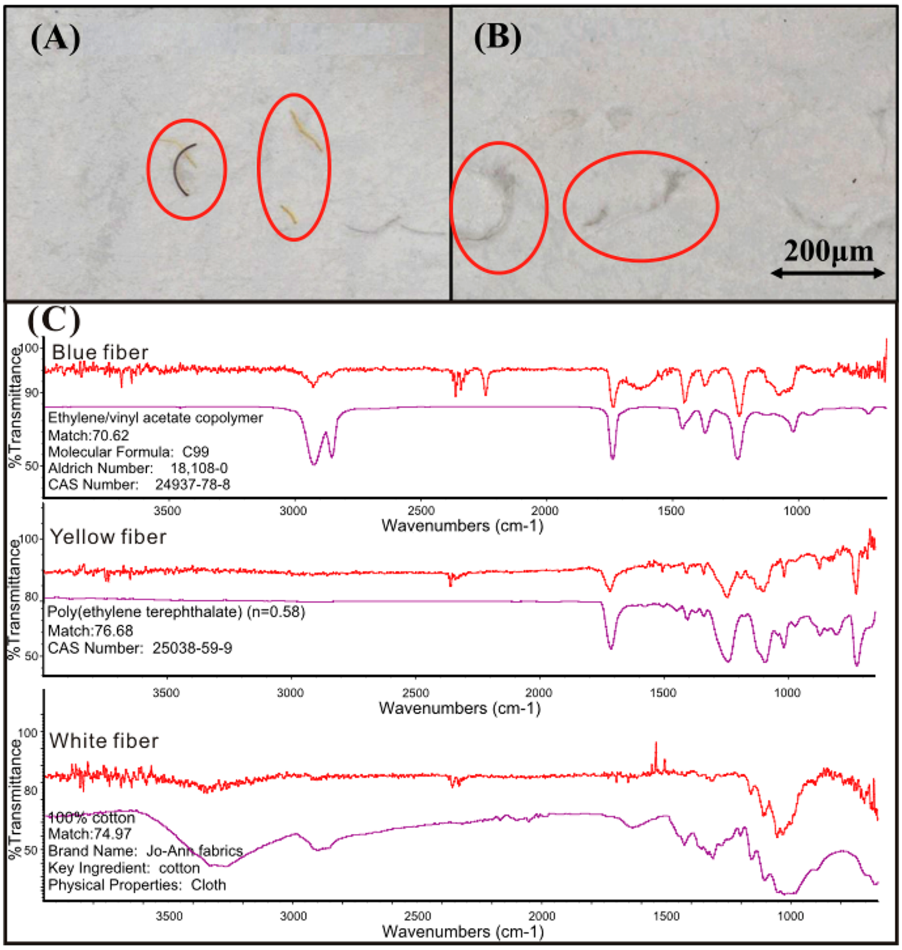

Figure 2. Images acquired using a Nikon microscope: (A) blue and yellow microfibers released from polyester textiles and (B) white microfibers released from cotton textiles. (C) Sample spectra and their matched spectra from the library.

Data Analyses. Statistical analyses were performed by Microsoft Excel 2016, OriginLab OriginPro 2015, and IBM SPSS Statistics 19. Prior to the use of parametric statistical procedures, the Shapiro−Wilk test was conducted to test for the normality of the data (Text S2). Pearson correlation analysis was conducted when the data met the assumption of normality; otherwise, Spearman correlation analysis was conducted. Finally, a linear regression was conducted to show the relationship between the number of microfibers generated from the polyester and cotton clothing and the mass of the loaded clothing.

■ RESULTS AND DISCUSSION

Microfibers Collected from Vented Air during Drying. A household tumble dryer is a potential atmospheric source of microfibers. A mean value (±SD) of 270 ± 30 microfibers was collected during the 15 min drying of polyester textiles, while a mean of 165 ± 27 microfibers was observed for cotton textiles (Table S3). The 11 ± 2 microfibers collected in the field blank sample represented the background level in ambient air, while the 24 ± 0 microfibers in the process blank sample were collected when the dryer was in operation without textiles. A total of 19 ± 4 microfibers were collected between trials to eliminate the remaining fibers from the previous load from being ignored. As the number of microfibers in the blank samples was less than 10% of that in the real samples, the contamination could be considered negligible. Therefore, the number of fibers in the samples was not corrected by the blank.

