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*Review*

# Microfiber Fragment Pollution: Sources, Toxicity, Strategies, and Technologies for Remediation

**James McCay and Sunidhi Mehta** *

Davis College of Agriculture, Natural Resources and Design, West Virginia University, Morgantown, WV 26505, USA; jtm0003@mix.wvu.edu
* Correspondence: sm00038@mix.wvu.edu

**Abstract:** With the pervasive consumption (currently >65% of total market shares and steadily increasing) of petroleum-derived synthetic textiles, the escalating concern of microfiber fragment (MF) pollution has emerged as a formidable menace to our ecological equilibrium. Over the lifetime (pre- and post-consumption) of these textiles, they shed tiny fibers recognized as MFs. These MFs are carriers of persistent organic pollutants and have been linked to cytotoxicity, oxidative stress, and genotoxicity, even at minimal exposures via air and water sources. Grounded in the state-of-the-art literature, this review discusses the primary and secondary sources of MF release, their fate, transport, environmental impacts, and novel technologies for MF pollutant remediation. Our results infer that MF pollution is a multifactorial issue with serious environmental and public health implications, as studies reported their presence in human blood, feces, and urine samples. We recommend a multifaceted approach to increase sanitation coverage, ensuring adequate wastewater treatment prior to environmental discharge for MF pollution mitigation. Additionally, transformation is warranted for consumers' use, care, and purchase behavior of textile products. Government regulation of fast fashion (a major user of synthetic textiles), exemplified by recent French legislation, is essential to preventing microfiber pollution. We urge similar policy-making efforts globally to safeguard public health.

**Keywords:** microplastics; microfiber fragments; environmental pollution; water pollution; textile sustainability; synthetic textiles

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## 1. Introduction

Microplastic pollution (MP) stands as a prominent anthropogenic challenge in the contemporary world [1]. Human activities are rapidly disrupting freshwater reservoirs and natural ecosystems, polluting water bodies with extensive quantities of diverse contaminants [2]. These include organic substances like pharmaceutical residues, dyes, plastics, and pesticides, as well as inorganic pollutants such as heavy metals, all being discharged into aquatic environments [3]. The detrimental impacts of MP pollutants (stemming from diverse sources) on human health still remain elusive to humankind; nevertheless, our comprehension of the serious environmental consequences of these pollutants is considerable enough for us to act against them. Among the broader category of MPs, the microfiber fragment (MF) pollution originating from manufacturing and uses of petroleum-based synthetic textiles is the least understood to date. Liu et al. [4] define MFs as "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". Due to their minuscule size (less than 5mm in any direction), the MFs released during routine home laundering often remain unnoticed and even escape filtration in wastewater-treatment plants [2].

Synthetic textiles are known to persist in the environment for extended periods due to their highly crystalline morphology and mechanical strength [5]. Poly(ethylene terephthalate), or PET, which is commonly recognized as polyester, dominates the synthetic textile market and constitutes roughly 84% of its share [6], as noted in Figure 1. PET is either used as a pure or blended fiber in the apparel industry; conversely, elastane, which shares about 1.6% (Figure 1) of the synthetic fiber market share, is always blended in small proportions with both natural and synthetic textiles. These synthetic textiles are notorious for their poor biodegradability and thereby have the propensity for waste.

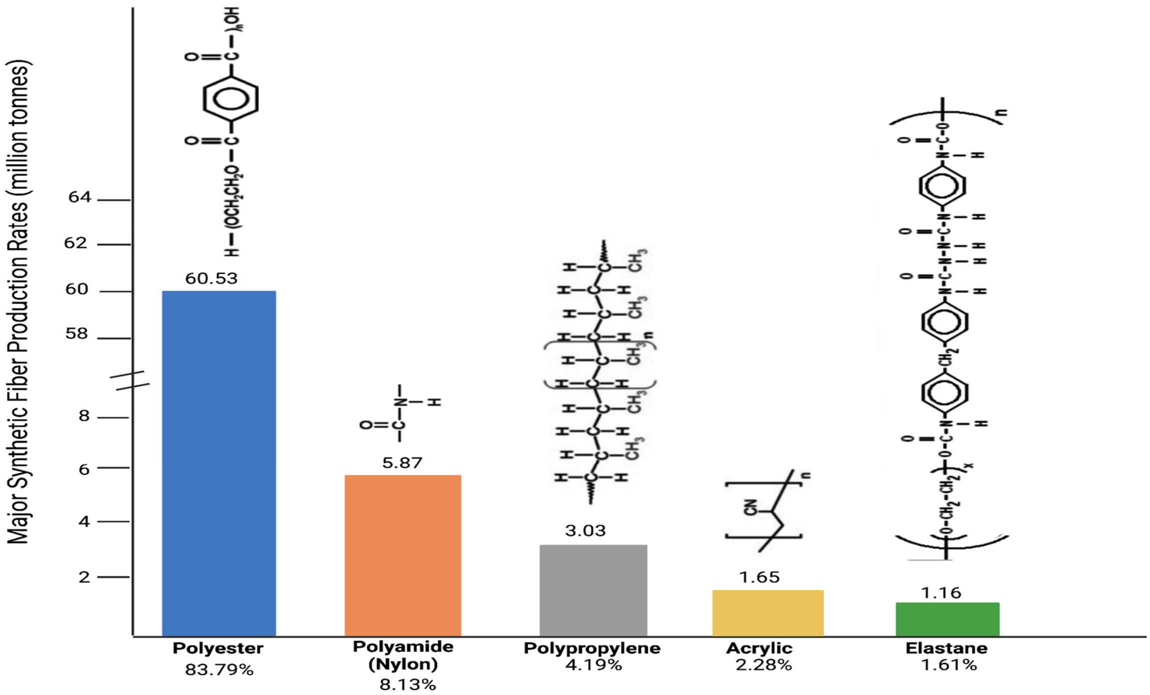


**Figure 1.** The market shares and chemical structures of the most popular synthetic polymers used in the textile industry. The source for statistical figures is the latest annual report published by Textile Exchange [6]. Accumulation [5]. PET textiles alone are responsible for 35% of the total MP in aquatic ecosystems [7], with the remaining 65% attributed to other sources of MP such as personal-care-product packaging, fishing and aquaculture, agriculture, road transport, plastic manufacturing, and tourism industries [7].

