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Review

A Systematic Literature Review for Addressing Microplastic Fibre Pollution: Urgency and Opportunities

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Abstract: Microplastic fibre (MPF) pollution is a pressing concern that demands urgent attention. These tiny synthetic textile fibres can be found in various ecosystems, including water and air, and pose significant environmental risks. Despite their size (less than 5 mm), they can harm aquatic and terrestrial organisms and human health. Studies have demonstrated that these imperceptible pollutants can contaminate marine environments, thereby putting marine life at risk through ingestion and entanglement. Additionally, microplastic fibres can absorb toxins from the surrounding water, heightening their danger when consumed by aquatic organisms. Traces of MPFs have been identified in human food chains and organs. To effectively combat MPF pollution, it is crucial to understand how these fibres enter ecosystems and their sources. Primary sources include domestic laundry, where synthetic textile fibres are released into wastewater during washing. Other significant sources include industrial effluents, breakdown of plastic materials, and atmospheric deposition. Additionally, MPFs can be directly released into the environment by improperly disposing of consumer products containing these fibres, such as non-woven hygienic products. A comprehensive approach is necessary to address this pressing issue, including understanding the sources, pathways, and potential risks of MPFs. Immediate action is required to manage contamination and mitigate MPF pollution. This review paper provides a systematic literature analysis to help stakeholders prioritise efforts towards reducing MPFs. The key knowledge gaps identified include a lack of information regarding non-standardised test methodology and reporting units, and a lack of information on manufacturing processes and products, to increase understanding of life cycle impacts and real hotspots. Stakeholders urgently need collaborative efforts to address the systematic changes required to tackle this issue and address the proposed opportunities, including targeted government interventions and viable strategies for the industry sector to lead action.

Keywords: microplastic fibres; microfibres; fibre fragmentation; shedding; microplastic pollution; domestic laundry; wastewater; wastewater treatment

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1. Introduction

The issue of microplastic pollution, mainly caused by microplastic fibres (MPFs), has been widely recognised for some time. Despite being first identified in 2011 by Browne et al. [1], progress in addressing this problem has been slow compared to other forms of microplastic pollution, as specific research on MPFs remains relatively limited. Researchers have consistently recommended taking measures to standardise methodologies and reporting units and adopt a more systematic approach to evaluating textile parameters. They have also suggested taking a balanced approach to regulations and public education [2–5]. This systematic literature review aims to identify existing knowledge gaps and priority steps that the textile sector can take to mitigate this issue promptly and where it can help to speed up progress.

According to the Textile Exchange [6], synthetic textiles will have the largest global textile fibre production share in 2021, at 64%. The global fibre production demand has significantly grown from 8.4 kg per person in 1975 to 14.3 kg per person in 2021, with less than 0.6% recycled from pre-consumer or post-consumer textiles. If the business persists with the status quo, the definite growth trajectory will be 34% from 2020 to 2030. The reason for the growth and shift in the use of fossil fuel-based plastic fibres is because they cost less and provide better functional performance than natural fibres such as cotton [7,8].

MPFs/MFs are widely distributed and are found in diverse environments such as oceans, freshwater, and air. Browne et al. [1] first estimated that the accumulation of MPs is associated with shoreline population density worldwide, indicating that 85% of MPs are MPFs. According to Boucher and Friot [9], synthetic textiles account for 35% of the global release of MPs into the ocean, with 25% emerging from the wastewater pathway. Based on research conducted by the Ellen MacArthur Foundation [10], the current rate of domestic washing is projected to release approximately 22 million tons of MPFs into the ocean by 2050. Like MPs, MPFs are non-degradable, accumulate, and take hundreds of years to decompose [11,12], thus inevitably building up in the environment. This alarming statistic highlights the pressing need to address MPF pollution before it becomes increasingly challenging.

Increasing evidence indicates that MPFs are the most common type of secondary MP present in marine environments [12]. The most prominent and broadly reported sources of MPFs are shedding during domestic laundry and manufacturing processes [13]. For an average wash load of 6 kg, over 700,000 fibres could be released per wash and discharged into the aquatic environment via wastewater treatment plants (WWTPs). Although WWTPs are reported to be 95–99% effective, they are not explicitly designed for MP/MPF retention so they can bypass WWTPs. Owing to their enormous discharge volumes, there is compelling evidence that WWTPs are significant sinks for MP pollution [14]. Apart from wastewater from WWTPs, other release sources may be solid waste or sludge disposal. Sludge, a by-product of WWTPs commonly applied to agricultural land as fertilisers, has been found to contain MPFs/MFs. Tao et al. [15] estimated that during a 15 min drying process, over 90,000 microfibres could be released from 1 kg of polyester and cotton textiles. The release of MPFs from drying clothes can represent a source of airborne MP pollution [15–17]. These by-products, which appear as airborne textile fibres, can also cause persistent terrestrial contamination [18–21]. These are all pathways for the release of MPFs into the environment.

