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REVIEW

Microfiber Pollution in the Earth System

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Abstract

Microfibers, as emerging contaminants, pose a growing threat to the global environment. Microfiber pollution has been one of the hot research topics in environmental science. However, there is no consensus on microfiber definition from ecological and environmental perspectives. The underestimated sources, the distribution in the ocean and the atmosphere, the transport pathway, the potential human exposure, and mitigation strategies of microfibers from a global perspective have not been systemically discussed. So, we aim to discuss and analyze these concerns in this review. Firstly, the definition of microfiber pollutants from the ecological and environmental perspectives is proposed. Secondly, the largest source and some emerging sources of microfibers on the Earth have been explored. Thirdly, the distribution and transmission path of microfibers in the ocean and the atmosphere are discussed. Fourthly, the exposure path of microfibers to the human body is analyzed. Lastly, some applicable measures to control microfiber pollution are proposed from global environmental sustainable development perspectives.

Keywords Microfiber pollution · Potential sources · Textiles and apparel · Domestic washing · Fiber loss · Mitigation strategy

Introduction

Since the first thread of wild flax fibers was used to create strings about 30,000 years ago, the demand for fibers has driven and enriched human civilization as time moves on (Dyer 2021; Kvavadze et al. 2009). In 2020, the total volume of global fiber production accounted for 120 million tonnes or almost 16 kg per capita on average for consumption (Engelhardt 2020). Synthetic fibers amounted to 74 million tonnes, accounting for 61.77% of the total global fibre production, with an annual growth of up to 5% (Liu et al. 2021). However, the production and consumption of textiles and apparel for decades also resulted in multiple environmental problems, including the discharge of industrial wastes, including toxic chemicals, wastewater, greenhouse gases as well as microfibre pollutants (Muthu 2017).

Microfiber has been strictly defined as a staple fiber or a filament with a linear density ranging from 0.3 dtex to 1 dtex (Song 2011), where 1 dtex means one gram per 10000 m. The diameter of microfiber is usually less than 10 μm, and the lengthto-diameter ratio is on the order of 10^3 (Liu et al. 2019c). Polyester (PET) and polyamide (PA or Nylon) are the two main types of microfiber widely used

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as raw materials in the textile and apparel industry. Although acrylic, viscose, and polypropylene (PP) are also widely produced and applied in the textiles and apparel industry, they only account for a proportion of no more than five percent (Acharya et al. 2021). Microfibers have excellent properties contributing to human comfort. Clothes made of microfibers are usually strong and durable, lightweight, resist wrinkling and pilling, and have luxurious and various colors (Song 2011). As an emerging contaminant, microfiber has been gradually raising concerns because of the systematic research and mitigation measures for microplastic pollution (Rathinamoorthy and Balasaraswathi 2021). Microfiber is also called microplastic fiber, synthetic fiber, or even chemical fiber with a length of less than 5 mm when referred to as an environmental pollutant.

Microplastic fibers or plastic microfibers are a prevalent type of microplastics, where their potential ecological and toxicological impacts have been systematically discussed (Il Kwak et al. 2022; Woods et al. 2018). However, there is still no clear consensus on a definition that is extensive enough to encompass all necessary parameters to describe microfiber when studied as a global environmental pollutant, although microfiber only refers to synthetic fiber in the textile industry. Natural and regenerated cellulosic fibers have dominated microfibers in the atmosphere and freshwater (Finnegan et al. 2022; Stanton et al. 2019). So, we need to redefine microfiber from ecological and environmental science perspectives. In addition, microfibers are always subcategorized as microplastics and called microplastic fibers or fibrous microplastics despite their differences in shape, size, production mechanism, spatial distribution, transport pathway, and human effect. An extensive and critical review of the sources of microfiber, especially the textile and clothes chain, and some new emerging sources, such as clothes dryers, face masks, wet wipes, and cigarette butts, are not symmetrically performed. The review of the potential human exposures, including textile mill workers and infants, is limited. Furthermore, very few potential strategies have been widely adopted to control and mitigate microfiber release from textiles during the production, usage, caring, and disposal stages (Ramasamy and Subramanian 2021).

We propose a general definition of microfiber as an environmental pollutant and review the potential sources and distribution of microfibers in the ocean and the atmosphere, human exposure to microfibers, and applicable measures to mitigate microfiber pollution globally. Firstly, the definition of microfiber pollutants from the ecological and environmental perspectives is proposed. Secondly, the loss rate of fibers in spinning, weaving, finishing, and garment processing, some essential and indispensable processes of the cotton textile industry, is used as an index to analyze and clarify that the largest source of microfibers should be the textile and garment processing industry chain, not home laundering. Thirdly, we point out that the longer-range or global transport of microfiber through the atmosphere is another important transmission path that is not limited to rivers. The specific characteristics of microfibers, such as small fineness, low density, large surface area, and natural or artificial curling shape, make them more susceptible to airborne transport. Fourthly, we propose that the harmful path of microfibers to the human body is not only through the food chain but also through inhalation of respiratory diseases. Lastly, some applicable measures to control microfiber pollution, combined with the United Nations Environment and Development Programme UNEA 5.2 resolution and the United Nations Sustainable Development Goals (SDGs) are proposed from the perspective of global environmental sustainable development.

Definition of Microfiber Pollutant

The term ‘microfiber’ in the textile industry is usually confused with the term ‘microplastic fiber’ in the area of microplastic pollution (Xu et al. 2021). The concept of microfiber was initially proposed by the Japanese fiber manufacturing company, Toray, to represent micro-denier products during the 1970s, followed by mass production in Europe and America during the 1980s and 1990s (Song 2011). In textile engineering, microfibers are formally defined as staple fibers or filaments of linear density with no more than one denier and above 0.3 deniers (Liu et al. 2019b). Denier (abbreviated D), a unit to describe the linear mass density of fibers, is the mass of grams per 9000 m of the fiber. The natural reference of a denier is a 9000-m strand of silk that weighs about one gram (Amutha 2016). The definition of microfiber in textile engineering is a clear consensus that has been widely accepted from a professional textile engineering point of view. However, there is still no clear consensus on a definition that is extensive enough to encompass all necessary parameters to describe microfiber when studied as a global environmental pollutant with a ubiquitous distribution. In 2019, we proposed a general and extensive definition of microfiber pollutants as “Microfibers are any natural or artificial fibrous materials of threadlike structure with a diameter less than 50 μm, length ranging from 1 μm to 5 mm, and length to diameter ratio greater than 100” (Liu et al. 2019c). Since microfiber is one type of emerging pollutants and their related research is at the beginning, the definition of microfiber is a methodological challenge and an on-going debate, although we all attempt to reach a consensus on a definition for microfiber from the ecological and environmental perspectives.