The fast-fashion industry relies heavily on the use of synthetic textiles (especially PET) due to their cost-effectiveness, perpetuating the cycle of disposable clothing. The fast-fashion market, characterized by its rapid trend turnover, fosters the production of inexpensive, low-quality garments designed for short-term use, leaching out MF pollutants into the environment upon disposal. These ephemeral styles are quickly discarded by consumers after minimal use, which has contributed to the overaccumulation of synthetic textile waste [5,8]. To combat this issue, France's lower house of parliament unanimously passed legislation (as announced earlier this March) targeting ultra-fast-fashion brands like Shein and Temu from China. The legislation is anticipated to soon become a law and proposes a phased escalation of fines, potentially reaching 10 euros (~$11) per garment by 2030, along with prohibiting advertising for ultra-fast-fashion products [9]. Legislature efforts like these are commendable and are in support of (or at least control, if not) mitigating the climate change threats posed by the textile industry.

Upon entering the aquatic systems, all MPs (including synthetic MF pollutants) accumulate and biomagnify within the food web, posing a threat to lower trophic level organisms, such as invertebrates, and subsequently affecting aquatic organisms through predation [10]. As a part of their manufacturing process, plastics include a suite of additives such as plasticizers, crosslinking agents, flame retardants, and synthetic pigments, etc., for enhanced aesthetics and functionality. Therefore, MPs and MFs emanating out from various plastic products may serve as carriers of phthalates [11], polychlorinated biphenyls (PCBs) [12], per-fluoro-alkyl-substances (PFAS) [13], and heavy metals [14–16] leaching into the environment. Human blood samples have revealed exposure to these toxic compounds through ingestion, transdermal contact, and through the food chain [17]. Consequently, the European Union's Action Plan 'Towards Zero Pollution for Air, Water, and Soil' aims to achieve a 50% reduction in plastic litter at sea and a 30% reduction in MPs by 2030 [7,15]. Similarly, United Nations Sustainable Development (UN SDG) target # 14.1 aims at significantly preventing marine pollution, including plastic debris in water bodies, by 2025 [18].

This global commitment to MP mitigation has propelled increased attention among researchers in the last few decades. In this review, we sense an urgency in the research and development (R&D) of scientific solutions aiming at preventing and mitigating MP (and MFs) and their impact on aquatic organisms as a paramount priority for public and environmental health. We present state-of-the-art research on the release of synthetic MFs, including their sources, mitigation strategies, and the novel innovative treatment mechanisms currently employed as well as in the R&D phase. Based on the key research gaps identified through this literature review, we also suggested preventive strategies for the remediation of MF pollution. We anticipate that this information will be utilized in policy making and further research in this field to lower the environmental impact of MF pollution on our biosphere.

In the subsequent sections, we discuss the issue of increasing global textile production rates and associated MF pollution related to their use and disposal.

### 1.1. Current Trends in Textile Production

In the year 2022, global fiber production reached an unprecedented pinnacle, registering a remarkable 116 million tons with a projected growth of ~150 million tons by 2030 with the business-as-is approach (Figure 2) [6]. As per the Textile Exchange's 2023 annual report, the synthetic fibers, which are renowned for their exceptional performance and functionality, asserted dominance in the worldwide fiber market, contributing a cumulative output of 75.4 million tons in 2022. This signifies a substantial 65% foothold in the global fiber market, surpassing the combined share of natural fibers sourced from organic origins and man-made cellulosic fibers, which collectively accounted for only 28.6% and 6.3%, respectively (Figure 2) [6].

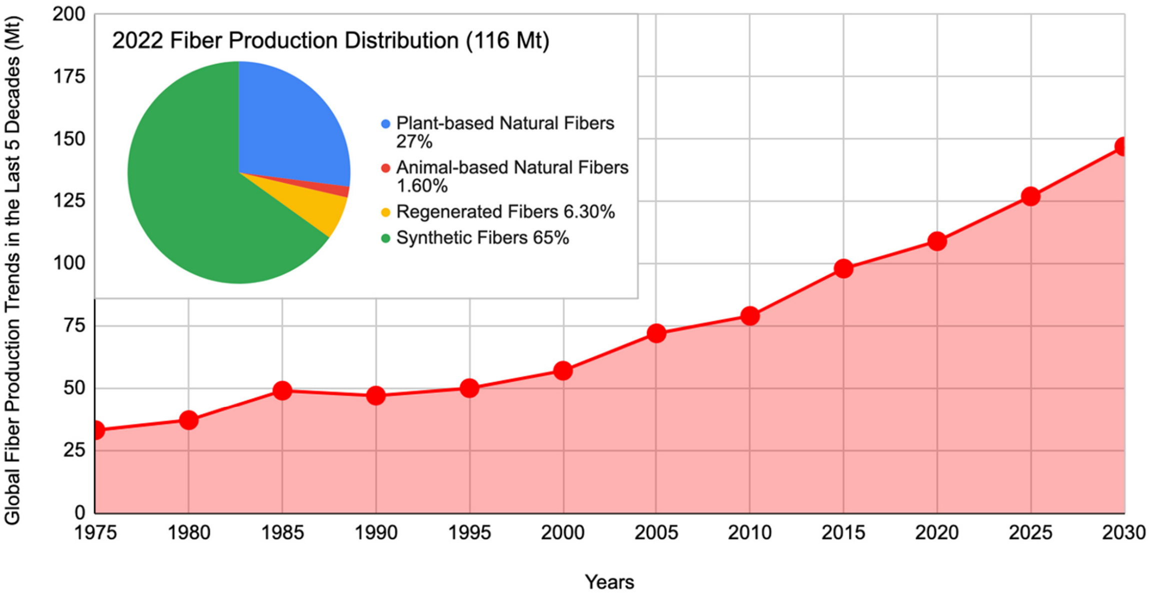


**Figure 2.** Increasing trend in overall global fiber production rates in Mt (million tons) from 1975 to 2022 with estimated projection through 2030. The inner pie chart shows the overall market share of each of the main fiber categories [6].

In light of the pervasive use of synthetic fibers in textile manufacturing, the textile industry emerges as a prominent contributor to the issue of MP [19–21]. The existing operational framework within the fashion industry, characterized by the encouragement of excessive consumption [5], is poised to further exacerbate this environmental challenge. As discussed previously in the Section 1 of this paper, the apparel industry's shift towards fast fashion, characterized by high volumes of low-cost clothing, is significantly shaping consumer purchasing behaviors. This trend fosters impulsive buying tendencies and a perpetual desire for new trends. In turn, this leads to adverse environmental impacts associated with excessive production and consumption rates and the improper disposal of apparel and further exacerbates MF pollution in the aquatic environments.

