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Review

Understanding the Flows of Microplastic Fibres in the Textile Lifecycle: A System Perspective

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Abstract

Microplastics released from synthetic garments pose a complex challenge to society and the environment. Textiles contribute to microplastic pollution throughout their entire lifecycle—from design and production to washing and use to their disposal—and can enter the environment through wastewater, soil, and air. The detachment of fibre fragments and their fate in the environment has received attention in the recent literature but lacks a harmonised research methodology and a holistic approach to the topic. This work presents a model to estimate the flows of microplastic fibres and synthetic garments in geographical Europe, expressed in tonnes per year. It was developed through a search of the literature to provide an estimate of synthetic fibres entering the environment and to identify the connections between the stakeholders involved. A first-level multicriteria decision analysis was conducted to recognise relevant pollution flows: the study revealed significant but poorly understood pathways, such as the flow of microplastics in the indoor and outdoor air during garment wear. Also, the flow of microplastics from the combined sewer overflow of untreated water during heavy precipitation and the flow to the agricultural land from the application of sewage sludge result in relevant pathways to water and soil, respectively. By fostering collaboration across multiple actors, the transition toward sustainable textile practices can significantly reduce fibre pollution.

Keywords: microfiber; lifecycle analysis; textile sector; microplastics

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1. Introduction

Plastics pose an environmental issue due to their vast uncontrolled disposal. Adding to the conventional pollutants, microplastics (MPs) are found in every environmental compartment. They are defined as "pieces of plastic smaller than 5 mm" [1], but up to now, there is a lack of a shared legal definition. Primary microplastics are directly released into the environment in the form of small particulates, while secondary microplastics degrade from larger plastic items in the marine environment [2]. Microplastics are contaminants of concern because of their ubiquity, mobility, and persistence [3,4]: they can be found in water, soil, and air, and can also be transported to pristine environments [5–10]. Microplastics have been reported to act as endocrine disruptors due to the release of additives such as phthalates and bisphenol [11], and they can act as carriers of hydrophobic pollutants such as polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbon (PAHs), pesticides adsorbed on their surface [12], or even bacteria and pathogens [13]. They are also found to increase the abundance of antibiotic resistance genes [14]. Microplastics have been detected in human organisms by several studies, mainly in lung tissue, followed by the small intestine, large intestine, and tonsils [15]. The potentiality of microplastics (MPs) and nanoplastics (NPs) to pose a concrete menace to health is disputable because studies reporting ecotoxicological effects on organisms were performed at very high concentrations [16], but as the Science Advice for Policy by European Academies Report stated in 2019 [17], the situation could change if the rate of microplastic pollution remains the same. No EU law, currently in place, addresses microplastics in a comprehensive manner, but there exist several specific laws with partial objectives in the context of the European Union's zero-pollution action plan, which set the target to reduce microplastic pollution by 30% by 2030, restricting the use of intentionally added microplastics to products, and reducing unintentional microplastic releases [18].

It is estimated that synthetic textiles of petrochemical origin (e.g., polyester (PET), polyamide (PA), and polypropylene (PP)) are responsible for the release of between 200,000 and 500,000 t of microplastics every year, and that 16–35% of microplastics released to the oceans on a global scale are from synthetic textiles [2], making the discharge of MPs from textile washing one of the biggest sources to the overall microplastic pollution in the oceans and freshwater [4,19].

This study focuses on fibrous microplastics from textiles, here described as synthetic "fibre fragments", which is a nomenclature suggested by the Euratex Cross Industry Agreement, while "textile fibre" is a unit of matter characterised by its flexibility, fineness, and high ratio of length to maximum transverse dimension [20], and "microfibre" is a fibre with linear density less than 1 decitex or a diameter less than 10 μm [21]. Global fibre production has passed from 58 million t in 2000 to 116 million t in 2022, and, if business continues as usual, it is expected to go beyond 147 million t [22]. Synthetic fibres have, over the past decades, managed to dominate the textile industry: about two-thirds of all textile fibres produced are synthetic, and polyester clothing, manufactured from oil-based polyethylene terephthalate (PET), accounts for 54% of the global market. The share of synthetic fibres in garments and home textiles has constantly increased since their introduction in the market because synthetic fibres have good mechanical properties, durability, and affordability [23–25]. The estimated release of synthetic fibres into the environment shows a significant increase, rising from around 122 tons annually in the 1950s to nearly 360 kilotons by 2016, with an annual growth rate of 12.9% [26]. The definition of proper actions on the topic must build on the understanding of the emission routes. This study aims to provide a quantitative estimate of plastic fibre flows among environmental compartments throughout the textile lifecycle, to support the identification of emission paths that require particular attention and to inform policymaking on the topic.

The objective of this study is to map the flows of synthetic fibre fragments to the environment along the textile lifecycle, from production to use to disposal. Several studies have already performed a similar modelling, but often lacked a sector-specific point of view. For instance, a study performed by Schell et al., 2020 [16] conducted a comprehensive mapping of flows of plastics and microplastics from production to disposal by revising the existing literature, but did not focus on microplastics of textile origin. Gavigan et al., 2020 [26] estimated emission routes and quantities for synthetic fibres worldwide by connecting regionalised global datasets on apparel production, use, and washing with emission and retention rates during washing, wastewater treatment, and sludge management, but did not consider the release from the production phase nor the air flows. Studies performed by Belzagui et al., 2020 [27] and Wang et al., 2020 [28], presenting models to quantify the flows of synthetic fibre fragments, are textile-oriented but focused on a specific route: they both described the flows from domestic washing to wastewater treatment plants (WWTPs) to the aquatic environment, but did not consider the textile lifecycle from a broader perspective and, in particular, did not take into account the flows of fibres from the manufacturing phase [29] and the flows to air and terrestrial environment (via biosolid application, and via landfill leachate).

There is a gap in the comprehensive modelling of fibre-fragment release across the entire textile lifecycle. Existing studies tend to focus on specific stages—mainly fibre release into wastewater—while neglecting other phases such as production, disposal, or release into air. This limits their usefulness for system-level insights and policymaking. Additionally, broader microplastic models often do not differentiate textiles from other plastic sources, lacking the sector-specific detail needed to guide design improvements.

These limitations are explored in more detail below:

- Holistic modelling of fibre-fragment release throughout the entire textile lifecycle.
  Some studies have specifically examined fibre-fragment release during individual stages of the textile lifecycle, particularly the flow into household wastewater and municipal effluents (for example, Gavigan et al., 2020 [26]; Belzagui et al., 2020 [27]; Wang et al., 2020 [28]). However, these studies do not consider other critical stages, such as fibre release to air or during production and disposal. While such modelling can offer precise estimations for isolated stages, it lacks a systems perspective, making it difficult to compare impacts across the lifecycle or advise policymakers on where to prioritise mitigation efforts.
- Sector-specific modelling of microplastics focusing on textiles.
  Other models address microplastic pollution more broadly without distinguishing between sources or shapes (for example, Schell et al., 2020 [16]). This approach has the advantage of addressing the plastic issue in a broader context, but it lacks the sector-specific terminology and lifecycle approach that are necessary to inform design changes.

This study aims to fill these gaps by answering the following questions:

RQ1: What is the lifecycle of the synthetic fibre fragments from textile, from production to disposal and dispersion? What are the resulting flows that can be derived from the previous studies in the field?

RQ2: How much load do these flows pose on the environment?