Review Methods

A mini literature review was conducted on microfiber pollution in the earth system from 1995 (the earliest research about the effect of cotton dust pollution on textile worker health) through October 2022. The literature search included title search and abstract search using Web of Science, and title searches and keyword search using SCOPUS with the given terms as: "microfiber pollution"; "microplastic fiber" OR "microplastic fibre"; " microplastic textiles"; " microplastic" AND "synthetic fibers" OR "textile fibers"; "plastic microfibers"; "microplastic" AND "natural fiber" or "natural fibre"; " textile pollution". For all 4017 retrieved references, the title was identified first before abstract and keyword screening to exclude those deemed irrelevant articles. After the abstract screening, eligibility assessment, and relevant analysis, 194 related articles are selected and included in this review. The review framework is demonstrated in Fig. 1.

Potential Sources of Microfiber Pollution

Domestic Washing was Initially Identified as the Primary Source

Initially, microfibers were more likely described as synthetic fibers shed from clothing during laundry (Napper and Thompson 2016). It was reported that approximately 700,000 microfibers (about 0.5 g in weight) could be discharged with laundry sewage every cycle the washing machine drum rotates (Karkkainen and Sillanpaa 2021; Napper and Thompson 2016). So, domestic and commercial washing was primarily identified as a leading potential source of microfibers (Cai et al. 2020a). As many as 700,000 can be released into the wastewater each cycle, weighing approximately 0.5 g in total. Globally, it is estimated that 500,000 tonnes of microfibers are released into the ocean because of domestic washing annually (Boucher and Friot 2017). Textiles contribute about 14% of plastic waste production by sector, the second source of plastic pollution following packaging (Smith and Vignieri 2021). Therefore, domestic washing was regarded as a leading potential source of microfibers at the beginning (Cai et al. 2020a).

Fiber Losses in the Textiles and Apparel Industry have been Underestimated

The fiber losses in the production process of the textile and apparel industry are inevitable but usually ignored and rarely reported, which may lead to the relevant research underestimating the emission capacity of this part of microfibres towards the environment. From raw materials to the end-product, fiber losses occur at each step of the textile production processes, including spinning, weaving, dyeing, finishing, cutting, trimming, and sewing, especially through the wet-processing dyeing and finishing mills (Chan et al. 2021). For example, in different manufacturing processes, cotton fiber loss rates for different end-products are listed in Table 1, released by Better Cotton Initiative (2022) through member survey responses in 2020 (Initiative 2020). 6% to 43% of fibers were lost during each process (Table 1). If the fiber loss rate is simply set at 30% from fiber to end-product, about 70,000,000 tonnes of cotton were globally wasted in 2020 (James Johnson, 2021). Assuming that the microfiber loss rate is 1% from fiber to end-production during the home textiles and apparel production, nearly 1.1 million metric tons of microfiber, which is 2.2×10^6 times the weight of the estimated ones being released from domestic washing. Although the detailed loss rate of synthetic fiber during

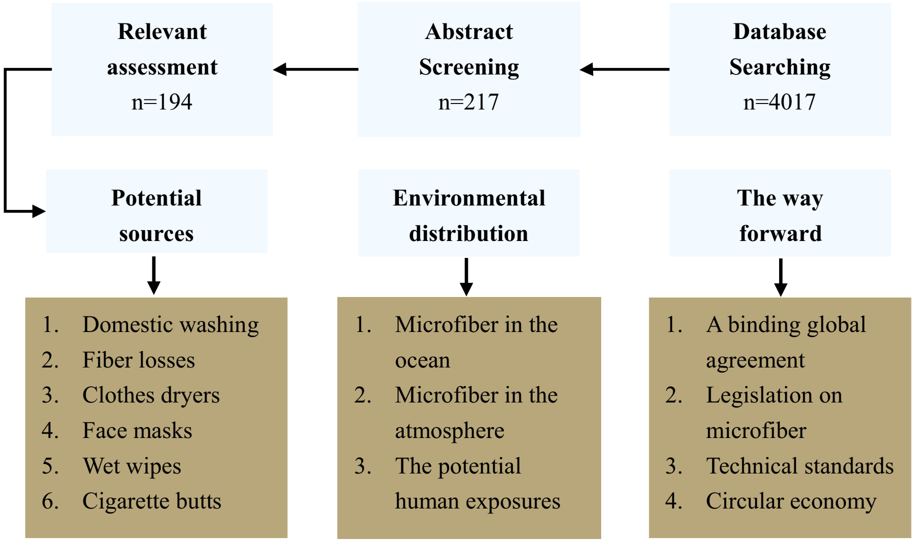

Fig. 1 The review framework of microfiber pollution

Table 1 Cotton fiber loss rates for different intermediary products and end-products (Initiative 2020)

Loss rate (%)	Home textiles	Apparel: denim	Apparel: wovens	Apparel: flat knits	Apparel: circular knits
Fiber-to-yarn (open-end)	10%	–	–	–	–
Fiber-to-yarn (carded)	–	12%	12%	–	–
Fiber-to-yarn (combed)	–	–	–	21%	21%
Fiber-to-fabric	20%	17%	21%	–	31%
Yarn-to-fabric	11%	6%	10%	13%	18%
Fiber-to-end-product	24%	30%	35%	31%	43%
Fabric-to-end-product	5%	15%	18%	13%	18%

production is so far unclear, the mismanagement of the fiber losses at spinning mills, fabric mills, and manufacturing factories of home textiles and apparel, as well as a sale and usage stages, should not be ignored (Cai et al. 2020b). Incineration and landfills have been the main measures to prevent microfiber from being directly released into the environment for those who originated from dry processes such as spinning, weaving, and sewing (Periyasamy and Tehrani-Bagha 2022). Therefore, compared to domestic washing, the microfibres s of microfiber are the spinning mills, fabric mills, and manufacturing factories of home textiles and apparel compared with domestic washing.