The ecosystem impacts of MPs/MPFs have the potential to occur through physical, chemical, and biological pathways. Woodall et al. [12] initially reported the ingestion of MPFs by deep sea organisms in a natural setting. The concern regarding MF buildup in the environment is due to their fibrous nature. MPFs tend to entangle and block the digestive tract, leading to the starvation and impaired growth of microorganisms [21]. The longer-term impacts include the capacity to absorb harmful chemical substances from fibres associated with dyes or additives used in textile manufacturing. Several studies have reported that MPFs can transfer contaminants. The ingestion of MPFs by various aquatic species, including turtles, seabirds, fish, and lobsters, has been associated with reduced feeding and reproductive abilities.

Furthermore, owing to the large surface areas of MPs/MPFs, toxic compounds can be introduced into humans by them eating higher trophic level species because the compounds are transferred along the food chain [22]. A recent study by Ragusa et al. [23] identified MPs in human placentas. Increasing evidence for the presence of MPFs in the atmosphere has recently been reported. The flying MPFs inhaled by humans can be deposited in lung tissue [24] and may lead to tumours. According to Cole [25], nanoscopic and microscopic fibrous materials can also be carcinogenic and fibrotic, whereas particles of the same content are comparatively benign. The fact that MPFs are increasing and accumulating toxins dangerous to marine life and potentially humans will only magnify and become more challenging to resolve if further action is delayed.

Microplastics (MPs) are synthetic polymers often defined as plastic particles smaller than 5 mm [26], which include particles in the nano-size range (1 nm) [27]. Figure 1 shows a microscopic view of different types of MPs. Microplastic fibres (MPFs) are petrochemicals derived from synthetic fibre-based textiles and are considered a subset of MPs [28]. MPFs are also commonly described as fibrous or thread-like pieces of plastic with a length between 100 µm and 5 mm and a width of at least 1.5 orders of magnitude shorter [7]. MPFs are extensively distributed across various environments, including air, marine, landfill, and terrestrial. Like MPs, once in the environment, they take hundreds of years to degrade and are challenging to remove. In this study, our primary focus was on MPFs.

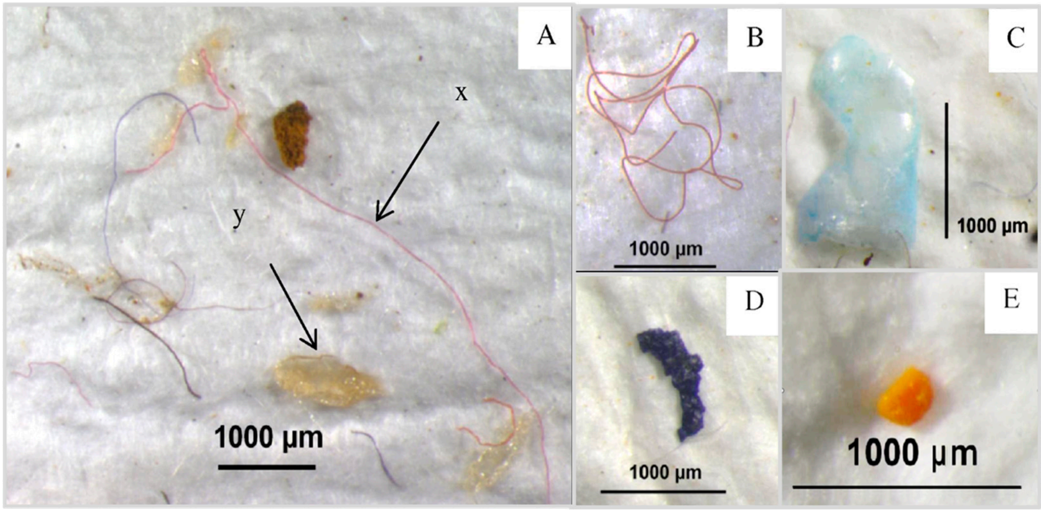

Figure 1. Microscopic views of the different types of microplastics. Adapted from [29]. (**A**) Photograph of a typical filter paper under a stereomicroscope, where x = microplastic fibre and y = biogenic material paper; (**B**) synthetic microplastic fibre, (**C**,**D**) synthetic fragments; and (**E**) synthetic bead.

Microfibres (MFs) were first produced in Japan in the 1970s and have exceptionally fine diameters for the textile industry. According to the industry definition, MFs generally have a linear density smaller than one decitex (as shown in Figure 2), a linear density unit of one gram per 10,000 m, or a diameter < 10 µm [30]. They are typically made of synthetic fibres. Nonetheless, growing concerns about fibre fragmentation have led to expanding the definition of fragmented fibres. This is commonly generalised to encompass both natural and man-made cellulosic fibres that exhibit characteristics of lengths less than 5 mm [31] and length-to-diameter ratios greater than three [32]. The most remarkable difference between MPFs and MFs is the origin of the fibres. MPF refers to fibres of synthetic origin only, and MF refers to all types of fibres. Therefore, when MFs are referred to in this study, this refers to the generalised definition of fragmented fibres of all material types that are shorter than 5 mm.