FTIR spectral results for the microfibers showed polyethylene terephthalate (PET) and polyvinyl chloride vinyl acetate (PVC) produced by polyester textiles, respectively (Figure 2). These two kinds of microfibers were also identified as microplastic contaminants. PET is a typical textile used in daily life, especially in fabrics used in sportswear, because it is handy and easy to dry.[46] It has been reported that ingesting PET fibers resulted in the increased mortality of crustaceans.[47] PVC microfibers might be used as a decorative element on clothing. Cotton microfibers (100%) were detected in our experiment after cotton textile drying (Figure 2). Cotton fibers, such as denim microfibers, have been identified as a new challenge in the field of microfiber pollution. Recent research has reported that cotton fibers are widespread in aquatic environments from temperate to Arctic regions.[5] Anthropogenically modified celluloses are often chemically processed and are sufficiently persistent to undergo long-range transport and accumulation in environmental compartments, where they could be of concern for biota.[5]

Effects of Mass Range and Drying Duration on Features of Microfibers. There were differences in the production of microparticles between polyester and cotton. There was a significant, positive correlation (Pearson's correlation coefficient, $r = 0.836$, $n = 9$, $P < 0.01$) between the number of microfibers released and the mass of polyester textiles put into the dryer (Figure 3, Table S4). In contrast, no significant correlation was observed between the mass of cotton textiles in the dryer and the number of microfibers released (Figure 3; Spearman's correlation coefficient, $r = 0.46$, $n = 9$, $P > 0.05$). Cotton, a natural fiber, also has a polymeric structure comprised mainly of cellulose. Since cotton requires several stages of chemical treatments before use in manufacturing textiles, cotton fibers contain some residues of chemicals, such as fluorescent whitening agents and azo dyes.[7,48]

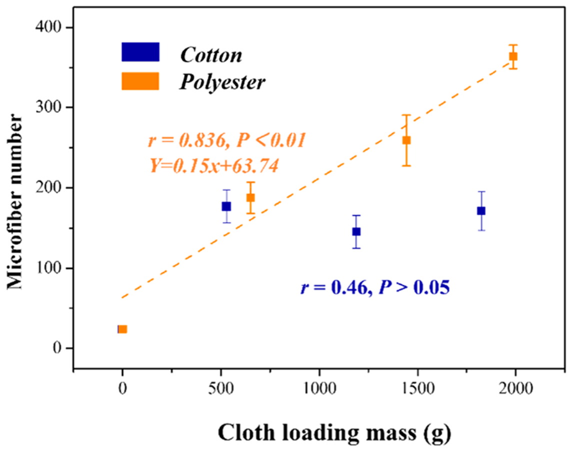

Figure 3. Relationships between the clothing (textile) load in the dryer and number of microfibers released into the air for polyester textiles and cotton textiles.

Evaluation of Microfibers Released from Driers. In this study, the air sampler only collected a partial ventilation air sample from the dryer. On the basis of the practical air evacuation rate of the dryer, the total amount of microfibers released from the dryer can be calculated. In addition, the number of microfibers released from various masses of polyester textiles, which was 214 ± 39 microfibers (Figure 3), can be estimated by a regression model. Cotton textiles produce stable amounts of microfibers (165 ± 27) after drying regardless of the mass of textiles in the dryer.