### *1.2. Environmental Toxicity of MF Pollution*

Textiles composed of natural fibers have exhibited a higher propensity for shedding fiber fragments, as documented by De Felice et al. [22], Sillanpää and Sainio [23], and Zambrano et al. [24]. However, natural fiber fragments are considered (relatively) environmentally benign due to their inherent biodegradability as opposed to petroleum-based synthetic textiles that tend to bioaccumulate in the environment [5,22–24]. There are several biotic (microorganisms such as bacteria, protozoa, fungi, etc.) and abiotic (such as sunlight, temperature, water, etc.) factors that lead to the biodegradation of textiles [5,24]. Recycled fibers, a relatively new category in the realm of textiles, contribute to the establishment of a more circular fashion supply chain. However, they often exhibit significantly higher MF-shedding behavior [25] during laundering compared to textiles made from virgin synthetic fibers. This increased MF-shedding behavior is attributed to the lower tensile strength of the recycled fibers [26]. Several studies concluded that virgin PET fibers are known to have a higher mechanical strength and crystallinity compared to recycled PET fibers [27–29].

In addition, the amplified use of chemicals (including toxic chemicals) is prominent in the textile industry. All types of textiles including natural fibers are susceptible to chemical treatments that impede their natural degradation [5,30]. Regrettably, natural fibers often necessitate an increased application of chemical finishes to attain the desired performance characteristics of their synthetic counterparts. Typical finishes encompass softening agents, dyes, anti-wrinkle treatments, and water-repellent coatings [31]. These enhance fabric performance and resist the deterioration of fabric quality due to usage and washing. However, these chemical treatments may linger upon shredded MFs, impacting human health and the environment [32,33]. The reactive dyes used for cellulosic fibers contain anthraquinone, which is known to cause genetic mutations and acute toxicity [34]. Additionally, disperse red 1 and disperse orange 1, common dyes for polyester, are toxic and even considered carcinogenic at higher concentrations [32], posing serious hazards to aquatic environments and eventually leaching through the food chain.

The oceans, where MP and MFs tend to accumulate in the highest concentrations, raise concerns for marine life and aquatic organisms [31]. MFs have been detected in various oceanic levels, including beaches, surface waters, water columns, and deep seafloors [35,36]. Due to their micron size, the MFs are frequently ingested by smaller marine life, particularly marine invertebrates crucial to food chains [36]. The ingested MFs accumulate within the organisms and resist digestion, leading to starvation [36,37]. They can also carry toxic contaminants on their surfaces, potentially causing diseases and fatality upon ingestion [37]. Furthermore, the nanoscale plastics, as demonstrated by Mattsson et al. [38], can infiltrate the brains of fish due to their acutely small size inducing, significant behavioral changes. While some health impacts of MP and MFs on marine organisms are known, further research is imperative for a comprehensive understanding of these impacts.

## 2. Sources of MF Emissions into the Environment

### *2.1. MF Release during Home Laundering*

In the typical lifecycle of a garment, the use and care stages put the garment through several physical stresses that can cause fibers to break down, come loose, and become transported to the garment's surface. The severity of the impact depends on several factors including fiber length, chemical composition, the mechanical strength of the fiber, yarn twist and diameter, fabric construction, and chemical finishes [39–41]. Additionally, care procedures followed by the users, and normal wear and tear, can also influence a garment's reactions to mechanical stresses [42,43]. Due to the agitation combined with water temperature and chemicals used in the laundering process [44], they weaken and ultimately loosen tiny fibrils, which can get released to the water effluent during the washing process. Based on the literature reviewed, we summarized the key factors that impact MF shedding in the order of their impact in Figure 3.

Several studies showcased the release of varying amounts of MFs into laundering effluent [23,45,46]. A typical consumer laundry cycle often consists of a mixture of different textiles that release fragments of natural and synthetic fibers [23,24,45]. The fiber type and the length of fibers can have a large impact on the release of MFs from a textile product. For example, textiles made from natural staple fibers such as cotton have been found to release more MFs than synthetic fibers such as polyester [22–24]. This can be attributed to the lower tensile strength and shorter/staple length that natural fibers like cotton exhibit [24,43,47]. Despite a relatively higher tendency for fiber-fragment shedding, natural fibers typically undergo biodegradation at higher rates compared to their synthetic counterparts, thereby aiding in reduced longevity and persistence in the environment.

Yarn thickness and hairiness can influence MF shedding during laundering. A study conducted by Periyasamy [48] suggested that yarn hairiness causes an increase in MF shedding due to loosely twisted fibers in a yarn strand to achieve the hairiness effect. These tiny fibrils get entangled to form pilling on the fabric surface during regular use, which can also shed during laundering [48,49].

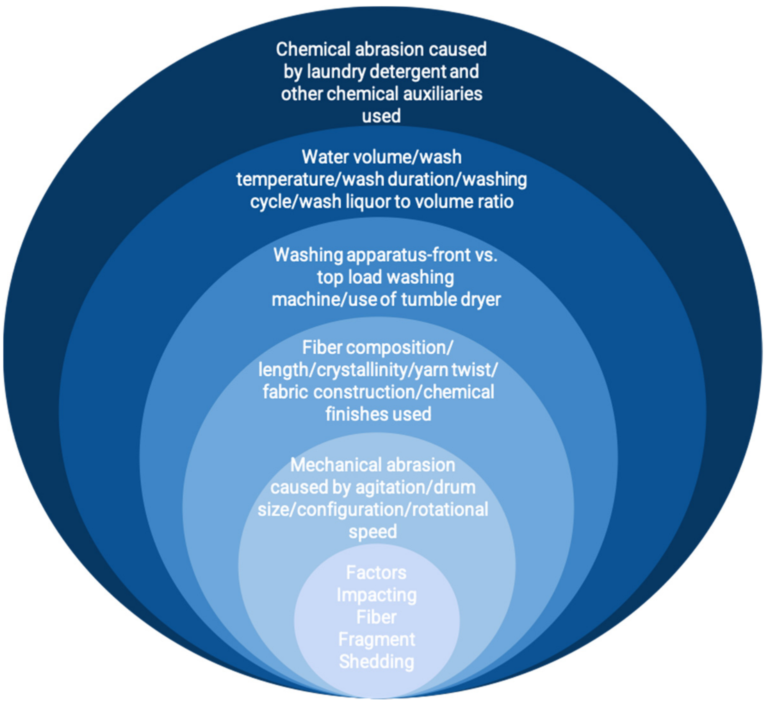


**Figure 3.** Key factors impacting MF shedding during the laundering process. The factors are presented in the order of impact, with the highest impact factor being closest to the figure core and the lowest impact factor being the farthest [31,39,40,42,43,45,50–56].