This study distinguishes itself from prior research through both its comprehensive scope and its sector-specific focus. Specifically, it seeks to encompass the full life cycle of synthetic textile products and to account for all potential environmental pathways of synthetic fibre fragments, with an emphasis on the textile sector. By systematically integrating all stages of synthetic textile production, use, and end-of-life management, the study proposes a holistic yet targeted modelling framework. Although several studies have assessed the environmental impacts associated with the textile lifecycle, their analyses have predominantly concentrated on carbon dioxide emissions and water consumption [30,31], rather than on the release of fibre fragments. Furthermore, current estimates of fibre release remain highly uncertain, primarily due to the absence of standardised methodologies for the sampling and analysis of microplastics [17].

This study aims to contribute to the ongoing effort to harmonise existing models and findings to enhance the comparability of the expanding body of literature on fibre fragment pollution. In this way, it provides a scientifically grounded tool that can support policymakers and decision-makers in designing effective mitigation strategies and regulatory frameworks targeting synthetic fibre emissions.

2. Methodology

This section illustrates the method adopted to go towards a quantitative assessment of synthetic fibres in the textile lifecycle and to identify the most significant flows. A literature review was performed considering both the scientific literature and official reports. Flows of synthetic fibres were investigated in terms of clothing items consumed (macrofibres, MaF) and microplastics detached from textiles and dispersed in the environment (fibre fragments, mF). The fraction of synthetic fibres makes up about 60% of clothing [32], with polyester, manufactured from oil-based polyethylene terephthalate (PET), accounting for 54% of the global market [22]. Natural fibres and man-made fibres of natural origin (viscose, lyocell, etc.) were not considered, although they have an impact on the environment, acting as a source of various polluting chemicals associated with fibre production [33,34]. The spatial scale adopted for the mapping covers geographical Europe formed by 38 countries (Albania, Austria, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Cyprus, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Macedonia, Malta, Moldavia, Montenegro, Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, Ukraine, and the United Kingdom). The estimation was performed on a time scale of one year (365 days) using a mass-balance approach, with the mass of synthetic fibres per unit of time (tonnes per year) adopted as the unit of measure. It was often necessary to harmonise the unit of measure to compare data from different studies. An insight into existing policies and regulations in the European area was conducted to understand if the critical flows are receiving adequate attention.

2.1. Methods—Mapping of Flows (RQ1)

A literature search was performed through the database Scopus, considering the published literature from the year 2010, when the corpus of studies about microplastics started to increase (see Figure 1), to 2024. The search terms used were “microplastic fibres” and “plastic microfibres” and “synthetic fibres”, in combination with other keywords including “flows”, “fluxes”, and “assessment”, and similar searches were performed for all the steps of the textile lifecycle (Table S1 from Supplementary Material). The search was limited to the English language and journal papers (no conference papers). Only papers about textile microplastics were included (not microplastics from other sources), and only monitoring campaigns or models referring to microplastic flows in terms of the number of fibres (or mass) per unit of time. Papers reporting only concentrations, toxicological effects, or removal technologies were excluded.

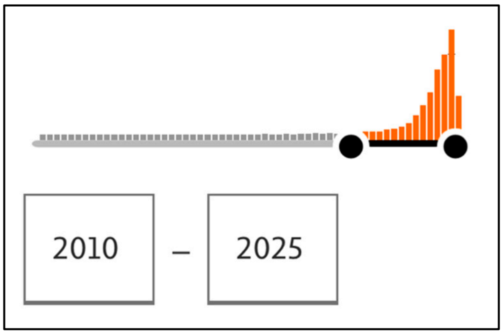

Figure 1. Publication trends since 2010 retrieved using the keywords “microplastics”, “microfibre”, and “flow”, “flux”, or “assessment” in the Abstract or Title. (Source: Scopus, date of search: 20 April 2025). The highlighted years are displayed as orange columns positioned between the two black dots marking the year range.

An extensive review of official documents and reports concerning garment production and consumption was undertaken to identify data related to plastic macrofibre flows. The data collected were systematically organised and synthesised into a flow map. In cases where the available data were site-specific (originating from monitoring campaigns rather than estimative approaches), they were scaled up to the study area using official statistics and reports on production, consumption, and import and export volumes, as well as the number of textile-manufacturing facilities, demographic characteristics, and laundering practices.

To express fibre flows on the reference scale in tonnes per year, the raw data—typically reported in the literature as the number of fibres per unit volume or time—were converted to a weight basis. This conversion used the average weight of a synthetic fibre fragment, which was estimated based on the average density of three synthetic polymers used for textiles, polyester (PES), polypropylene (PP), and polyamide (PA), reported in Table S2, as well as various size distributions and diameters for a single fibre (modelled as cylindrical in shape). To estimate a confidence interval for the fibre fragment flow, minimum and maximum average weights were calculated by combining the range of fibre sizes and polymer densities. These values were then used to establish lower and upper bounds for the estimated flow in tonnes per year (see Table S3A,D).

Flows of mFs and MaF in water and air were included in a flow map based on a previous mapping by the European Topic Centre on Circular Economy and Resource Use (ETC/CE) [35]. The main areas of the textile lifecycle and the fate and transport of synthetic fibre fragments, from "upstream" to "downstream", are described in the section below.

2.1.1. Manufacturing Phase

This phase includes the processing of raw material into fibres and yarns, the production and finishing of textiles (knitting, weaving, dyeing, finishing), and the manufacturing of the final product (cutting, sewing, stitching, and printing). Due to the lack of data, all the intermediate steps between material processing and the final product have been considered as one single step. Recent studies highlight that it is very likely to find release paths by searching in the textile-manufacturing phase: for instance, fibre fragments can be embedded in textiles already in the process of yarn production [29] and can be emitted during textile screen printing [36]. Several studies investigated the presence of microplastics in textile industrial water effluents [37–40] and showed that the concentration of fibre fragments in textile-manufacturing wastewater is 10–10,000 times higher than their concentration in the influent of municipal wastewater treatment plants, although the removal efficiency is the same for both.

Flows from textile industries have been identified:

- MaFs flow of clothing items towards use and care (fibre item net consumption, with "net" referring to "production + import − export").
- mFs flow in air deriving from the manufacturing process.
- mFs flow in wastewater: one fraction of the total textile industry has its own industrial wastewater treatment plant, another fraction discharges water to municipal wastewater treatment plants, and another fraction discharges directly into surface water [38].

2.1.2. Use and Care Phase (Home Washing, Drying, and Wearing of Garments)

This step involves the washing and drying of clothing and the daily wear and tear. Numerous studies highlighted that a single household wash of 5–6 kg of synthetic clothes could be responsible for the emission of thousands of fibre fragments [41,42]. Most of them are released the first few times textiles are washed [43]. Fast fashion generates high levels of such releases: garments account for a high share of first washes, as they are used for a short time and, due to their low quality, tend to wear out quickly. The use and care phase contributes to fibre pollution, also causing the release of fibres into the air, an emission route of the same order of magnitude as domestic laundry in terms of number of fibres [33]. In fact, fibre fragments are found in the air in both indoor and outdoor environments [5–7].

Routes identified in this phase are the following:

- MaFs flow of clothing items towards disposal.

- mFs flow in water during home washing.
- mFs flow in air and water during tumble drying.
- mFs flow in the air while wearing.