It was estimated that 93,635 ± 17,026 and 72,188 ± 11,813 microfibers could be released from 1 kg of polyester and cotton textiles, respectively, during a 15 min drying process (eq 1). The present results are compared with those reported in the literature for washing and drying machines or washing machines (Table 1). In most cases, regardless of whether the textiles are cotton or polyester, for 1 kg of textiles, a dryer can generate more microfibers (7.2−9.4 × 10^5 microfibers) than that generated by a washing machine (0.23−5 × 10^5 microfibers) (Table 1).[5,6,28,31,44,49−51] When combining reported values for washing and drying machines, the results of recent research have shown that 1 kg of 100% polyester textiles can even generate as many as 31 × 10^5 microfibers per cycle.[31] When a washing machine is used, the detergent might seriously damage the structure of the clothes, which could result in more microfibers being released during drying.[52]

The capacity of a common household washing machine is approximately 6−7 kg.[53] The estimated number of microfibers produced per dryer could be between 433,128 ± 70,878 (6 kg cotton textiles) and 561,810 ± 102,156 (7 kg polyester textiles) microfibers per 15 min drying cycle. This estimate of such airborne microfibers is greater than the number of microfibers generated by a washing machine. A washing load of a polyester−cotton blend has been estimated to release 137,951 microfibers into the drain.[28] In Canada and the United States, after washing clothes, people usually dry them in a separate dryer. The average Canadian household washes 219 loads of laundry annually.[54] Here, we estimated that the average Canadian household could release 9 × 10^7 to 12 × 10^7 microfibers from a dryer annually. That is, a significant number of microfibers are discharged into the atmosphere, which could be potentially inhaled and ingested by humans and animals. The microfibers released from tumble dryers are, therefore, likely to represent a substantial contribution to microplastic contamination in the environment globally.

Cotton microfibers discharged into the environment can be ingested by organisms, but they are not as persistent as polyester microfibers.[2] For the same drying duration, cotton textiles produce more stable amounts of microfibers (165 ± 27) after drying regardless of the mass of textiles in the dryer. In comparison, polyester textiles can generate more microfibers than cotton textiles according to the current results. Microfibers generated from polyester textiles are of special concern since their bioaccumulation potential increases with decreasing size.[7] The microfibers might be ingested by organisms ranging from zooplankton to fish and birds and transferred into food webs.[10]

A study by the Italian National Research Council (2020) found that the number of plastic microfibers released can be

Table 1. Comparison of Numbers of Released Microfibers from Cotton and Polyester Textiles after Drying and/or Washing Per Cycle

Process mode	Type of textile	Materials composition	Mean number of fibers per kg materials (×10^5)	ref
Drying	Pants and T-shirts mixed	100% cotton	7.2	This study
Drying	Pants and T-shirts mixed	100% polyester	9.4	This study
Washing and drying	T-shirts	100% polyester	31	31
Washing and drying	Fabric	100% polyester	1.8	31
Washing and drying	Blanket	100% polyester	1.9	31
Washing	Blue jeans	100% cotton	1.3	5
Washing	T-shirts	100% polyester	5.5	6
Washing	Fabric	100% cotton	10	49
Washing	Fabric	100% polyester	5	49
Washing	Fleece blanket	100% polyester	2.2	50
Washing	Fabric	100% polyester	0.36	51
Washing	Jacket	100% polyester	0.83	28
Washing	Jacket	100% polyester	0.23	44

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reduced by nearly one-third when washing with fabric softeners.[55] This is because the softener reduces friction between the fibers.[45,49] However, the application of softeners might lead to harmful chemicals entering surface waters.[56] This challenge clearly requires a better solution. In China, the Public Environmental Audit Committee has turned its attention toward transforming the clothing industry to make it prosperous and sustainable.[1] However, it is unrealistic for plastic microfibers to be eliminated in the short term without the substitution of more environmentally friendly textiles. At present, many researchers and research organizations have been studying alternative textile materials such as those made of seaweed, banana peel, and even milk.[57,58] It is essential to make better textiles and clothes with more wear resistance, longer wearing time, and enhanced environmental friendliness. Before the realization of better replacements for synthetic fibers such as polyester, it is feasible to minimize the release of microfibers from tumble driers by the installation of a simple, engineered filtration device at the end of the emission pipeline.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.estlett.1c00911.

Textiles and tumble dryer (Tables S1 and S2), supporting results of the study (Table S3, Figures S1 and S2), and detailed description of the experimental design and statistical analysis (Texts S1 and S2)(PDF)

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Notes

The authors declare no competing financial interest.