In Table 1, a considerable amount of fiber loss is reported, although a remarkable difference exists between intermediary products, i.e. yarn, fabric, and end-products, including home textiles and four types of apparel. The fiber loss during spinning, weaving, dyeing, finishing, cutting, trimming and sewing processes is the major microfiber source in the textile and clothes industry. If the expected fiber loss is set at 30% from fiber to end-product and the weight of a cotton bale is 200 kg, more than 35.0 million bales of cotton, about 7,000 million kilograms of cotton was globally wasted in 2020 (James Johnson, 2021). The mismanagement of the fiber loss at spinning mills, fabric mills, and manufacturing factories of home textiles and apparel will generate an enormous amount of microfiber in solid wastes and contaminants in wastewater. Additionally, the origin of microfibers within the production, sale, and usage stages of chemical fibers and industrial textiles should not be ignored (Cai et al. 2020b).

The wastewater discharged from the wet-processing stages, including dyeing, sizing, post-processing, and finishing, is another direct and significant route for the fiber losses entering the environment. Microfiber released from textile wastewater is considerably higher than from municipal sewage treatment plants, heavily contributing to microfiber pollution. The microfiber concentration was up to 54,100 microfibers/L in textile printing and dyeing wastewater sampled in three typical textile mills in Keqiao textile industrial park in southeast China (Zhou et al. 2020). Correspondingly, the effluents from the centralized wastewater treatment plants (WWTPs) of the same park reached as high as 537 microfibers/L, which means that 430 billion microfibers were discharged daily by WWTPs (Zhou et al. 2020). Microfiber released from textile wastewater is considerably higher than municipal sewage treatment plants, significantly contributing to microfiber pollution (Liu et al. 2021). Azizi et al. reported that the microfibres took average 57% of the microplastics in the wastewater sampled after each treatment step in conventional WWTPs according to the results of the meta-analysis (Azizi et al. 2022). Bao et al 2022. sampled the wastewater after each treatment process of a tropical urban WWTP and pointed out that 79.7% and 82.9% of microplastics detected in the wastewater are fibers during dry and wet seasons, respectively (Bao et al. 2022). Hu et al. analyzed the physical characteristics of microplastics in 48 WWTPs in China and concluded that the maximum percentage of fibers was higher than 70% in both influent and effluent samples (Hu et al. 2022a). Other microfiber research indicates that fibers contribute up to 50% of the total microplastic mass in WWTPs (Roscher et al. 2022; Shan et al. 2022; Sun et al. 2019). Additionally, the sewage sludges used by WWTPs could also act as another important route for microfiber to enter the environment when the sludges were piled or buried in the terrestrial environment (Liu et al. 2021; Takdastan et al. 2021).

Clothes Dryers, Face Masks, Wet Wipes, and Cigarette Butts are Emerging Sources

An electric clothes dryer is one of the important emerging sources of discharging microfibers toward the environment but is also easily underestimated (Yousef, 2021). In 2021, the global clothes dryers market grew steadily and will gradually become a common household appliance for the middle class in the next five years (Ahmadi, 2021). However, it was reported that 35 and 70 mg of microfibers could be released by 100% polyester fleece blankets when dried by two different types of domestic dryer (Kapp and Miller 2020). It is imperative to install a novel filter for the clothes dryer to capture microfiber to significantly reduce the amount of microfiber directly entering the environment (Karkkainen and Sillanpaa 2021).

The tools that human beings used for controlling the COVID-19 epidemic, may also become emerging sources of microfiber pollutants. Wearing a face mask is considered to be one of the effective ways to reduce the spread of COVID-19. Surgical masks, made of polymeric nonwoven materials consisting of polypropylene-based and polyethylene-based microfiber, were widely used worldwide. The daily face mask production and consumption have been up to 110 million, with growth at 450% in China since February 2020 (Wu et al. 2022). Worldwide, approximately 129 billion face masks have been demanded each month to effectively deal with the COVID-19 pandemic since 2020, with a 40% monthly increase (Fadare and Okoffo 2020; Prata et al. 2020). The demand for face masks is expected to be substantial during the post-pandemic period, with an estimated annual growth of 20%, from 2020 to 2025 (Singh et al. 2020). A dramatic increase in face mask production and consumption leads to a rapid accumulation of used PPEs in domestic solid waste streams. If only 1% of face masks are inappropriately disposed of, about 10 million masks, nearly 30–40,000 kg of microfibers, will be globally released into the environment every month (De-la-Torre et al. 2022; Fadare and Okoffo 2020; Torres-Agullo et al. 2021). Thus, microfiber and nanofiber from face masks will sharply increase in the Earth system in the future (Akhbarizadeh et al. 2021a).

Wet wipes with alcohol-based sanitizers for disinfection and sterilization during the COVID-19 pandemic have also been identified as a potential source of microfibers (Shruti et al. 2021). The Discarded wet wipes and disposable face masks will degrade into microfibers with the help of solar radiation, mechanical friction, and microbial corrosion (Hu et al. 2022b). Although wet wipes are not widely used as face masks for the public in the COVID-19 era, the risk of microfiber pollution caused by discarded wet wipes and other personal protective equipment cannot be neglected (Briain et al. 2020; Haque and Fan 2022).

Cigarette butts are also an emerging microfiber source. Cigarette butts are made of cellulose acetate fibers. A cigarette butt comprises more than 15,000 cellulose acetate microfibers (Shen et al. 2021). Cigarette butts will release about 300,000 tonnes of potential microfibers annually into global aquatic environments (Belzagui et al. 2021). Although the amount of microfibers released from smoked cigarette butts is relatively smaller than other discussed microfiber sources, the joint ecotoxicity of microfibers and toxic pollutants (i.e. nicotine, carcinogenic tar, and polycyclic aromatic hydrocarbons) to the environment cannot be ignored. The leachate of five smoked cigarettes dissolved in 1L of water will cause 60% to 100% mortality of four types of freshwater invertebrates within five days (Green et al. 2020). A few butts in the soil could cause decreased activity in soil-dwelling invertebrates (Gill et al. 2018) (see Fig. 2). A summary of the potential sources and the release volume of microfibers each year is demonstrated in Table 2.

Degradation offers a strategy for microfibers to mitigate microfiber pollution. Four degradation methods include photodegradation, electrochemical oxidation, thermodegradation, and biodegradation. The products of PET, PA, polyacrylonitrile (PAN), and wool include Bisphenol A, bisphenol S, benzophenone-3, and some volatile organic compounds through photocatalytic oxidation in seawater and freshwater media over ten months (Sait et al. 2021). The thermodegradation and biodegradation of the synthetic and cellulosic microfibers, especially biodegradation using functional microbial and multiple enzymes, can provide sustainable concurrent routes to producing biofuel and mitigating environmental pollution (Arpia et al. 2021; Du et al. 2021).