Similarly, fabric characteristics such as construction type and thread count have also been found to influence MF shedding. A study by Carney et al. [44] found that textiles with relatively looser fabric constructions tend to shed more MFs per wash compared to fabrics with tighter constructions. The study found loose-knit fleece to shed an average of 1210 ± 96 MFs per 100 $cm^2$ of fabric in comparison to the 9 ± 7 MFs per 100 $cm^2$ of fabric released by tighter-knit fabrics [44]. Additionally, researchers found that thicker fabrics tend to shed more fibers due to a higher yarn count per surface area [47,50].

Additionally, as reported by several research studies, the laundering apparatus affects the amount of MF shedding [24,44,57]. Many studies used accelerated laundering methods using simulated laundering devices such as Gyrowash [44,58,59]. Such devices use steel balls to create agitation for the textiles, which results in a higher release of MFs than typical domestic laundering [24]. Zambrano et al. [24] found that accelerated laundering machines generated approximately 40 times as many MFs per mass of fabric as home laundering machines [24]. Other studies have used different models of domestic washing machines in their experiments [51,60–62], which are used for home laundering. These laundering machines use large amounts of water and have more surface area within the washing drum, making MF recovery more difficult [24]. Thus, the type of laundering apparatus plays a huge role in MF release research.

Apparently, conflicting conclusions have been reported when it comes to the impact of detergent on MF shedding. Some studies test the release of MFs during laundering without the use of detergent [22,63,64], with liquid detergent [39,40,44], and with powder detergent [45,51]. Many research studies [39,40,51–53] reported the use of detergent increased the amount of MF shedding, while Cesa et al. [54] found that the use of detergent decreased the amount of MFs shed. These conflicting results could be caused by differences in methodologies followed and the laundering apparatus used by the researchers. The literature reviewed for this paper did not provide concrete evidence of a correlation between the use of detergent and the amount of MF shedding during the laundering process.

Other variables such as water volume, wash temperature, and subsequent washings have been found to impact MF release [31]. Recent research studies found a higher water volume [50,55] and increased wash temperatures [45,52,65] to increase MF shedding. Contrastingly, Hazlehurst et al. [56] found that increasing wash temperature from 40 °C to 90 °C decreased MF shedding. With subsequent washings, many studies found a decreasing trend of MFs released after the first wash, and a plateau was reached around the fifth wash [39,66]. Additionally, fiber identification and quantification methods vary significantly among studies [43]. Frost et al. [43] found that only 5 out of 25 studies chemically identified fiber types before quantifying them. Many studies only measured the mass of MFs released and then estimated the number of fibers based on that mass [39,46,47,67]. Previous studies have shown this variance with reported values of 1900–110,000 fibers shed per garment, 22,600–13,100,000 fibers shed per kg of fabric, and 7–1240 mg of fibers shed per kg of fabric [43].

Most users in developed countries tumble dry their clothes as a part of the laundering process, with 80% of North American Households using tumble dryers [68]. This causes an increase in the shedding of loosened fiber fragments during the washing process [64]. Fiber fragments shed during the tumble drying process are not immediately emitted into water systems as they are often caught in lint filters featured within machines [62]. However, these fiber fragments are discarded by the operator and often find their way into natural environments through landfills [62]. Tumble drying also emits fiber fragments into the air, which can carry them into natural environments [69]. Kärkkäinen and Sillanpää [62] quantified the release of MFs during the first tumble drying of various synthetic textiles to range from 10 to 1700 mg of fibers/kg of textile. The additional MF shedding from tumble drying was also confirmed by a study finding an increase of 58 ± 60 fibers per 660 g blanket emitted into the air [69].

*2.2. Wastewater Treatment Plants (WWTPs) and Persistence of Synthetic MFs in Them*

The wastewater systems are designed to convey effluent water discharged from laundry appliances to wastewater-treatment plants (WWTPs), aiming to eliminate pollutants prior to their discharge into various water bodies [31]. In a study conducted between 2012 and 2013, Dutch WWTPs were identified as harboring MFs as the predominant type of MP pollutants [70]. The study revealed that approximately 72% of the MFs entering Dutch WWTPs were successfully removed, while the remaining 28% leached out of the WWTP, resulting in an estimated 52 MFs per liter discharged into the water bodies [70].

In another study by Peller et al. [71], the researchers investigated a WWTP in Michigan, USA, reporting a phenomenal removal rate of 97% for MPs. The majority of removed MPs were sequestered from the sludge generated during wastewater treatment [17]. Nevertheless, Leslie et al. [70] reported that the WWTP sludge contains an average of 650 MP particles per kilogram of wet sludge. The major concern with these remaining MPs in the sludge is due to their frequent reuse as a fertilizer that reintroduces MPs into the environment [17]. Alternatively, its landfilling or incineration as noted by Leslie et al. [70] presents further environmental-pollution challenges due to the release of toxins.

The distinctive characteristics of MFs, characterized by their smoothness and high length-to-width ratio, render them particularly challenging for WWTPs to successfully capture and remove from the wastewater [17]. Dris et al. [72] found that smaller MFs < 800 µm exhibited a higher likelihood of passing through WWTPs, constituting approximately 70% of MFs in the wastewater. Similarly, Fortin et al. [73] identified MFs ranging from 1 to 10 µm as the most prevalent in the water samples extracted from post-WWTP. The concern arises from the fact that the seemingly small percentage of MFs evading WWTP removal poses a significant threat due to the substantial daily release of laundry effluent, amounting to a considerable influx of MFs into water bodies [47,74]. Vassilenko et al. [47] estimated that 22 kilotons of MFs enter WWTPs annually in the U.S.A. and Canada combined through discharged laundering effluent. Assuming an average 96% removal rate of the MFs, suggested by the majority of studies conducted in Northern America, the estimations show emissions of a whopping 878 tons of microfiber fragments into the Northern American aquatic environments annually (Figure 4) [47]. This is a serious environmental concern.