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Supplementary Information

Microfibers released into the air from a household tumble dryer

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Table S1 Descriptions of 12 polyesters and 10 cotton textiles.

No.	Description	Composition	Mass (g)	Color
1	T-shirt	100% polyester	163.99	orange
2	T-shirt	100% polyester	129.348	gray
3	Pants	100% polyester	123.39	black
4	Pants	100% polyester	116.51	black
5	Pants	100% polyester	159.75	blue
6	Pants	100% polyester	172.82	blue
7	Pants	100% polyester	201.91	black
8	Shorts	100% polyester	125.06	black, dark green
9	Shorts	100% polyester	141.11	blue, white
10	Pants	100% polyester	168.18	black
11	Pants	100% polyester	180	red
12	T-shirt	100% polyester	148.5	red
13	T-shirt	cotton	161.92	black
14	T-shirt	94% cotton	225.89	black
15	T-shirt	cotton	117.41	white
16	T-shirt	cotton	145.36	yellow
17	T-shirt	cotton	185.92	white
18	Pants	82.8% cotton	387.84	black
19	T-shirt	cotton	218.8	black
20	T-shirt	cotton	175.71	white
21	T-shirt	cotton	167.32	red
22	T-shirt	47% cotton	200.65	white

*Cycle ① consisted of No.1-4; cycle ② consisted of No. 1-8; cycle ③ consisted of No. 1-12; cycle ④ consisted of No. 13-16; cycle ⑤ consisted of No. 13-19; cycle ⑥ consisted of No. 13-22.

Table S2 Technical specifications of the dryer adopted in this study.

Parameter	Specification
temperature (°C)	60
Drum volume (L)	200
Capacity (kg)	8
spin-dry rate (rpm)	2800
Air evacuated rate (m^3/h)	525

Table S3 Correlations between numbers of microfiber released as a function of the mass of textile dried.

		Mass	Microfiber number
Mass	Pearson *r*	1	0.836**
	P-value		0.002**
	N	9	9
Microfiber number	Pearson *r*	0.836**	1
	P-value	0.002**	
	N	9	9

** There was a significant correlation at P < 0.01.

Text S1

To maintain the consistency of the experiments, 500 mL tap water was mixed with the textiles for each trial. The air released from the dryer was discharged through a pipe connection on the shutter. A vacuum pump was placed behind the exhaust of the dryer outlet. The flow rate of the air vacuum sampler was set to 20 L/min. The pump was started when the drying process began. The targeted microfiber in the air was filtered onto Whatman GF/C glass fiber filters (1.2 μm pore size). In each trial, the duration of drying was 15 min. Before the start of a trial, a new glass fiber membrane was placed in the sampler. The pump was started when the drying process began. The microfiber released from the dryer in the air at the vent-pipe outlet was filtered onto Whatman GF/C glass fiber filters. For each trial, three parallel experiments were carried out according to the above operational procedure, and the average of the three experiments was used for estimation. After sampling, the glass fiber filter was carefully transferred to a petri dish with stainless steel tweezers and sealed with parafilm. The glass fiber filter was then examined under a microscope, and any microfibers present were carefully counted by an experienced researcher. The individual microfibers on the filters were identified based primarily on shape, surface texture, and color and were counted under a stereomicroscope at up to 40× magnification.

S2 Statistical analysis

Prior to the use of parametric statistical procedures, the normalities of the mass and microfiber numbers were assessed by the use of the Shapiro–Wilks test. For cotton textile: mass: W=0.890, $P > 0.05$, the data were normally distributed; microfiber number: W=0.829, $P < 0.05$, the data were not normally distributed. For polyester textiles, mass: W=0.881, $P>0.05$; microfiber number: W=0.940, $P>0.05$, both datasets were normally distributed.