Microfibers in the Ocean

Microfibers are the most common types of microplastics identified in the ocean (Belzagui et al. 2019; Mishra et al. 2019; Salvador Cesa et al. 2017; Suaria et al. 2020). Microfibers in the ocean, including polyester, acrylic, polypropylene, polyethylene, and polyamide, are widely and mainly used in the textiles and apparel industry(Garlapati 2019; Mishra et al. 2019). Especially polyester fibers account for more than 50% of the collected microplastic samples (Mishra et al. 2019). Fibrous microplastics, 0.1—1.5 mm in length, are predominantly 91% of microplastics in a global marine microfiber contamination study of surface water samples (Barrows et al. 2018). Synthetic fibers released from domestic washing have ever been considered the major microfiber source in the marine environment (Belzagui et al. 2019; Salvador Cesa et al. 2017). However, fibrous materials, including various textiles and apparel, are the main sources of microfibers in the ocean, which are released during the whole life cycle of fiber production, use, care, and waste disposal (Liu et al. 2021).

Microfibers are dispersed and accumulated throughout the global ocean and are recorded in the samples from surface and subsurface seawater to deep-sea sediments and organisms. Microfibers ingestion is ubiquitous in marine organisms and biota because of their high bioavailability in benthic and pelagic habitats. Microfibers are susceptible to ingestion by a wide range of marine organisms, from zooplankton (Botterell et al. 2020, 2019; Sun et al. 2018, 2017), fish (Akhbarizadeh et al. 2020a; Neves et al. 2015), shellfish (Ding et al. 2020), reptiles (Duncan et al., 2019), and seabirds (Provencher et al. 2018) to mammals (Zantis et al. 2021). The microfiber abundance in the various tissues

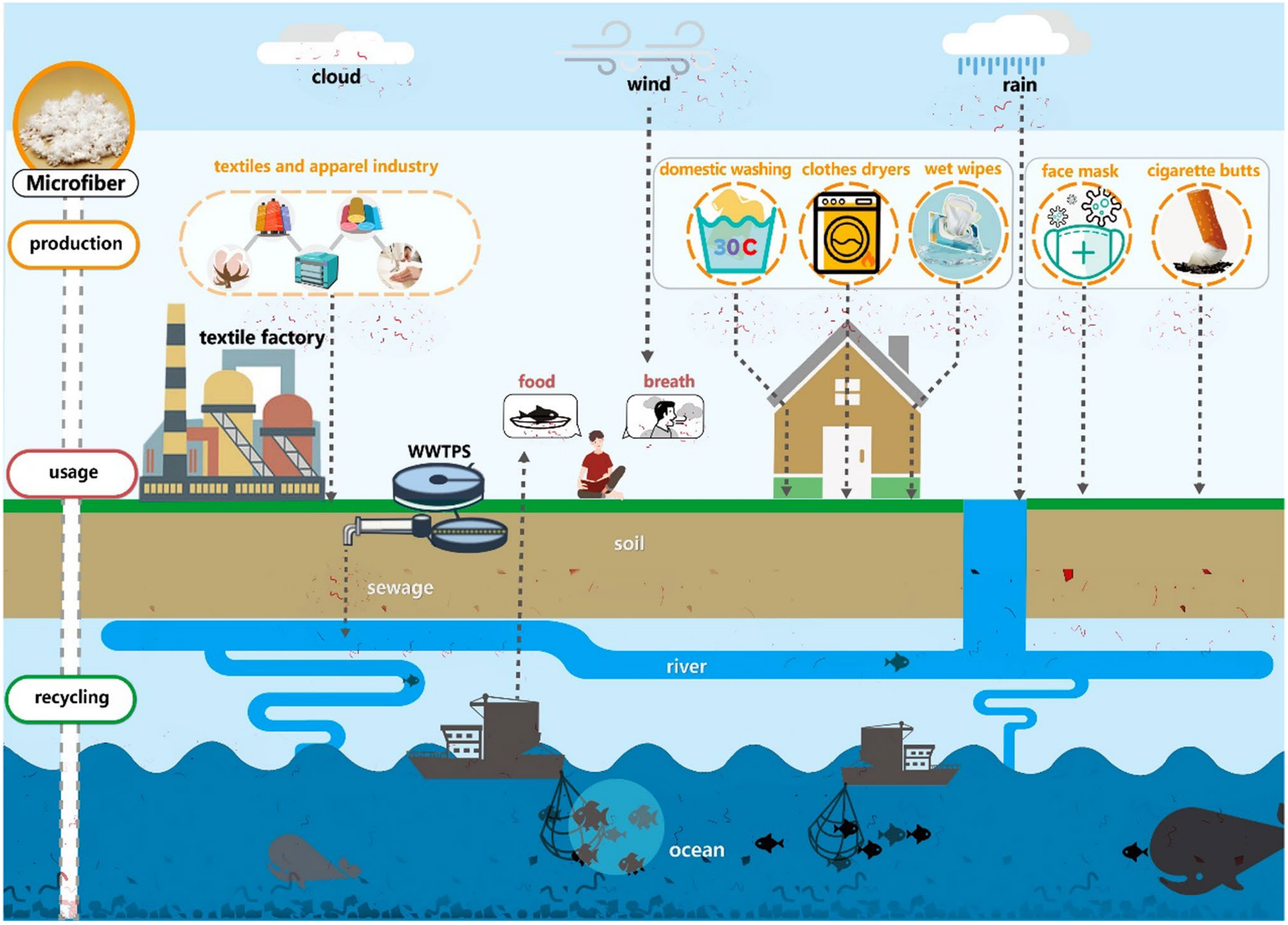

Fig. 2 The potential sources of microfibers

Table 2 Microfibers from various sources

Source	Amount of release per year	Potential harm
Domestic washing	500,000 tonnes	The harmful effects on the ocean and freshwater system
Fiber losses	1,100,000 tonnes	The harmful effects on the ocean, air, soil, and human
Clothes dryer	/	The harmful effects on the air
Face masks	360–480 tonnes	The harmful effects on the ocean, freshwater, and soil
Wet wipes	/	The harmful effects on the ocean, freshwater, and soil
Cigarette butts	300,000 tonnes	The harmful effects on the freshwater system and soil