2.1.3. Municipal Sewage Systems and Combined Sewer Overflow (CSO)

Households are connected to the sewage network via two different pathways: the first is the separate sewer system (SS), in which domestic and industrial wastewater on one side and rainwater on the other are drained separately. The second type is the combined sewer system (CS), in which both types of wastewaters are channelled together in one sewer to the sewage treatment plant. With CS, heavy precipitation can overload the storage capacity for the mixture of rainwater and wastewater located upstream of the municipal treatment plant: in this case, combined sewer overflow (CSO) occurs, meaning that some of the mixed wastewater bypasses the sewage treatment plant and is channelled into surface waters [44,45]. During these events, microplastics from household wastewater, industrial wastewater, and city dust (for instance, tyres, paints, and other sources of microplastics) massively pollute surface water in addition to other contaminants.

2.1.4. Municipal Wastewater Treatment Plants (WWTPs)

Municipal wastewater treatment plants (WWTPs) are potential contributors of microplastics to the aquatic environment by collecting them from various domestic and industrial applications [46]. Despite the high retention of MPs by urban WWTPs, taking into consideration the large volumes treated daily, more than one million particles can enter the aquatic environment through each WWTP [47,48]. WWTPs include preliminary treatment, primary treatment, and secondary and tertiary treatment, which is optional [49,50]. MFs with high-density are generally retained in sewage sludge during primary and secondary treatment, while low-density high/medium-sized MFs are retained with the tertiary treatment. In contrast, low density with small size MFs, especially the fraction below 300 µm, tend to float with the effluent. No distinction between treatment stages was made, only overall removal efficiencies. The routes are specified below:

- mFs flow in water effluent to surface water or irrigation.
- mFs flow to sewage sludge.

2.1.5. Sewage Sludge

Sewage sludge is the semi-solid residue generated during the treatment of wastewater at sewage treatment plants. Sludge treatments include dewatering and other treatments that do not affect microplastics' mass but alter their shape and size. A study conducted by Magni et al., 2019 [47] showed that a WWTP in northern Italy can release 3400×10^6 microplastics with sewage sludge daily. Sewage sludge can be disposed of through incineration or landfill [51,52], or can be reused in agriculture or as biogas [8,53]. The routes are specified below:

- mFs flow to the soil through biosolid application on land for agricultural purposes.
- mFs flow to energy production (biogas).
- mFs flow to incineration.
- mFs flow to landfill.

2.1.6. Environmental Routes in Soil, Water, and Air

Microplastics in the air can travel long distances through wind dispersion, contaminating urban and remote environments, contributing to airborne pollution [54,55]. They can deposit and accumulate indoors and can be resuspended due to movement and ventilation [5–7]. Microplastic pollution indoors is up to 100 times higher than outdoors. Recent research highlights that we inhale up to 130 small plastic particulates every day [56].

Microplastics in the soil can travel with water runoff into rivers, but this pathway has not been experimentally proven [16]; they can be taken up by earthworms and transported in deeper soil layers [57,58] or ingested and transported by animals [59]. Plant uptake is another potential route in soil, particularly for nanoplastics [60]. These phenomena can lead to the following potential exposure routes for human beings:

- mFs flow to drinking water [61];
- mFs flow to air and potentially inhaled [6,56];
- mFs flow to food [62].

2.1.7. Disposal Routes of Clothing Items

At the end of their life cycle, clothing items follow various disposal routes that significantly impact the environment. The following key flows are associated with clothing disposal:

- MaFs flow from clothing items to landfill, incineration, recycling, and reuse.
- mFs flow in air from landfills.
- mFs flow in water from landfill leachate.

2.2. Methods—Identification of Significant Flows (RQ2)

The scope of this section is to describe the procedure followed to identify the emission paths requiring urgency for intervention between the following:

- Flow in water from textile industries.
- Flow in water from household washing machines.
- Flow in the air from wearing.
- Flow in water from combined sewer overflows (CSOs).
- Flow in water through wastewater treatment plants (WWTPs).
- Flow through sludge.

The criteria took into consideration the number of fibres passing through the flows mentioned above using Equation (1):

$$C = MAX\,[F \times EL] \tag{1}$$

where

F = Flux entity [tonnes per year]: fibres released in a certain step of the textile lifecycle (resulting from the mapping).

EL = Environmental Load [%] defined as the fraction of flow going directly to the environment with no further treatment.

The current policies referring to each step of the textile and wastewater lifecycle were considered to assess how much public attention is devoted to a specific flow and what level of priority is perceived by policymakers in the EU.

Policies were divided into three categories, as indicated in Table 1.

Table 1. Presence of relevant policies and their respective scores.

	Score
YES—existing or proposal policy with a specific time horizon	2
YES—at monitoring level	1
NO—only general objectives	0

3. Findings

3.1. Results—Mapping of Flows (RQ1)

Utilising available data, indicative estimations have been conducted to assess the relative magnitude of contributions from different sources of microfibre (mF) and macrofibre (MaF) emissions across the textile lifecycle (Figure 2).

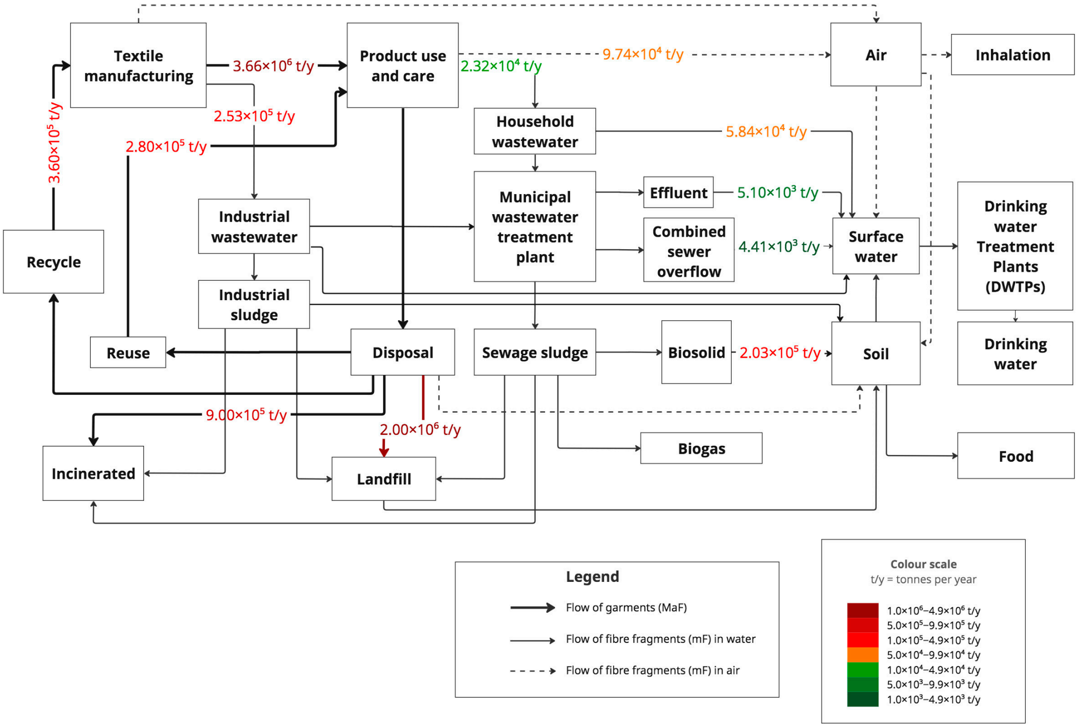

Figure 2. Micro-(mF) and macro-(MaF) fibre flux estimation throughout the textile lifecycle. Values are expressed in t/year (t/y) and visualized using a color scale.

To obtain a flow in t/year on the reference scale, raw data were scaled up as described in the following paragraphs.