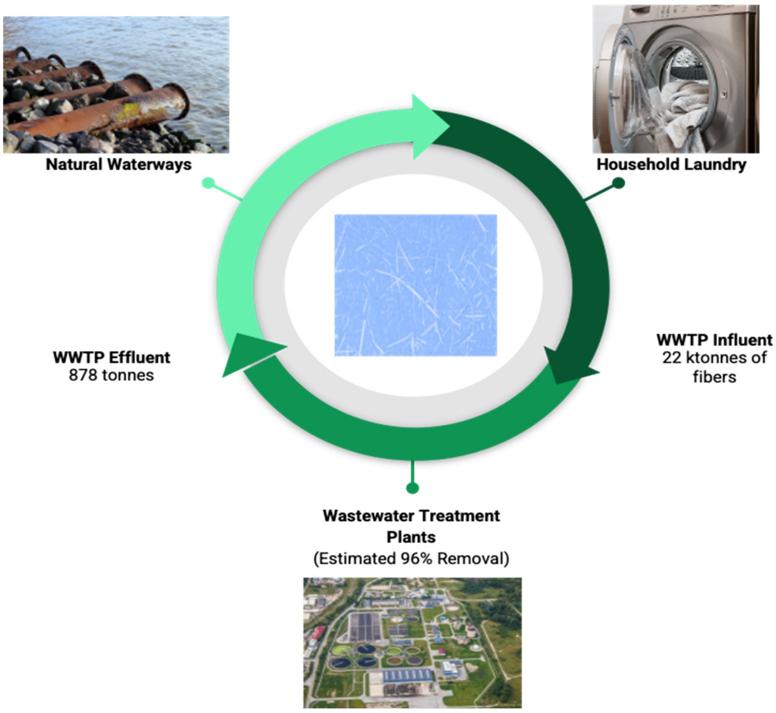


**Figure 4.** Annual MF influent from home laundering and post-treatment effluent released in the environment in Northern America [47] (images are copied from pixabay.com under CC0 license).

Hartline et al. [75] estimated that if a WWTP serving a population of 100,000 people achieved an MF removal rate of 98.4%, it would still release approximately 1 kg of MFs into water bodies daily. Correspondingly, Uddin et al. [76] reported that globally, WWTP-treated water contributes to the annual release of 1.47 $\times$ $10^{15}$ MPs into oceans, while approximately 50% of global wastewater (especially in under-developed nations) remains untreated, resulting in the emission of approximately 3.85 $\times$ $10^{16}$ MPs annually [76]. In a nutshell, the efficacy of global WWTPs in eliminating MPs displays considerable variation [77]. The developed nations have far more advanced WWTPs compared to the developing and under-developed countries, where a lack of wastewater resources poses a serious threat to public health and the environment.

MFs passing through WWTPs pose more than just a plastic pollution threat; they also act as carriers of toxic chemicals and substrates for microbial growth including pathogens [33]. Henry et al. [33] underscored that MPs traversing WWTPs can absorb pathogens from wastewater, transporting them into natural environments. Kirstein et al. [78] validated this by discovering pathogenic bacteria on MPs from the North and Baltic Seas, suggesting MPs as potential disease transporters. Australian marine waters contain small floating plastics' host bacteria, cyanobacteria, and fungi [79], heightening the risk of disease transmission to humans and wildlife. Lamb et al. [80] reported a substantial increase in disease prevalence, ranging from 4% to 89%, in corals in contact with plastics.

Additionally, wastewater treatment plants (WWTPs) play a role in producing secondary MPs, which upon partial degradation can manifest as nanoparticles and nanofibers [41]. Conventional WWTP treatment processes, including sand filtration, ultraviolet disinfection, and biological processes, can induce further degradation of MPs into submicron particles, complicating detection and leading to the underestimation of MP emissions in prior studies [41]. The abundance of nanoplastics, estimated to be $10^{14}$ times higher than MPs due to their origin from fragmentation processes [81], necessitates additional research for a comprehensive understanding of the detrimental impacts of MPs on public health.

## 3. Fate, Transport, and Persistence of MF Pollutants in Our Biosphere

MFs, as indicated by Palacios-Mateo et al. [82], ubiquitously contaminate global aquatic ecosystems. These minuscule plastics exhibit prolonged dwellings in the aqueous environment, undergoing microbiological interactions across various strata of the water column before eventually settling on the seabed—a process that occurs over multiple years [83,84]. Notably, all MPs possess the capability to absorb deleterious contaminants, including Polycyclic Aromatic Hydrocarbons (PAHs), Dichlorodiphenyltrichloroethane (DDT), Polychlorinated biphenyls (PCBs), and dioxins [31,85] and transport them to other places. Additionally, MFs specifically are carriers of several toxic pigments, PCBs [12] and PFAS [13,14]. Sadly, oceans, being a primary repository for these plastic pollutants, have become susceptible to these toxins and have transported them to aquatic life [31]. The ingestion of MP and MFs by aquatic organisms, such as fish, results in the bioaccumulation of these toxins, traversing the food chain and eventually impacting human health [70], as depicted in Figure 5.

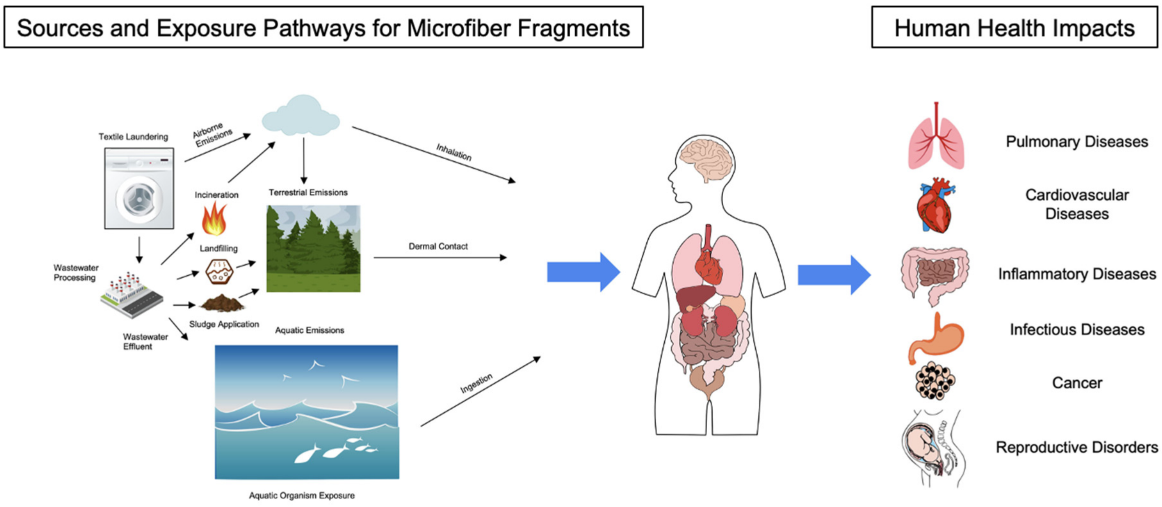


**Figure 5.** Sources and existence of MF emissions within the environment, their exposure pathways to humans, and the health impacts stemming from the prolonged exposure [86,87] (individual images are copied from pixabay.com under CC0 license).