of marine organisms was significantly correlated with those of the surrounding seawater (Sui et al. 2020). Thus, some marine organisms, such as zooplankton species, can be used as indicators of microfiber pollution in marine ecosystems (Kvale et al. 2021). The ingestion, trophic transfer, accumulation, and potentially toxic effects of microfibers in the marine ecosystem are still poorly understood (Athey and Erdle 2022). However, microfibers have properties similar to those of microplastics, which makes them have potentially negative effects on the organisms that ingest them. The surfaces of microfibers have high adsorption capacities for organic, inorganic, and mixed pollutants (Zhao et al. 2022), such as the adsorption of sulfonamides on virgin PA (Jiang et al. 2022), carcinogenic polycyclic aromatic hydrocarbons on polyester fiber (Wisniowska and Wlodarczyk-Makula 2022), and Pb, Cd, Cs, and Zn onto PE (Besson et al. 2020; Li et al. 2022b). Additionally, more than 100,000 chemical additives, such as natural and synthetic dyes, softening, ultraviolet protective, and antimicrobial and antiviral agents, have been widely used during fiber, yarn, and fabric manufacturing or finishing processes to endow some special functional properties to textiles, for example, dope additives, including but not limited to plasticizers, dyes, pigments, fire retardants, and UV absorbers, which might be ecotoxic. Considering that microfibers in the marine environment are the reservoirs for antibiotic, metal-resistance genes (Akhbarizadeh et al. 2020a) and microbial communities (Mishra et al. 2022; Yang et al. 2019), the toxic substances adhering on or released from microfibers may threaten the survival, feeding, and fecundity of marine organisms, and represent a great risk for marine biodiversity (Guzzetti et al. 2018; Vroom et al. 2017).

Although rivers and urban runoff are implicated as major pathways of microplastics and microfibers transporting to marine environments (Gago et al. 2018; Hajiouni et al. 2022; Wang et al. 2022), the transportation of fibrous materials from land to coastal areas and deep ocean is still poorly understood. Atmospheric transport, that is, wind entrainment, has been proposed to be a novel pathway for microfiber movement, although only a handful of related studies have been carried out. Microfibers are preferentially transported to a longer-range or global scale by wind entrainment and erosion because of its smaller size and lighter density compared to plastic microbeads and fragments (Bullard et al. 2021). Microfibers were found in most samples, accounting for 92%, through atmospheric deposition in central London with higher deposition rates of up to 1008 fibers/m^2/d (Wright et al. 2020). Atmospheric microfiber transport has been considered a significant pathway for microfiber to the ocean from the indoor origin in times of favorable wind speeds and trajectories (Brahney et al. 2020; Kash et al. 2022). It was estimated that 7.64–33.76 tonnes of microfibers were globally generated in 2018, constituting a great proportion of ingestible solid pollutants in the ocean air and marine ecosystem (Il Kwak et al. 2022; Li et al. 2022a; Liu et al. 2020). Furthermore, sea ice is also considered an important temporal transport for microfiber in the Polar regions, which is transported by oceanic currents in different seasons (Peeken et al. 2018).

Mathematical modeling provides an effective means to explore the transport mechanism of microfiber in the aquatic environment. Liedermann et al. proposed to measure microplastic transport in large or medium rivers using a net-based device with different net sizes exposed in three different depths (Liedermann et al. 2018). Sheerman and Sebile proposed a model based on satellite-tracked buoy observations to simulate the transport of plastic floating on the ocean surface from 2015 to 2025 (Sherman and van Sebille 2016). Choi et al. proposed an orientation-dependent drag model, considering the secondary motion, toward realistic predictions of microfiber transport in aquatic environments (Choi et al. 2022). Mathematical modeling provides an effective means to explore the transport mechanism of microfiber in the aquatic environment. Through a systematic review, Uzun et al. deduced that more reliable results are obtained using hybrid methods, especially the coupling of hydrodynamic and process-based models and hydrodynamics and statistical models (Uzun et al. 2022). The research on the microfiber transport mechanism is limited. In the future, more data in longer periods and a variety of properties of microfibers are required to increase the robustness and accuracy of mathematical modeling of microfiber transport in the aquatic environment.

Microfibers in the Atmosphere

Microfiber released from the various textiles and garments production, including spinning, weaving, dyeing, cutting and sewing, shedding from clothing during normal wear and laundry drying, emissions from outdoor textile sports equipment, and discarded textiles, are the principal sources of microfibers in the atmosphere. Though synthetic microfibers have been widely reported as the majority of microplastic pollution in the air, natural fibers also constitute a more significant proportion of the atmospheric pollutants transported by wind and rain (Rochman and Hoellein 2020; Stanton et al. 2019). Furthermore, some research indicated that atmospheric microfibers are dominated by natural and regenerated cellulosic fibers instead of synthetic fibers (Finnegan et al. 2022; Li et al. 2020). Microfibers in the atmosphere will lead to direct respiratory exposure to human health, especially for textile and clothing factory workers. Recent research indicated that at least 13,000 to 68,000 household dust microfibers have been inhaled from textiles per year (Catarino et al. 2018). Additionally, several additives, such as inorganic salts, metal nanoparticles, and natural and synthetic macromolecular substances, will release from microfiber into the atmospheric and aquatic environment as environmental hormones (Lin et al. 2018). The desorption of fiber additives in the atmosphere, such as disperse dyes, UV stabilizers, and degradation products, is the most important contact allergen in textile dermatitis (Malinauskiene et al. 2013; Sait et al. 2021). Exposure to mixed airborne microcontaminants, including fine particulate matter ($PM_{2.5}$) microfibers and polycyclic aromatic hydrocarbons, will increase the cancer risk in winter (Akhbarizadeh et al. 2021b).

The low density, moderate length, natural or artificial crimp, and greater surface-area-to-volume ratios of microfibers compared with plastic microbeads and fragments facilitate their wind entrainment and regional transport from 10 to 1000 km (Brahney et al. 2020), which means the atmospheric environment is also an important pathway to spread microfiber pollution. Especially dry microfibers are susceptible to atmospheric conditions, mainly contributing to the longer-ranger or global transport rather than regional areas through several suspension-deposition cycles for years (Brahney et al. 2020). Though high-altitude winds and rainstorms have been considered the main forces that transport and circulate atmospheric microfibers globally, the route of microfibers to the atmosphere and the transport pathway with air have not been clarified. Applying concepts and methods from geosciences will accelerate our understanding of the mechanism of atmospheric pollution of microfiber, the fate of microfibers in the atmosphere, and how microfibers affect air quality (Stubbins et al. 2021).