3.1.1. Flow from Manufacturing to Wastewater Treatment Plants (WWTPs) to the Environment

Considering the manufacturing phase, no study quantifying the emission of fibre fragments to the air during production has been retrieved.

Regarding the flows of synthetic fibre fragments from textile industries to water, only local monitoring campaigns have found plastic fibres measured in industrial effluents in terms of concentrations and of mF per year. Data was scaled up with Equation (2):

$$F_{ind} = flow_{ind} \times 365 \times W_{i_A} \times 10^{-6} \tag{2}$$

where $flow_{ind}$ is the flow of fibres in industrial wastewater reported in the monitoring campaigns, expressed in items/day/industry, W_{i_A} is the average weight of a microplastic fibre (based on the average density of polyester fibre, see Tables S2 and S3A in the Supplementary Material), and “no. of industries” is the number of textile industries in the area selected. This process was repeated using the concentration of fibre fragments reported in the following studies: Xu et al., 2018 [37], Zhou et al., 2020 [38], Lv et al., 2019 [39], Chan et al., 2021b [63], Deng et al., 2020 [64], and Sun et al., 2019 [65], resulting in total flows ranging from 1.24×10^2 to 2.89×10^7 (in t/year) with a median value of 4.40×10^5. A local monitoring campaign performed by Long et al., 2021 [66] highlighted that the mPs abundance (in terms of items/litre) in industrial wastewater was more than twice as much as in domestic wastewater, suggesting that microplastic abundance in wastewater is higher from industrial sources than from domestic sources [67,68].

Assuming that 50% of the textile industry is connected to a centralised or municipal wastewater treatment plant with a median removal efficiency of 97.5% for microplastics (see Table S5 in Supplementary Material), the annual emission of fibres from manufacturing processes reaching the environment would range between 6.63×10^1 and 1.55×10^7 t/year (median value of 2.53×10^5).

The wide range of values for the flow released during this stage of the textile lifecycle mirrors a high uncertainty due to these factors:

- It was not possible to scale up data referring to textile industries based on company size or sales (on the assumption that larger companies release a larger amount of mFs), due to the lack of a comprehensive mapping of textile industries throughout European countries; hence, a substantial simplification has been introduced.
- The fraction of textile industries connected to sewage systems is unknown, so both the amount and the fate of this flow have a high degree of uncertainty.
- Since the industries mentioned in the studies are located in China rather than Europe, the findings may be influenced by a different regulatory environment and contextual factors, which could lead to a different level of microplastics in the discharge. Therefore, the concentrations detected in the effluents for those companies may not be representative of the European context.

3.1.2. Flow from Product Use and Care to Municipal WWTP via Water

To estimate the flow of fibres from home washing to domestic wastewater, the following information is essential [69]:

- Data for purchasing garments versus demographics.
- Data required for the type of garments, fibre types, and fabric types.
- Data for washing or tumble drying per person

Belzagui and colleagues [27] estimated the mass flow of fibre fragments detached from garments from home washing reaching the aquatic environment on a global basis, using a set of parameters gathered in Table S4, including data about the detachment rate of fibre fragments from different textile garments, the volume of laundry effluents, the percentage of municipal water that has been treated, and the proportion of front- vs. top-loading washing machines, see Equation (3) (Source: [27]):

$$f_{hb} = flow_h \times Q_{w_m} \times [D_{UA} + I_{UA}\,(1 - R) \times S \times (W_F + W_T \times y)] \quad (3)$$

where f_{hb} is the annual flux of mFs reaching aquatic environments, in items/year, $flow_h$ is the flux of fibres in terms of items/litre, Q_{w_m} is the annual volumetric flow of washing machines' effluents in L/year, and D_{UA} is the proportion of municipal water directly discharged to aquatic environments. I_{UA} is the proportion of treated municipal usedwater, R is the proportion of retained microplastics as a function of the existing municipal treatment technologies, S is the proportion of synthetic versus natural fibres used globally in the manufacture of textile garments, W_F is the volume distribution factor for front-loading washers, and y is the factor describing the detachment rate between top- and front-loading washing machines, while W_T is the volume distribution factor for top-loading washers.

The flow was expressed in mass units using the procedure described in Belzagui et al., 2019 [70]; the linear weight of an individual filament fibre was calculated with Equation (4) (Source: [70]):

$$C = d_{avg}^2 \times \frac{\pi * \gamma}{400} \tag{4}$$

where C is the linear weight of a microplastic expressed in decitex (1 dtex = 1 g per 10,000 m), d_{avg} is the average diameter of the microplastic (20 µm [70]), and γ is the specific weight of the fibres, in g/cm^3, and then estimating the annual mass flux by multiplying the flow by the linear weight of an individual filament fibre per L_{avg}, which represents the average length of a fibre (0.30 mm as in [70]), see Equation (5):

$$F_{hb} = f_{hb} \times C \times L_{avg} \times 10^{-9} \tag{5}$$

Wang et al., 2020 [51] developed a spatial model that integrates a range of variables such as gridded population data, fibre product consumption rates, laundry frequency, lifetime of garments in apparel, and MPF emission factors during household washing processes, described through Equation (6):

$$F_{hw} = P_i \times SC_i \times LT \times f_i \times P_{MW} \times EF \tag{6}$$

where P_i represents the population in each grid box i ($30'' \times 30''$); SC_i refers to the annual consumption of synthetic fibres per capita (kg per capita per year); LT is the average number of years that synthetic fibres are used in clothing, f_i is the laundry frequency conducted in a standard household washing routine within a year (times per year); P_{MW} is the ratio of laundry cycles conducted using a washing machine to the total number of laundry cycles within a year; EF is the microplastic emission factor during machine washing (mg per kg). This information is summarised in Table S4 (Supplementary Material).

The data calculated in the studies mentioned above were already available for the reference scale chosen for this study in spatial terms (geographical Europe) and time unit (1-year balance). The resulting flow from domestic wash ranges between 2.32×10^4 and 4.50×10^5 t/year. These results come, respectively, from the studies of Belzagui et al., 2020 [27], representing the lower value in the range, and Wang et al., 2020 [28], representing the upper value in the range. These values are in line with results reported by Gavigan et al., 2020 [26], which theorised that 1.80×10^4 t/year of synthetic fibres were released in Europe in 2016. The median value for this flow results in 2.32×10^4.

3.1.3. Flow from Product Use and Care to the Environment via Water (Untreated)

It is estimated that about 85% of the European population is connected to centralised wastewater treatment plants (WWTPs) with secondary or tertiary treatment, while the rest (15%) are connected to a WWTP with primary treatment only or not connected at all. In Schell et al., 2020 [16], the daily input of microplastics via untreated wastewater into European surface water is estimated to be 2.70×10^9.

The data was scaled up by the authors using Equation (7):

$$F_{un} = f_{un} \times 365 \times W_{i_B} \times 10^{-6} \tag{7}$$

where f_{un} is the input from households not connected to sewer systems in terms of items/day, and W_{i_B} is the average weight of a microplastic (see Table S3B).

The resulting average flow of microplastic fibres coming from untreated domestic wastewater on a yearly basis is 5.84×10^4 t of fibres/year to the environment. This small fraction of untreated wastewater generates a load that is higher than the load from the larger fraction of treated wastewater.