During the use and care phases of garment life cycles, the release of MFs into the atmosphere leads to their dispersion in both indoor and outdoor settings [82,88,89]. Within indoor environments, MFs may descend to the floor [90], contaminate food [91], be inhaled through their presence in the air we breathe, and be transported to our respiratory system [69,92]. Conversely, outdoor-released MFs are prone to long-distance transport by atmospheric fallout through wind, rain, and stormwater [93], reaching other places [88,93,94].

Environmental contamination by MFs is a multifaceted issue, involving their introduction via sewage sludge used as fertilizer [86] and airborne transmission, as well as water (containing MFs) used for irrigation (Figure 5) [87]. MF pollution adversely affects soil properties, disrupting its natural microbiome and causing harm to the soil-dwelling organisms [95,96]. Impacts on plants include growth inhibition, altered physiology [96], and nutrient-uptake restrictions [97]. Furthermore, germinated seeds in polluted soil can absorb MFs, which accumulate in edible plant tissues [98].

Furthermore, the breakdown of plastic products in aquatic ecosystems is influenced by various environmental factors, including water exposure, ultraviolet (UV) radiation, and physical agitation [24,99]. Over extended periods of exposure to these factors, this can induce the hydrolysis, photodegradation, and mechanical disintegration of MPs, leading to the fragmentation of the MPs into smaller nanoscale particles. These smaller fragments, once detached, can disperse over long distances via ocean currents [83], compounding the issue of MP. Laboratory experiments have identified numerous potentially hazardous compounds produced during the weathering and aging of plastics in aquatic environments [99].

Humans ingest these MFs through various sources such as seafood, water, beer, salt, sugar, and the air we breathe [90,100–104], with water being the primary source of exposure. We noted several potential sources of MF pollution, their exposure pathways, and their impacts on human health in Figure 5 above. Although the precise quantity of ingested MFs is uncertain [105], they are estimated to be ~0.5–1 grams per week. The potential impacts of MF ingestion on human health, including reproductive and developmental disorders correlated with endocrine-disrupting chemicals (EDCs) found in plastic additives, underscore the need for concern [20,36,106]. Inhalation of MP particles and MF fragments, as highlighted by Prata [92], poses a serious risk due to plastic's ability to absorb substances and leach harmful chemicals into the body. With the escalating levels and frequency of MP exposure [107], additional research is imperative to ascertain its potential to contaminate the human body and induce ailments such as leaky gut and permeable blood–brain barriers [108].

## 4. Innovative Treatment Technologies for MP and MF Mitigation

Wastewater treatment plants (WWTPs) are the primary recipients of MPs, prior to their discharge into natural water bodies. As noted in Section 2.2 of the paper, it has been established by several lab experiments and field studies that the MPs, specifically MFs, can escape WWTPs and eventually runoff in the water bodies. There are two broad categories for MF removal in WWTP: conventional and innovative. Conventional techniques include rapid sand filtration, adsorption, membrane bioreactor, and coagulation. In this section, we will discuss some innovative technologies for MP treatment. Some of these are scalable and are currently in use, while others are in further research and development phases.

### *4.1. Electrochemical Oxidation*

Electrochemical oxidation (EO) stands out as a sustainable wastewater-treatment technique that has garnered significant attention from researchers lately. The EO technique encompasses two distinct methods, namely anodic oxidation and indirect cathode oxidation [109]. This process involves using electrical energy to drive oxidation reactions that break down or transform organic compounds into simple and non-toxic by-products like carbon dioxide and water vapor without the addition of chemical agents [109,110]. EO is effective in degrading diverse organic pollutants including MP, antibiotics, antipyretics, and dyes by utilizing a selective degradation technique that focuses on particular pollutants while avoiding the production of harmful by-products.

Furthermore, EO yields potent oxidants such as hydroxyl radicals, hydrogen peroxide, and ozone that ensure the efficient degradation of organic pollutants while circumventing the formation of sludge waste [111]. The efficacy of the process depends on several factors such as the anode's surface area and its material, current intensity, type and concentration of electrolytes, and the duration of the degradation reaction [112]. Overall, it is a process-efficient and cost-effective technique. However, scaling up electrochemical oxidation processes from laboratory-scale to industrial-scale applications can present challenges related to the cost of electrode material, pH management, reactor designs, and system integration. Ensuring reliable and efficient operation at larger scales requires careful engineering and optimization.

### *4.2. Electrocoagulation*

As opposed to the traditional chemical coagulation that uses iron salts and ammonium-based chemicals, the electrocoagulation process employs an electrochemical reaction that is efficient in removing suspended, emulsified, and dissolved contaminants. This process emerges as a prosperous, sustainable, and highly efficient technique for ' the removal of MP pollutants from wastewater, amalgamating the favorable attributes of coagulation and electrochemistry [113]. Within electrocoagulation, flocs are generated from the cations formed by metallic electrodes under an electric current, leading to the creation of "micro-coagulants" and the disruption of suspended particle stability through coagulation [114]. Consequently, electrocoagulation surpasses the conventional method of chemical coagulation in its efficiency by eliminating the need for chemical coagulant materials, thereby reducing the operation time and costs [115]. The electrocoagulation process is effective in treating oily water as well by separating oils. Through this method, floating oils can be easily collected and removed, while the traditional chemical coagulation process fails to achieve this. Furthermore, electrocoagulation minimizes sludge waste, yields water with lower levels of total dissolved solids, and exhibits versatility in handling various wastewater qualities. This sustainable and cost-effective methodology has captured the interest of researchers as a viable alternative to traditional coagulation methods.

### 4.3. Photocatalytic Degradation

Photodegradation has been recognized as a highly efficacious approach to treating noxious organic pollutants, including MP within wastewater [116]. The method involves a semiconductor material absorbing visible or ultraviolet light, inducing the generation of reactive oxygen species (ROS) such as singlet oxygen and superoxide radicals [117]. These ROS attack the chemical bonds in the pollutant molecules, leading to their degradation into simpler, less harmful compounds, such as carbon dioxide, water, and other organic acids.