The Potential Human Exposures

Indoor and outdoor dust ingestion has been reported as human exposure pathways to microfibers of great magnitude (Dris et al. 2017). The highly concentrated microfibers have been detected in indoor dust, accounting for 88.0% of microplastics ranging from 1550 to 120,000 mg/kg (Liu et al. 2019a). The daily exposure for adults was 64.1 fibers/kg-bw/day, while a daily exposure risk of 889 fibers/kg-bw/day for infants and indoor dust accounted for 97% of the total exposure (Liu et al. 2019a). The daily exposure risk of microfibers for infants was more than ten times that of adults, likely due to increased dust ingestion caused by crawling behavior and the higher frequency of nibbling behavior of hands, feeding bottle, plush toys, and clothes (Liu, 2022). The potential pathways of microfiber exposure for infants are demonstrated in Fig. 3. The quantitatively instrumental analysis of polyethylene terephthalate (PET) and polycarbonate (PC) microplastics in infant and adult feces also supports the daily exposures from the diet of an infant are significantly higher than those of adults (Zhang et al. 2021). Common microfibers or microplastics, such as PET, PE, and PP have also been detected in human stool, placenta, and meconium in some clinical cases (Braun et al. 2021; Nor et al. 2021; Schwabl et al. 2019). The latest research indicated that common polymers applied in fibrous materials, such as PET and PE are bioavailable in the human bloodstream within nano-size, and the sum quantifiable concentration in blood was 1.6 μg/ml (Leslie et al. 2022). The microplastic beads ranging from 1 to 10 μm lead to significant mechanical stretching of the lipid membranes without inflammatory reactions and serious dysfunction of the cell machinery (Fleury and Baulin 2021). Correspondingly, the negative effect of microfiber on the micro-nanometers size of

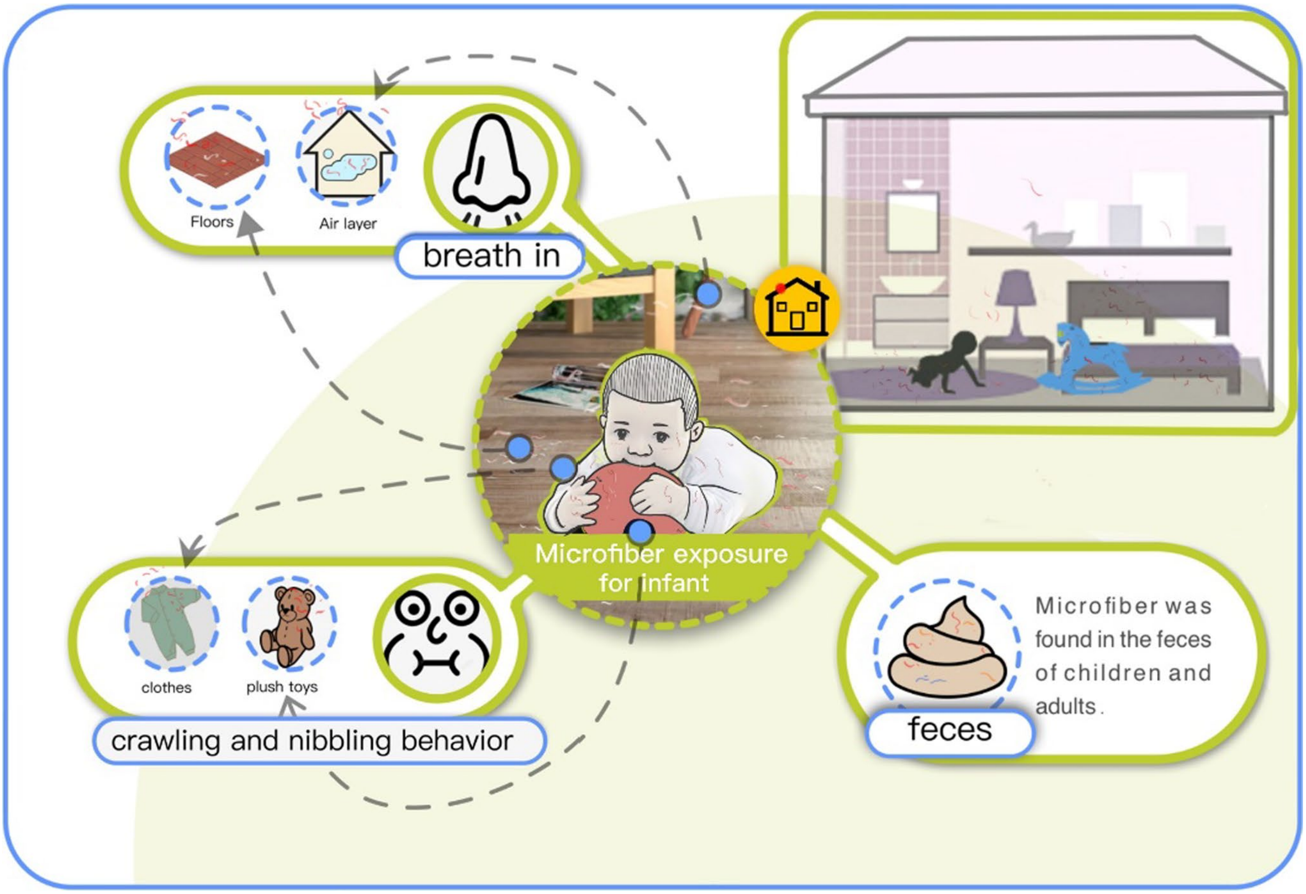

Fig. 3 The potential pathways of microfiber exposure for infants

cell membranes and their physiological toxicity of additive chemical content on the human digestive system should be experimentally and theoretically studied.