3.1.4. Flow from Product Use and Care to the Environment via Air

Some fibres broken by mechanical agitation during washing and drying remain weakly attached to the fabric surface and are released into the air when worn [69,71]. Fibre flows to air during the wearing of textiles have been measured by De Falco et al. in 2020 [33] in terms of fibre fragments per person, per year, making the following assumptions: (1) one person performs 55 laundry cycles per year with an average load of 4 kg of polyester garments per wash; and (2) one person wears 1 kg of polyester garments and performs similar movements simulated during the air tests for eight hours per day. The results suggest that one person wearing and washing polyester garments could release 2.98×10^8 fibre fragments/year to water by washing and 1.03×10^9 to air by wearing [33].

Scaling up the data to the European population and converting to mass by using data from Table S3C, results show emissions ranging from 8.60×10^3 to 1.86×10^5 t/year from wearing, with a median value of 9.74×10^4.

3.1.5. Flow from Sewage System to Combined Sewer Overflow (CSO) via Water

According to Kimmel et al., 2024 [45], who estimated the annual flows of synthetic microplastic fibres to surface water from CSOs, taking Germany as a reference scale, washing machines disperse 500 t/year into the sewer system, of which 24 t/year escape from wastewater treatment systems, and 21 t/year escape from CSOs untreated. Assuming that CSO frequency and household emissions in Europe are the same in Germany, the total flow for Europe was calculated with Equation (8):

$$F_{CSO} = f_{CSO_g} \times \frac{p_{eu}}{p_g} \tag{8}$$

where f_{CSO_g} is the flow of synthetic fibres from washing machines to CSOs in Germany expressed as t/year, and p_g is the population of Germany, while p_{eu} is the population of geographical Europe. The resulting flow ranges between 1.12×10^2 and 8.70×10^3, with a median value of 4.41×10^3.

3.1.6. Flow from Wastewater Treatment Plants (WWTPs) to the Environment via Water

Table S5 reports the microplastic concentrations detected in WWTPs' effluents. Equation (9) was used for calculating flows:

$$F_w = e_c \times Y \times f_s \times t_c \times 365 \times \frac{p_{eu}}{p_{eq}} \times W_{i_D} \times 10^{-6} \tag{9}$$

where e_c is the concentration of microplastics in the effluent expressed in items/litre, Y is the percentage of synthetic, f_s is the percentage of microplastics in the fibre shape, t_c is the capacity of the treatment plant in terms of litres treated per day, $\frac{p_{eu}}{p_{eq}}$ is the proportion between the population of geographical Europe and the population served by the treatment plant, and W_{i_D} is the average weight of a microplastic calculated in Table S3D.

In the cases where e_c was expressed as flow of microplastics per hour or day, the Equation was simplified as reported in Equation (10):

$$F_{ws} = e_c \times Y \times f_s \times \frac{p_{eu}}{p_{eq}} \times W_{i_D} \times 10^{-6} \tag{10}$$

This process was applied to data coming from the studies indicated in Table S5 (Supplementary Material).

The flow of microplastics from WWTPs to the environment, considering only synthetic fibres coming from domestic machine washing, ranges between 1.09 × 10^2 and 4.64 × 10^4 t/year, with a median value of 5.1 × 10^3 t/year.

These values align with those from a 2016 study by Hartline et al. [72], who used a different method to calculate that 2.70 × 10^3 tonnes of microplastics are released annually from WWTPs' effluents in geographical Europe. Assuming a 98.4% capture rate (based on Murphy et al., 2016 [73]), Hartline et al. extrapolated fibre release rates from polyester fleece jackets to estimate that approximately 1.02 kg of fibre fragments are discharged daily into WWTP effluent for an indicative city population of 100,000.

The values also align with a 2020 study by Wang et al. [28], which reported a value of 1.00 × 10^4 t/year. Wang and colleagues integrated microplastic fibre production data with the HydroWASTE, estimating the amount of microplastics from domestic wastewater removed by WWTPs on a global scale. Their findings highlighted that European countries account for half of the top 20 countries in terms of microplastic removal, and the studies retrieved and summarised by the authors in Table S5 indicate a median removal efficiency for microplastics of 97.5%.

3.1.7. Flow from Sewage Sludge to the Environment

Nizzetto et al., 2016 [8] theorised that 6.3 × 10^4–4.30 × 10^5 tonnes of MPs are added every year to European farmlands, while Mohajerani et al., 2020 report a range of 2.6 × 10^4–1.51 × 10^5 t/year [53]. These values are in line with results reported by Gavigan et al., 2020 [26], who determined that 2.40 × 10^4 tonnes of synthetic fibres were released on the terrestrial environment for the year 2016, and with results from calculations starting from the data of the monitoring campaigns retrieved in the literature by the authors (7.60 × 10^4–8.09 × 10^5 t/year) and presented in Table S6 in Supplementary Material. In fact, despite an estimation of microplastic flows from municipal sewage sludge to agricultural land found through a literature search, the flows of fibres on agricultural land from sewage sludge have been estimated also through Equation (11):

$$F_s = C_s \times f_s \times P \times L \times W_{i_s} \times 10^{-6} \tag{11}$$

where C_s is the concentration of microplastics in biosolids, f_s is the fraction of microplastics reported to have a fibre shape, P is the annual production of biosolids in Europe, L is the fraction of biosolid applied on agricultural land, and W_{i_s} is the average weight of a single microplastic fibre in sludge.

The values for biosolid production and the fraction applied in agriculture for Europe adopted in this study are indicated in Table 2. In the study, the average weight (W_i) of a microplastic is estimated to be 2.45 mg [53].

The resulting flow ranged between 2.60 × 10^4 and 8.09 × 10^5 t/year. These results come, respectively, from the studies of Mohajerani et al., 2020 [53], representing the lower value in the range, and Hernández-Arenas et al., 2021 [74], representing the upper value in the range. The median value resulting from all the values estimated is 2.03 × 10^5 t/year.

Table 2. Supporting data for calculating flows of microplastics from sewage sludge to agricultural land.

	Value	Source
P	11,000,000	[53,75]
L	47%	[53]
W_{i_s}	2.45	[53]

3.1.8. Flow from Production to Disposal Routes

To identify the release of fibre fragments, it is necessary to study the purchasing behaviour of consumers. This type of data was found in the Environmental Improvement Potential of textiles (IMPRO Textiles) by the European Commission Joint Research Centre [76] and in the European Environmental Agency Report [32]:

- Net synthetic fibre production for clothing: 3.60 × 10^6 t/year [32].

This data was calculated using Equation (12):

$$F_d = PROD + IMP - EXP \tag{12}$$

where $PROD$ is the flow of synthetic fibres produced in Europe, IMP is the flow of imports of synthetic fibres, and EXP is the flow of exports.

- Clothing reused: 8% [76], which, referring to net production, means $0.08 \times F_d$ and so 2.80×10^5 t/year;
- Clothing recycled: 10% [76], which means $0.1 \times F_d$, and therefore means 3.60×10^5 t/year;
- Clothing incinerated: 25% [76], which means $0.25 \times F_d$, so 9.00×10^5 t/year;
- Clothing landfilled: 57% [76], which means $0.57 \times F_d$, so 2.00×10^6 t/year.

3.2. Results—Identification of Significant Paths

Among the different paths involving macro-fibres (MaF in map), the highest flows in terms of t/year are identified in production (3.60×10^6 t/year of synthetic clothing) and disposal in landfill (2.00×10^6 t/year), as emerges in official documents and statistics.

Differently, among the paths involving fibre fragments (mF), the high variability and uncertainty in terms of orders of magnitude and approximation do not allow a direct comparison between different flows in the map. However, some flows requiring particular attention can be identified considering the orders of magnitude involved and the load of the flows in the environment (Table 3).