The photocatalytic semiconductor material absorbs light energy surpassing its bandgap energy, initiating electron transfer from the valence band to the conduction band, thereby creating holes in the valence band. Consequently, this process produces superoxide and hydroxyl radicals, instrumental in breaking down MP. The green-synthesized iron–zinc oxide nanocomposite has recently emerged as a prominent semiconductor material employed by Lam et al. [118] in the efficient photocatalytic degradation of polyethylene. Despite its efficacy, the photocatalytic degradation method necessitates the proper disposal of the residual sludge generated in the process and vigilant monitoring to avert any adverse impacts on the aquatic ecosystems [118].

### 4.4. Magnetic Separation

The process of magnetic separation is effective in removing pollutants from the wastewater. The contaminants adhere to the magnetic carrier substance, magnetite, and are subsequently extracted from the wastewater stream using a magnet. The magnetite is then reclaimed and reused within the treatment procedure. In the pre-treatment stage, the control of acidity and redox potential are required for the conditioning of the wastewater.

Several researchers [119–121] have worked to improve the efficacy of MP removal from wastewater through magnetic separation, including the documented high magnetic influence of the utilized materials and their substantive MP-removal capacity. Magnetic separation has recently found application in the removal of MFs from sediment, freshwater, and marine water samples [121]. Diverse materials, referred to as magnetic seeds, play a pivotal role in this removal process. These encompass iron nanoparticles and magnetic carbon nanotubes, for instance. Magnetic separation can be modulated through electrostatic interaction, hydrogen-bond formation, and complexation [122–124]. However, the presence of other pollutants adversely impacts the selectivity and removal efficiency of MPs [123], while the size and shape of MPs also influence the separation process [124].

These innovative techniques show great potential for the removal and treatment of all MP including MFs. Therefore, further extensive research is imperative to enhance their efficacy and scalability. Clearly, traditional approaches have not been fully effective, leading to the accumulation of microplastics in the environment. The scientists must further develop new innovative technologies for the selective treatment of MP and MFs in wastewater, including the improved efficacy of the ones discussed above.

## 5. Strategies and Policies for Reducing MF Pollution

Given the challenging nature of removing MFs from waterways, a more pragmatic and financially sustainable approach is needed to control MF pollution entering our water systems [20]. Addressing the intricate issue of MF pollution requires multifaceted strategies, and acknowledging its complexity. This paper advocates for the exploration of the strategies discussed below (and as summarized in Figure 6) to mitigate MF pollution:


**Figure 6.** Essential pre- and post-consumer strategies to mitigate MF emissions into the environment and thereby minimize their impact.

### *5.1. Increasing Consumer Awareness*

(a). Environmental agencies such as the United States Environmental Protection Agency (US EPA) and other stakeholders must develop educational campaigns to enhance consumer awareness regarding MF shedding, its environmental ramifications, and the influence of laundering behaviors on MF release;

(b). Encourage sustainable purchasing decisions for clothing items. This includes avoiding unnecessary consumption of synthetic textiles and opting for products with minimal harmful chemical treatments;

(c). Educating consumers on the optimal frequency of washing clothes, considering that frequent laundering directly correlates with higher MF release [75]. Drawing from empirical research on the factors contributing to microfiber shedding, we have outlined laundering variables influencing microfiber release during washing in Figure 3 of this paper. We trust that these findings will aid in developing strategies to minimize microfiber shedding during laundering processes.

### *5.2. Technological Solutions for Home Laundering*

(a). Investigate and adopt technologies designed for the improved capturing efficacy of MFs during laundering, including redesigned mesh bags or filters attached to the laundry-machine pipes;

(b). Explore the effectiveness of in-drum devices and filters in capturing MFs, with a focus on incorporating these technologies into consumer practices;

(c). Promote the development and adoption of new washing machines with built-in MF-catching technologies, reducing reliance on aftermarket solutions. It is important to recognize the potential of such technologies to significantly decrease MF emissions from laundry [17].

### *5.3. Prioritizing Mitigating MF Emissions during Textile Production*

(a). Prioritize efforts to reduce MF emissions, beginning with fabric production, given the substantial global textile production volumes discussed in Section 1.1 of this paper;

(b). Design textiles for increased durability, employing techniques such as avoiding loose constructions, using less hairy yarns, and incorporating fibers with higher breaking strengths to minimize shedding [44,48];
(c). Rethink mechanical and chemical finishing techniques to preserve fiber surfaces and reduce susceptibility to fragmentation [51];
(d). Introduce the prewashing of textiles and apparel with MF-filtering devices into the textile manufacturing supply chain to mitigate consumer washing impacts later on.

### *5.4. Regulating the Overproduction of Synthetic Textiles*

(a). Acknowledge the environmental threat posed by synthetic MFs and consider reducing the production of synthetic textiles to foster a more sustainable textile industry. As noted in several studies, synthetic-fiber-fragment pollution poses a major threat to our ecosystem and biodiversity [7,11–17]. Synthetic fibers offer important functional assets that may be inherently missing in natural fibers, hence their existence in the industry. It is important to regulate their production and consumption rates based on their functional uses rather than economic benefits so that we can continue reaping their functional benefits without having to ban them completely due to their harmful environmental impacts;
(b). Drawing inspiration from successful bans on plastic grocery bags in several countries, authorities can restrict the production and consumption of synthetic textiles to address the root cause of the issue, which will help mitigate synthetic MF emissions;
(c). Synthetic-fiber-fragmentation pollution is a real threat to our environment and must be addressed with synergistic efforts between producers, manufacturers, designers, consumers, government lawmakers, and environmental-regulation authorities.

### *5.5. Enhancing Global Wastewater Treatment Infrastructure*

(a). Mandate the improvement of global wastewater treatment plants (WWTPs) to incorporate technologies specifically designed for capturing MFs in influent water. We discussed several innovative wastewater treatment technologies in Section 4 of this paper that can be adapted by the WWTPs for MP and MF treatment;
(b). Regulatory bodies like environmental-protection agencies and governments can set standards for WWTPs, encouraging the adoption of advanced technologies capable of filtering out higher percentages of MFs from laundry effluent waters [77].