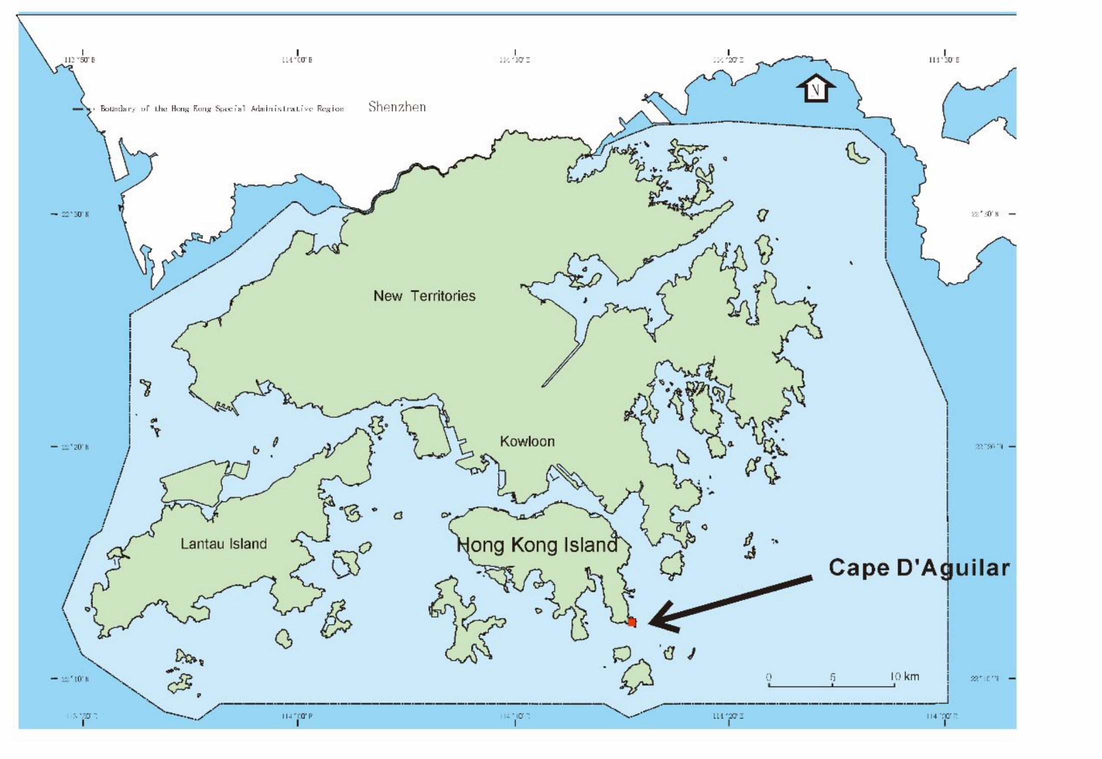

Fig. S1 Sampling location

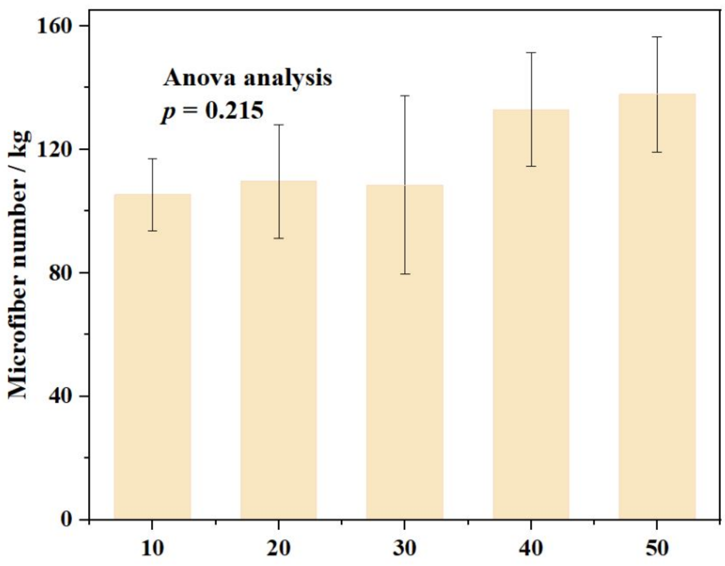

Fig. S2 Effects of duration time of drying on releases of microfibers number.