Table 3. Minimum, maximum, and median values for the flows of synthetic fibre fragments in terms of unit of mass released per unit of time in geographical Europe (F) and fraction loading on the environment (EL). For the EL column, [A] means assumption by the authors, and numbers in brackets mean literature reference.

	EL (%)	**F × EL (T/Year)**		
		Min	**Max**	**Median**
Flow from industrial processes via water	50 [A]	6.63×10^1	1.55×10^7	2.53×10^5
Flow from product use and care via air	100 [A]	8.06×10^3	1.86×10^5	9.74×10^4
Flow from wastewater treatment plants' effluent via water	2.5 (Table S5)	1.09×10^2	4.64×10^4	5.10×10^3
Flow from product use and care (untreated) via water	15 [16]	5.84×10^4		5.84×10^4
Flow from the combined sewer overflow via water	4.2 [45]	1.12×10^2	8.70×10^3	4.41×10^3
Flow from sewage sludge via soil	47 [53]	2.60×10^4	8.09×10^5	2.03×10^5

3.3. Existing Policies

The study examined whether policies or regulatory frameworks addressing the specified flows are currently in place. A summary is presented in Table 4.

Table 4. Presence of relevant policies and their respective scores—Results.

Flow	Existence of Policies
Textile industries effluents	1
Air during use	0
Washing machine effluent	2
Combined sewer overflow	0
Municipal water effluents	2
Municipal sludge	1

- Microplastic removal from wastewater treatment plants (WWTPs) was considered in the Directive 2024/3019/UE [77] with the aim of removing micropollutants, including microplastics, from urban wastewater through an extended producer responsibility (EPR) scheme and the introduction of quaternary treatment in large WWTPs with over a 150,000 population equivalent and over a 10,000 population equivalent in sensitive areas by 2045. Therefore, regulations addressing the flow from WWTPs to the environment via water currently exist with a specific timeframe: the authors assigned a score of 2.
- No proposal of regulation was explicitly made for microplastics released from textile wastewater, but an attempt was made in 2020 by France with a proposal stating that by 2025 every new washing machine must have a filter to catch plastic fibre fragments that come away from clothing during washing (France Law no. 2015-992 [78]). This proposal has been halted and is currently awaiting harmonisation at the EU level in terms of protocols for detecting and measuring microplastics. A recent review clause of the Ecodesign regulation (no. 2019/2023, Article 8, paragraph f [79]) provides that "by 25 December 2025, the Commission should assess the possibility of new requirements for reducing the amount of microplastics in the water outlet of washing machines, for example with filters or other technical solutions", so there is a scheduled revision of a regulation addressing fibre release from home washing via water. For this reason, the authors decided to assign a score of 2 for this flow.
- Directive 2024/3019/UE [77] also addressed textile industry effluents and municipal sludge, but only to commit to the realisation of the monitoring of microplastics in biosolids and in certain industrial wastewater effluents. For these two flows, the policy score assigned by the authors is 1 because regulation exists but prescribes only an intensification in controls and monitoring.
- No regulation addressed the emission of fibres in air, despite the Cross Industry Agreement promoted by Euratex [21] that paved the way for the eco-design of textiles in this direction. So, the authors assigned this specific flow a score of 0 because it lacks what they regard as existing policies.
- No proposal of regulation was made regarding microplastics released from CSOs: the authors assigned a score of 0.

4. Discussion

4.1. Mapping and Identification of Significant Flows

Production of textiles and landfill disposal are the two most significant flows of MaF (macro-fibres), each with a magnitude of 1.00×10^6 t/year. Landfill leachate is expected to release substantial amounts of mF (micro-fibre) fragments into the environment, as well, but current data is insufficient to estimate the exact quantity.

From Table 3, considering only the flows of fibre fragments (mF), the flows of fibres from industrial wastewater were the highest but also more uncertain, ranging several orders of magnitude; therefore, it was difficult to compare this flow with the others on the mapping, mainly because the secondary data used were not site-specific for the European area.

Considering the remaining flows, the emission paths requiring urgent intervention are the flows from municipal sludge to the soil and the flow from the use and care phase to the air. A total of 47% of sludge from WWTPs is recycled as biosolid on agricultural land in Europe, leading to potential adverse effects on soil organisms, altering the soil–plant system [80], and increasing the accumulation of other micropollutants, such as heavy metals [53,75]. Recent studies have investigated alternative methods to reuse municipal solid waste for energy recovery, aiming to promote sustainable development while mitigating microplastic pollution [81]. Fibres shed to the air from wearing of garments go directly to the environment without further treatment and are potentially inhaled, especially in indoor environments: this is reflected by the fact that, in the human body, the most significant fraction of microplastics is found in the lungs, as already highlighted in a study by Pauly et al. in 1998 [82]. The impact on the respiratory system of the inhalation of poorly soluble particles is explained by the mechanism of dust overloading [83,84].

In the past years, the emission of fibres via water from home washing was identified as the main pollution path by researchers, but fibre fragments are present in the air as well [5–7,33,85], with textile fibres of natural origin constituting a larger fraction than from a synthetic one (70–75% vs. 17–30%) [5,6,86]. Fibre emission in the air may be underestimated since there are no studies regarding emission pathways of fibres in the air from the industrial processes, nor from the disposal phase. As highlighted in Shao et al., 2022 [54], there is a need for a comprehensive inventory of airborne microplastics.

Studies show that the type of yarn, textile, and garment formation, as well as the abrasion caused by machine washing, influence the detachment of fibres from the garments and their air release [33]. A study by Cai et al., 2020 [87] highlights the role of processed textile surfaces and the cut edges in fibre shedding. Stanton et al. (2023) [88] highlight the crucial influence of garment design and manufacturing on global microplastic emissions in Global South communities: the study reveals that hand laundering, common in off-the-grid areas, sheds fibres comparable to machine washing, underscoring the need for an industry-wide action to address textile fibre pollution at the very early stages of design, rather than relying solely on the presence of fibre interception infrastructures, which are not available everywhere.

Additionally, the role of CSOs requires special attention. The contribution of city dust to global microplastic pollution is relevant in terms of loads to the environment: considering microplastics from tyres, 20,000 t/year enter the WWTPs, 957 escape from the treatment, while 856 escape from CSOs to surface water untreated. If we were to consider only textiles, installing filters or eliminating CSOs would in any case be equivalent to reducing the outgoing MPs load by half. Taking both textiles and tyres into consideration, the situation changes: intervening on CSOs with prevention or mitigation measures would have a larger impact than intervening in washing machine filters [45].

Interestingly, the flows that achieved a lower score in terms of flow and load on the environment are the ones that are subjected to a more stringent regulation (flow from washing machines and from WWTP effluent), while the flows that appear more significant (sludge and air) are the least regulated up to now, and more research is required on them.

This gap in regulation is particularly concerning given the growing evidence of the potential environmental impact of microfibres: their toxicity is not solely due to their physical presence, but is amplified by the functionalization of textiles and the tendency of microfibres to adsorb hazardous substances such as additives and dyes commonly used during textile production, increasing their overall environmental risk [89].

The most cost-effective way to tackle the issue is likely the implementation of a mix of actions throughout the entire lifecycle of textile products, from garment design and manufacturing to the effective treatment of wastewater [90]. This approach should foster a multi-stakeholder dialogue and promote a cross-value-chain perspective, shifting the focus towards pathways that have previously received limited attention.

4.2. Limitations of the Study

It is essential to notice that the model proposed has some limitations discussed hereafter.