### *5.6. Developing Sustainable Disposal Methods*

Investigate sustainable methods for the proper disposal of MFs, addressing the issue of MF emissions including waste-to-wealth processes such as torrefaction, pyrolysis, and enzymatic hydrolysis to transform MFs into biomass and biofuels, thereby minimizing environmental harm [125].

### *5.7. Implementing Labeling Laws for Consumer Education*

(a). Governments can establish clothing-labeling laws designed to educate consumers about the environmental impacts of synthetic garments and proper care techniques to minimize MF release [44];
(b). Enforcing eco-labeling practices on synthetic clothing would ensure that consumers are informed about the best methods to reduce MF emissions, promoting sustainable purchasing and laundering behaviors.

In order to comprehensively address the issue of MF pollution, a concerted effort involving industry stakeholders, consumers, and government bodies on a global scale is needed. The implementation of the strategies proposed in this paper can contribute to a more sustainable and responsible approach to mitigating the adverse impacts of MF pollution. We propose a comprehensive multi-step strategy, commencing with enhancing the textile-manufacturing process to minimize microfiber emissions at the manufacturer level. This should be followed by promoting improved laundering practices and utilizing advanced laundering devices at the user level. Additionally, treatment measures should be implemented for post-consumer textile waste leaching MF pollutants to the environment.

## 6. Major Knowledge Gaps and Future Research Directions

The limitations inherent in current MF research stem from the notable lack of reliability and consistency of methodologies used for quantifying MF shedding. Though our initial literature search resulted in thousands of published papers, we observed that the lack of consistency in terms of methods, results, approach, and laundering apparatuses led to the potentially unreliable findings of these studies. Many studies employ disparate approaches for identification, quantification, experimentation, and quality control, yielding a wide spectrum of reported MF concentrations, as clearly noted in this review. Consequently, confirming the accuracy, relevance, and comparability of the existing literature within the field becomes a formidable challenge. To avoid these inconsistencies, errors, and biases in the MF literature, the following recommendations for future research are proposed.

### *6.1. Development of Standardized Experimental Method*

This was perhaps the largest gap we found in the MF-shedding studies. While ASTM, ISO, and AATCC provide standards for determining fiber loss during textile laundering, these methods vary a lot in their methodology and are not widely acknowledged in the literature. The researchers often deviate from these standards in their methodology, leading to unreliable findings that are hard to be reproduced. For future research, we recommend the following:

(a). Devising a universally accepted experimental method and updating standards for the quantification of MF shedding during laundering, which is reproducible is imperative;
(b). Furthermore, it is crucial to develop standard laundering apparatuses for laboratory experiments that can mimic household laundry emissions. The procedure for filtration methods, testing methodology, quality assurance protocols, and a comprehensive analysis of the entire laundering cycle, including tumble drying. must be developed.

### *6.2. Technological Advancements for Identification and Quantification*

Another important lag we observed in the MF research is the lack of standard methods for MF identification and quantification. While some researchers used optical microscopes to manually count the amount of microfibers shed during the experiments, others used more sophisticated instruments to quantify the MFs released. For further research in this area, we recommend the following:

(a). Pioneering new technologies to enhance the accurate identification and quantification of MFs;
(b). Explore common methods such as optical microscopy, scanning electron microscopy, Fourier transform infrared (FTIR) spectroscopy, and Raman spectroscopy to further refine accuracy [33].

### *6.3. Human and Environmental Impact Studies*

There is a limitation on research focused on studying the impacts of MF pollution on human health. We found some papers discussing findings related to MP leaching from plastic sources and found in human blood [126], feces [127], and urine [128] samples, but this field of research is still in its infancy. Although these studies were conducted on toxic chemicals leaching out from plastic products, it is important to study the presence of these toxic compounds in MF pollutants as well. We recommend further in-depth research studies with larger sample sizes of MF pollutants to be conducted in this area. Furthermore, there is a critical need for long-term studies to assess the implications of continuous exposure to and the ingestion of microfibers (MFs). These studies should draw attention to potential health and ecological risks associated with prolonged MF exposure, thereby highlighting the importance of understanding the long-term consequences of MF contamination.

### *6.4. MF Biodegradation Studies*

There are some studies as reviewed in this paper that focused on the aquatic biodegradation of MFs. However, further in-depth investigation on how the MFs (once released in water bodies) biodegrade and their potential impact on the health of freshwater systems is needed. For future research, we recommend the following:

(a). Extended research efforts towards investigating the biodegradation behaviors of both natural and synthetic MFs in natural environments are recommended. Both biotic and abiotic factors must be taken into account in such studies. This approach is currently lacking in present lab-based research in this area.

(b). Address the lack of studies that assess the degradation of MFs in aquatic environments, acknowledging the well-established resistance of plastic products to biodegradation [31].

### *6.5. Leaching of Toxic Chemicals from Textile Finishes*

This relates to our Sections 6.3 and 6.4 above. It is extremely important to understand how MFs disintegrate and leach out chemical (including toxins) compounds into the aquatic environments.

(a). Conduct in-depth research on the leaching of toxic chemicals from applied textile finishes during degradation processes. We did not find many studies focusing on the breaking down of textile finishing compounds and their impacts on aquatic life through MF carriers;

(b). Examine the toxicity of these leachates to better understand the potential environmental impacts and health risks associated with chemical release from synthetic textiles.

### *6.6. MF Sorption of Harmful Chemicals and Pathogens*

As discussed in Section 2.2 of the paper, there is (although very limited) research that discusses microplastics to transport pathogens and chemicals from wastewater sludge to the environment. We recommend future researchers study this in depth with more scientific evidence:

(a). Explore the ability of MFs to absorb harmful chemicals and pathogens from the wastewater sludge and disperse them into other settings;

(b). Adapt techniques from research on the sorption of metals and metalloids by MP particles during wastewater treatment plant (WWTP) processes [43].

In conclusion, numerous research gaps identified and reported in this review necessitate further examination and exploration in future studies concerning MF pollutants. These include the need for more in-depth research on the ramifications of MF on human health, pinpointing specific mechanisms underlying their detrimental effects, delving into potential risk factors influencing human exposure, and formulating effective mitigation strategies to safeguard public health. Moreover, additional research is essential to comprehend both the acute and chronic toxic effects of MF pollutants on humans and aquatic life, while concurrently devising methods to avoid MF shedding. Finally, selecting a strategy to reduce the use of synthetic textiles should consider factors such as infrastructure, economic conditions, alternative fiber options, and fashion brands' readiness to transition to a non-synthetic textile-dependent industry.

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