Inhalation and ingestion are the two main pathways for daily human exposure to microfibers. For inhalation, the significant correlation between microfiber exposure and the occupational health of textile workers has been confirmed in massive clinical cases (Hussain et al. 2019; Karanikas and Hasan 2022; Lai and Christiani 2013; Too et al. 2016). Long-term and high exposure to organic dust containing hemp and cotton microfiber through inhalation and skin contact has negative effects on textile workers' byssinosis, respiratory diseases, allergies, and epithelial growth (van Dijk et al. 2020; Zele et al. 2021). A cross-sectional study in Pakistan has indicated that 35.6% of textile workers suffer from byssinosis, especially those in spinning and weaving mills exposed to a higher density of microfiber (Memon et al. 2008). The worldwide prevalence of byssinosis among textile workers is up to 40% (Murlidhar et al. 1995). Particularly in low/middle countries, byssinosis has been a basic occupational disease for textile workers. Respiratory diseases, including reversible or irreversible obstructive lung diseases (i.e., asthma or chronic obstructive pulmonary disease), and restrictive lung diseases, are prevalent in textile workers (Lai and Christiani 2013). Polypropylene and polyethylene terephthalate fibers (≤ 3 μm) were most abundantly identified using μFTIR spectroscopy in all regions of 13 human lungs collected from thoracic surgical procedures at Castle Hill Hospital in the United Kingdom (Jenner et al. 2022). Microfibers are reservoirs for additive chemical content (Sait et al. 2021), volatile and semivolatile organic compounds, bacteria, and fungi in indoor and outdoor environments, acting as selective pressure within developing respiratory and gut microbiomes (Gardner et al. 2020) (see Fig. 4).

Microfibers have been documented in the digestive tract, gills, and the select internal organs of commercial marine species such as bivalves, crabs, and fish (Dawson et al. 2021). Therefore, seafood has been regarded as the main transfer pathway of microfibers to humans by the public. However, the tissues are always discarded instead of eaten by seafood consumers. Drinking water (Akhbarizadeh et al. 2020b; Gouin et al. 2021; Zhang et al. 2020), and salt (Peixoto et al. 2019; Zhang et al. 2020) are other ingestion ways for microfibers to enter human bodies. The exposure data, adsorption model, and health risk evaluation of microfiber in humans are inadequate. The adverse health effects on humans at different levels, including cytotoxicity, immune response, oxidative stress, and barrier attributes of microfibers of human cells, are still unknown (Danopoulos et al. 2022).

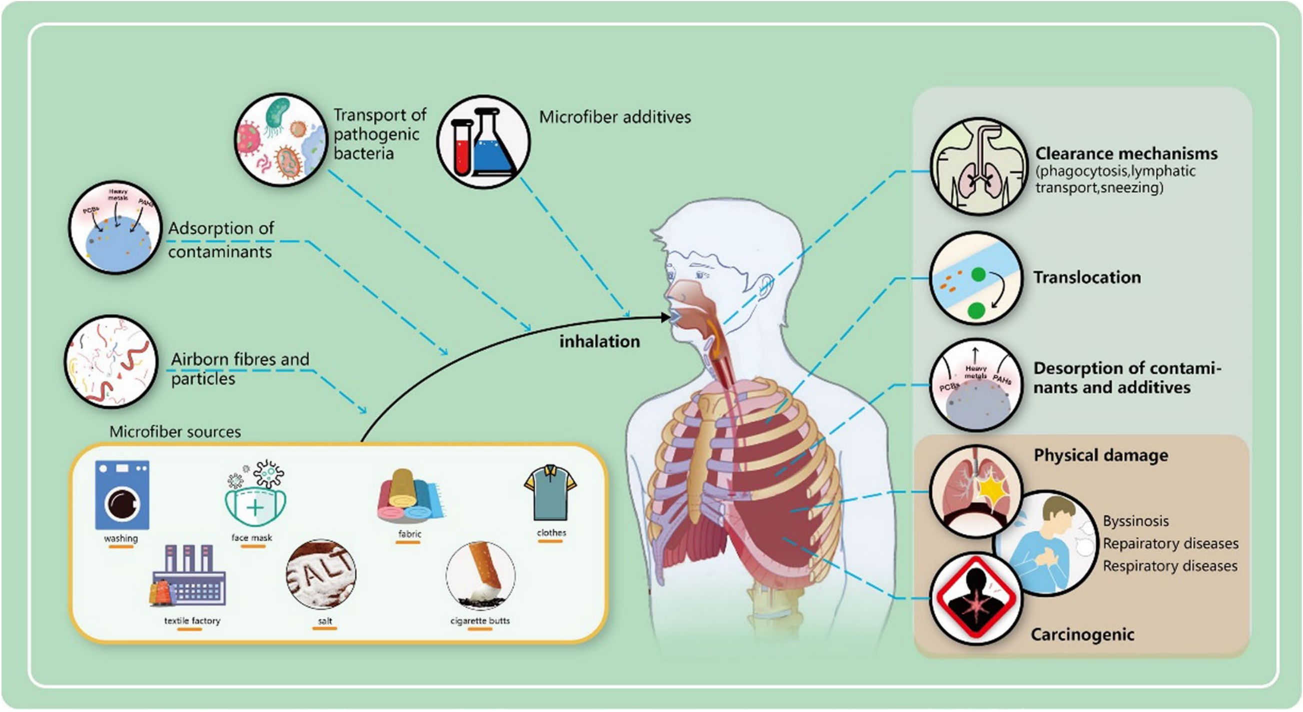

Fig. 4 Implications of microfibers inhalation and possible consequences in the human respiratory system

The Way Forward

At present, the abundance, distribution, and mechanism of environmental microfiber pollution are still unclear, which makes it difficult for stakeholders and the public to pay attention to the management of microfiber. In recent years, with the increasing exposure to microplastic pollution in mass media, relevant practitioners began to focus on the problem of microplastic fiber pollution. However, it should be clarified that microfiber is not directly equivalent to microplastic fiber. Microfiber sometimes refers to a wider group of materials than microplastic fiber. Therefore, it is necessary to study and understand the short-term, medium-term, and long-term mechanisms of microfiber pollution, and gradually realize the management of microfiber pollution in industry and daily life.

A Binding Global Agreement

In February 2021, an international agreement to combat plastic pollution has been proposed by many governments at the fifth summit of the United Nations Environment Assembly (UNEA) (Simon et al. 2021). A draft resolution on a global binding to reduce the discharge of plastics throughout the plastic life cycle has been negotiated at the UNEA5.2 on March 2, 2022. An internationally legally binding agreement to effectively curb increasingly serious plastic pollution will be a historic initiative and advance for humans. However, the plastic pollution problem mentioned in the agreement has not specifically included microfiber pollution, although more than 35% of microplastics are fibers coming from textiles. If the microplastics from textile sources are included in the draft resolution to be further negotiated at the UNEA5.2 framework in 2024, urgent actions on plastic and microplastic pollution will be strengthened within a more comprehensive scope through more holistic and prospective responses.