In general, local monitoring campaigns were more frequently found in the literature. They perform site-specific detection of fibres by sampling a volume of water. The resulting unity of measure was, in most cases, in the number of items per unit of volume, often scaled up in time (for instance, from daily to yearly basis) but not in space. Papers referring to t/year modelled the specific route of mFs to washing machines through WWTPs, since emissions from home washing are often referred to as mg fibres per kg of textile washed. If data on weight were not readily available, then a conversion was performed by calculating the average weight of a singular fibre fragment, starting from average densities of three types of polymers and size ranges of microplastics detected in different steps of the textile lifecycle, even though it introduces an approximation.

The results of the two studies that modelled fibre emissions (Belzagui et al., 2020 [27]; Wang et al., 2020 [28]) differ by an order of magnitude: it is hard to establish which one of the two studies underestimated/overestimated the flow with respect to the other because, although they refer to the same geographical area, they adopted two different approaches to go towards a mass balance (Belzagui started from volumes, Wang from consumption rates) and focused on different parameters (Belzagui on front-load vs. top-load washing machines, Wang et al. on machine washing vs. hand washing). Moreover, the high variability in release data from domestic washing machines might be due to cultural differences in laundry behaviours across different countries [91].

Studies examining later stages of the textile lifecycle, such as wastewater treatment plants and sludge, report the presence of microplastics in various shapes (e.g., fibres, fragments, and others). However, it is difficult to determine whether a fibre-shaped microplastic originates from fashion garments, home textiles, or other textile products unrelated to clothing or home use.

Regarding industrial wastewater effluents, only local monitoring campaigns were found, and these led to values that ranged between several orders of magnitude. This situation can originate from different reasons discussed hereafter:

The factors influencing the natural variation in values inside a specific range are often not identified in existing studies about microplastics. Concentrations of MFs in wastewater show some seasonal, week/weekend-based, and diurnal variations due to human activities and water consumption rates [92–94]. mF occurrence seems to be highly variable, depending on different environmental (weather, season, etc.) and behavioural variables (cultural differences in laundry behaviours, consumption habits, etc.) [91].

Data inconsistencies are present due to a lack of shared analytical protocols for sampling and measuring microplastics, leading to different units of measure for microplastics that are difficult to compare, as readily available conversion factors are not available. There is no consensus on how to measure microplastics: detection involves several analytical techniques, including SEM, FT-IR, Raman, and others, resulting in inconsistencies between different studies. Moreover, a drawback of conventional methods is their high costs, labour-intensive procedures, and limited accessibility. Recent studies are exploring alternative approaches to detect and quantify microplastics, such as fluorescence-based techniques [95] or methods utilising spectrophotometry [96], but further research is needed on this topic. Also, the lack of a shared lower size limit [16] can lead to inconsistencies: most procedures allow sampling particles down to a minimum size of 20 µm, while very few studies measured smaller particles, despite the fact that they are more frequently found in the environment and more interesting from a toxicological point of view since they could enter cells [97]. The lack of common ground limits the comparability of available studies and is also reflected in the extensive range of values reported in the flow-map for this study. A standard nomenclature and classification, and shared sampling and analytical methods, should be defined to maintain consistency across studies and legislation [98,99].

The estimates are based on studies conducted between 2016 and 2024, a period marked by an increasing use of synthetic polymers. However, the underlying data were not collected uniformly across time or under consistent conditions. As a result, the model may underestimate current flow magnitudes, particularly where recent trends suggest accelerated growth. This temporal and contextual variability is acknowledged to ensure transparency and to appropriately frame the findings within the limitations of the available data.

4.3. Further Limitations

Natural fibres were not included in the present model due to limited available data. However, future research studies should prioritise their investigation, as they may also pose environmental risks. Although derived from natural sources, these fibres often undergo extensive processing involving potentially hazardous chemicals [100], leading to the leaching of substances such as chemical dyes and finishing agents [101]. In addition, natural fibres have been shown to adsorb environmental pollutants, including heavy metals, pharmaceuticals, and other organic contaminants. Structural modifications intended to improve their performance in the textile industry can further reduce their biodegradability [34]. Some studies report that natural textile fibres are the dominant fibre type found in freshwater and atmospheric environments [86] and in air in indoor and outdoor environments [6,10,85] with a fraction of 67% natural vs. 33% synthetic, 83% vs. 17%, and 73% vs. 27%, respectively. During machine washing, natural fabrics tend to release more fibre fragments than purely synthetic fabrics: natural fibres are staple, and, therefore, they are likely to be more easily released compared to synthetic fibres, which are often present in the form of filament yarns [102]. For these reasons, the authors recommend including natural fibres in future flow-mapping efforts, as their role in waterborne and airborne pollution may be underestimated.

Some flows could not be quantified in the flow map developed in this study due to a lack of data identified in the literature. While landfills are often considered “sinks” for household and industrial plastic waste, the presence of microplastics in landfill leachate suggests they may also act as sources of pollution [103–106]. For instance, He et al. (2019) reported a concentration of microplastics in landfill leachate ranging between 0.42 and 2.46×10^4 mF/m^3 [106]. However, data on contaminants in landfill leachate are scarce due to limited monitoring requirements [107]. There is a lack of regulation in the EU to monitor the volumes or concentrations of contaminants occurring in landfill leachates. For this reason, it was not possible to estimate the flows of synthetic fibre fragments from landfill leachate.

Also, data regarding the flow from manufacturing processes to air, and from industrial washing machines to water, were scarce, so these flows were excluded from the analysis. This could lead to a potential bias in the decision analysis, bypassing potentially relevant but understudied flows. Future research should focus on those pathways to provide a comprehensive mapping throughout the entire textile lifecycle.

Nanoplastics (<1 μm) were not part of this estimation. However, nano fibres are more difficult to detect, but they represent a higher threat with respect to larger fibres, since they can travel further inside the human body. For this reason, due to their toxicological relevance, it is imperative to direct research towards the detection of these compounds across different environmental matrices and to determine their origin and exposure pathways. In fact, considering the tonnage of microplastics, a bias could be introduced, since a small load of nano fibres could be more dangerous to ecosystems and human health than a high tonnage of larger, easily removable fibres. However, a lack of intervention on large loads of fibres can be detrimental in the long run, as over time those fibres will fragment into nanoplastics. The authors, therefore, recommend that future research integrate the flow maps with information about fibre size distribution and possibly correlate each flow with its potential ecotoxicological effect. For this purpose, performing a risk analysis may be helpful to connect the mapping of this study with the potential exposure pathways to the ecotoxicological relevance.

4.4. Sensitivity Analysis

The authors conducted a simplified sensitivity analysis to evaluate how varying the most uncertain values of the environmental load (EL) influences the scoring outcomes. Among the environmental load (EL) values presented in Table 3, two are based on assumptions made by the authors: the EL for the flow from textile manufacturing to water was assumed to be 50%; the EL for fibre release to air during garment use was assigned 100%.

The EL value for the flow from wastewater treatment plants to water was obtained by the median value of removal efficiencies reported in the literature. The EL value for untreated household wastewater comes from [16], for CSOs from [45] and for sludge application on land, the EL value comes from [53]. This value was triangulated with updated data from Eurostat regarding the application of biosolids on land.

Therefore, the sensitivity analysis focused solely on the EL for industrial processes and for release to the air during garment wear. A variation margin of ±25% was applied for the first and −30%/−15% for the second, and all possible combinations were analysed. Specifically:

- For the EL of the flow from textile manufacturing to water, the values 25, 50, and 75% were considered.
- For the EL of the flow of fibres to air during garment use, the values considered were 70, 85, and 100%.

As shown in Table 5, the ranking of the flows remains stable in cases A, C, D, E, and F, while in cases B, G, and H, a change in prioritisation can be observed: the flow of sewage sludge shifts from second to first place. These cases correspond to scenarios where the EL for textile industries is 25%. This indicates that when a significant proportion of industries are connected to wastewater treatment plants, sewage sludge becomes the most critical fibre flow. No shift is observed when changing the values of the load of fibres in the air in the selected range.

Table 5. Evaluation of sensitivity with respect to the environmental load (EL). The values of EL considered for the sensitivity analysis are shown in bold.

A	Original Situation EL Industry = 50 EL Air = 100		(A) EL Industry = 75 EL Air =100		(B) EL Industry = 25 EL Air =100		(C) EL Industry = 50 EL Air = 85		(D) EL Industry = 50 EL Air = 70	
	EL	F × EL	EL	F × EL	EL	F × EL	EL	F × EL	EL	F × EL
Flow from industrial processes via water	50	2.53×10^5	**75**	3.80×10^5	**25**	1.27×10^5	50	2.53×10^5	50	2.53×10^5
Flow from product use and care via air	100	9.74×10^4	100	9.74×10^4	100	9.74×10^4	**85**	8.28×10^4	**70**	6.82×10^4
Flow from WWTP via water	2.5	5.10×10^3	2.5	5.10×10^3	2.5	5.10×10^3	2.5	5.10×10^3	2.5	5.10×10^3
Flow from product use and care (untreated) via water	15	5.84×10^4	15	5.84×10^4	15	5.84×10^4	15	5.84×10^4	15	5.84×10^4
Flow from CSO via water	4.2	4.41×10^3	4.2	4.41×10^3	4.2	4.41×10^3	4.2	4.41×10^3	4.2	4.41×10^3
Flow from sewage sludge via soil	47	2.03×10^5	47	2.03×10^5	47	2.03×10^5	47	2.03×10^5	47	2.03×10^5
B	Original situation EL industry = 50 EL air = 100		(E) EL industry = 75 EL air = 85		(F) EL industry = 75 EL air =70		(G) EL industry = 25 EL air = 85		(H) EL industry = 25 EL air = 70	
	EL	F × EL	EL	F × EL	EL	F × EL	EL	F × EL	EL	F × EL
Flow from industrial processes via water	50	2.53×10^5	**75**	3.80×10^5	**75**	3.80×10^5	**25**	1.27×10^5	**25**	1.27×10^5
Flow from product use and care via air	100	9.74×10^4	**85**	8.28×10^4	**70**	6.82×10^4	**85**	8.28×10^4	**70**	6.82×10^4
Flow from WWTP via water	2.5	5.10×10^3	2.5	5.10×10^3	2.5	5.10×10^3	2.5	5.10×10^3	2.5	5.10×10^3
Flow from product use and care (untreated) via water	15	5.84×10^4	15	5.84×10^4	15	5.84×10^4	15	5.84×10^4	15	5.84×10^4
Flow from CSO via water	4.2	4.41×10^3	4.2	4.41×10^3	4.2	4.41×10^3	4.2	4.41×10^3	4.2	4.41×10^3
Flow from sewage sludge via soil	47	2.03×10^5	47	2.03×10^5	47	2.03×10^5	47	2.03×10^5	47	2.03×10^5

Additional EL values were tested to identify thresholds that trigger changes in ranking. These were found to be as follows:

EL = 40% for the flow from industrial processes (values below this threshold cause sewage sludge to become the top priority);

EL = 60% for the flow from product use and care to air (values below this cause the garment wear to air flow to drop from third to fourth place).

Despite these variations, the overall prioritisation remains stable across a broad range of EL values, indicating that the study's conclusions are reasonably robust.

5. Conclusions

Emissions of fibres from synthetic textiles occur across various stages, including production, use, and waste management. Textile manufacturing releases fibre fragments into wastewater and air during processes such as cutting and weaving. Domestic washing and the use of garments contribute to the release of fibres into both water and air. WWTPs achieve high removal rates, but recycling of municipal sludge as biosolid contributes to polluting agricultural soils with microplastic fibres. Inconsistent methodologies and the absence of standardised detection and measurement protocols limit the reliability of current data.

However, from rough estimations in the context of European countries conducted by harmonising the existing literature, some conclusions are drawn. Regarding the flows of MaF, production and disposal to landfills account for the highest flows (1.00×10^6 order of magnitude). Although landfill leachate is likely to release significant amounts of fibre fragments (mF) into water and soil over the long term, current data are insufficient to support a quantitative estimate.

Considering the flows of mF, textile industries are suspected to release the highest flows of fibres in terms of tonnes per year in the textile lifecycle (median value is of the order of magnitude of 1.00 × 10^5). Still, the available data is not sufficiently precise or site-specific to perform a representative estimation. Following industrial discharges, municipal sludge from wastewater treatment plants and air emissions during the use and care phase are the next largest sources of fibre fragments (mF) released to the environment in terms of tonnes per year (median value is of the order of magnitude of 1.00 × 10^5 tonnes per year). Current regulation is unevenly distributed. In fact, significant flows such as biosolid application in agriculture and air emissions from wearing receive insufficient attention.

From a scientific perspective, these results help address existing knowledge gaps, particularly concerning understudied pathways of fibre fragments. These include flows from textile industries to water and air, as well as from landfill leachate to aquatic environments. The study also highlights the need to incorporate natural fibres into flow models and to integrate flow mapping with risk assessments by correlating identified pathways with their ecotoxicological relevance. This includes considering factors such as particle size (e.g., nanoplastics), toxicity mechanisms, and potential routes of intake. Future research should also prioritise the development of standardised methods for detecting and analysing fibre fragments to enable more accurate and comparable quantitative assessments. The authors suggest that, although the spatial reference for this study was limited to geographical Europe due to data availability and regulatory frameworks, the modelling approach is adaptable and should be applied to other regions of the world.

From a practical point of view, these results are helpful for decision-makers to simulate the impact of policies. The authors suggest that this study can contribute to strengthening regulations on sludge application on land and evaluating other management strategies. Furthermore, it encourages innovation throughout the textile lifecycle, beginning with product design and manufacturing, with the goal of minimising fibre shedding. The authors also recommend the introduction of a standardised metric for fibre shedding to support sustainability assessments of textile products.

Engaging with industry, policymakers, and civil society is essential to address microfiber pollution and lead to sustainable change.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su17198726/s1. References [108–115] are cited in the supplementary materials. Table S1. Search keywords and results from Scopus. Table S2. Average densities of three types of polymers commonly used for textiles. Table S3A. Calculation of the average weight (Wi) of one microplastic fibre—industrial effluents from textile manufacturing industries—in bold, and the minimum and maximum Wi selected to model the flow. Table S3B. Calculation of the average weight (Wi) of one microplastic fibre—water from domestic washing machine effluent—in bold, and the minimum and maximum Wi selected to model the flow. Table S3C. Calculation of the average weight of one microplastic fibre—air—in bold, and the minimum and maximum Wi selected to model the flow. Table S3D. Calculation of the average weight of one microplastic fibre—municipal wastewater treatment plant effluent—in bold, and the minimum and maximum Wi selected to model the flow. Table S4. Supporting data for modelling flows from machine washing. Table S5. Studies reporting microplastic concentrations in WWTP effluents. Table S6. Studies reporting microplastic concentrations in sewage sludge.

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