Legislation on Microfiber Pollution

Since February 2020, all newly sold washing machines are mandated to be equipped with a microfiber filter by 2025, which has already been adopted under a France law (Sánchez 2020). France is the first country in the world to reduce and control microfiber pollution from laundry through regulations. The experience of France shows that it is feasible to manage microfiber pollution by legislation. While controversially, France's legislation in the field of microfiber pollution is a viable response to the severe environmental and ecological problem. It is foreseeable that microfiber pollution will be legislated on a much broader level. As discussed in previous sections, the most important source of microfibers in the environment is not domestic laundry but the waste and wastewater produced in the relevant industrial production processes. Therefore, future legislation must focus on microfiber emission events in industrial production. It requires a quantitative evaluation and a lamination of the microfiber discharge from a technical point of view.

Development of Technical Standards on Microfiber Pollution

Some voluntary, consensus-based, or mandatory standards related to microplastics from textile sources will be developed to provide solutions to microfiber pollution. In 2022, the ISO/TC 38 subcommittees dealing with the sampling and measuring material loss for microfibers from textile end-products by domestic washing method, and the qualitative and quantitative evaluation of microfiber from domestic washing, approved the development of three technical standards on microplastic from end textile products (ISO 2021a, b, c). The implementation of measurement and quantitative evaluation standards on microplastic from textile sources will accelerate the innovation of fiber and yarn production, and the design evolution of fabric and clothes. A broad range of stakeholders of the textile and clothes chain including, but not limited to, the textile and fashion industry, and washing machine manufacturers, look for and promote solutions using strategic and tactical interventions throughout the full fibrous material lifecycle. In the future, a series of technical standards and guidelines will be amended and issued at multilevel in a bid to regulate the design and production, reuse, recycling, disposal, and retrieval of textiles and clothing (Simon et al. 2021).

Addressing Microfiber Pollution Through Circular Economy

The global annual textile consumption has reached up to 100 million tonnes, while only 15% was recycled in the last two decades (Shirvanimoghaddam et al. 2020). The disposal nature of fast fashion and "throwaway culture" in a linear economy has directly contributed to a large amount of textiles wastes (Bucknall 2020). However, this leads to not only a huge loss of valuable resources but an ever-increasing environmental problem. A circular textile economy provides a new approach to reducing textile waste and mitigating microfiber pollution. In general, reuse and recycling can maintain fibrous materials at their highest value and reduce environmental impact compared to traditional ways, such as landfills and incineration. The reuse of aged but wearable clothes, such as cotton clothes and synthetic fiber fashion without aging, through the sale of secondhand goods, is more beneficial than recycling (Cao et al. 2022; Sandin and Peters 2018). A circular textile economy, especially for some major textile and clothing production countries in Asia and Africa, will trigger and promote the adjustment of the textile value chain from a sustainable development perspective. Meanwhile, the circular textiles economy will drive advances in next-generation fibrous materials design from the environmental and ecological dimensions, increasing their end-of-life value in the long-term.

Conclusions

As an emerging pollutant, microfibers are now generally categorized as a dominant type of microplastics. In the future, microfibers will be systematically studied as an independent type of pollutant instead of a subgroup of microplastics. The knowledge gaps remain about the potential source, transport pathway, spatial distribution, environmental toxicity and fate, and risk of microfiber to ecosystems on the Earth. Microfiber, a suite of synthetic polymers intentionally created for the benefit of humans, is still being explored through holistic approaches to the extent that they are harming organisms and ecosystems on the Earth. However, we must urgently address the full lifecycle of microfiber, given the scale of microfiber pollution and our increasing levels of microfiber consumption.

In this review, microfiber as an environmental pollutant is defined. Some underestimated sources of microfiber are discussed. The potential human exposure to microfiber is summarized. Moreover, some feasible measures to migrate microfiber pollution are proposed.

(1) An extensive definition of microfiber as an emerging contaminant was proposed, including both natural and synthetic fibers. Considering that microfibers and microplastic fibers have many various commonalities, thus, it is necessary to further recognize the microfibres in the textile area from ecological and environmental perspectives.
(2) The potential sources of microfiber have been explored in different scenarios. Although domestic washing was always identified as the primary source, fiber losses in the textiles and apparel production processes have been identified as the main source that cannot be neglected and underestimated. We have also pointed out that clothes dryers, face masks, wet wipes, and cigarette butts are emerging sources.
(3) Atmospheric microfiber transportation is also identified as a significant pathway for microfiber to the ocean from its indoor origins, although rivers are implicated as major pathways of microfibers transport to marine.
(4) The research on the environmental impact of microfiber on organisms and ecosystems is just beginning. Inhalation and ingestion are the two main pathways for daily human exposure to microfibers. Textile workers' exposure to microfiber at high doses and for long periods can cause respiratory disease.
(5) Some feasible measures to mitigate microfiber pollution from the global perspective are also suggested, including global management of plastic pollution from textile sources, technical standards for microfiber pollution, and a circular economy pattern to reduce textile waste and mitigate microfiber pollution.

Future Outlook

It will be a difficult and long way to eliminate microfiber pollution. The research about the systematic source, patterns, and processes of microfiber transport around the globe could last for years, let alone the medium to long-term effects of microfiber pollution on environments and humans. However, despite the growing research on microfiber pollution, this field still has some limitations. The future directions included but were not limited to the followings,

(1) Collaborative research on the mixed micro-nano pollutants, including microplastic, microfiber, suspended fine particulate matter (PM2.5), polycyclic aromatic hydrocarbons (PAHs), heavy metals, and other emerging contaminants will reveal the real environmental risk and effects on human.
(2) The realistic and theoretical modeling of microfiber abundance, distribution, transport, and accumulation in aquatic, atmospheric, and marine-atmosphere environments will assess the feasibility and efficiency of migration methods.
(3) The industrial application of microfiber in energy and architecture will provide a sustainable concurrent approach to producing biofuel and fibrous composites and mitigating microfiber pollution.

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Declarations

Conflict of interest The authors declare that there is no conflicts of interest.

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