Sanchez-Vidal et al. [33] noted that while MPFs are the most prevalent form of MP pollution, research has focused primarily on MPs. Despite the thousands of research papers published on MPs, a mere two hundred studies specifically address the issue of MPF pollution, according to a search of Web of Science using the keywords "microplastic", "microfibres or microfibers or fibres or fibers" and "textiles or apparel or clothing" as of November 2022. Studies on MPFs have primarily focused on synthetic textiles and their shed rates during domestic laundering. Research on the loss of MPFs during the rest of the manufacturing life cycle still needs to be expanded. Our knowledge is incomplete and biased, which may lead to a conclusion that favours washing discharges directed to municipal WWTPs as the primary sources of fibres found in the sea and surface waters [1].

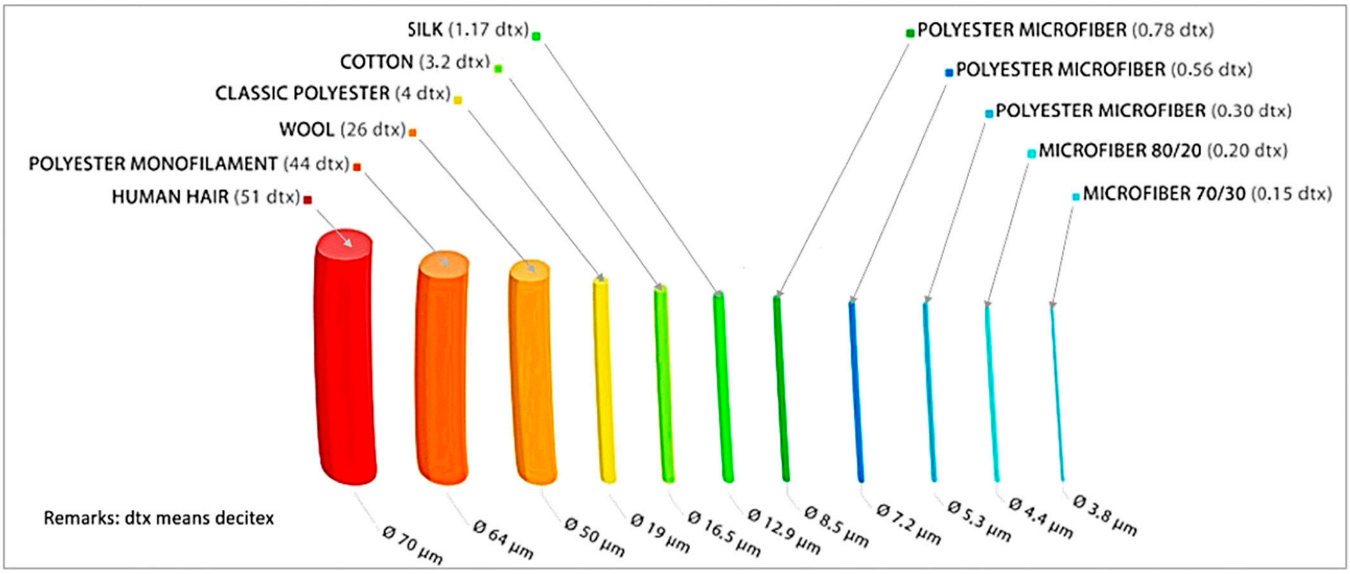

Figure 2. The illustration shows how microfibres are defined in terms of fineness (less than 1 decitex) compared to common textile fibres and human hair. Modified from [8].

Dealing with MPFs can be a challenging task, especially when it comes to managing and measuring irregular shapes that are easily tangled. Using a mesh size of 80 µm for sampling, researchers have captured fibres up to 250 times more effectively than with a mesh size of 300 µm, which has been commonly used in previous studies [34]. However, owing to inconsistent sampling and quantification methods at various locations, it is difficult to understand the magnitude of the MPF problem entirely, and MPFs are mostly underestimated [7,35].

Studies on MPFs should be connected to a broad range of industries. Instead, research has been mostly limited to laundry in the consumer phase without covering the entire production process. Therefore, current solutions focus only on a small part of the problem and cannot address MPF release across the complete product lifecycle.

Since there is yet to be a standardised method for analysing MPs and MPFs [36], the sampling and extraction techniques used to quantify MPs/MFs are inconsistent. As a result, the reported MPF concentrations among the studies were conflicting, varying, and divided, without a standardised concentration reference. Many studies have reported in oversimplified tones that are missing critical details. Concentrations of MPs/MPFs are relatively complex to compare because of the different units used [37]. Although efforts have been made to convert these units [38], the results can be biased or misleading because assumptions must be made.

As MPFs are currently the most prevalent MP source, targeted research is essential to understand this issue. This study used a systematic bibliometric approach to objectively review this subject and understand the knowledge gaps and how proliferation has led to the current state. It then focuses on insights that can help to prioritise mitigation actions for researchers, practitioners, and regulators to address this urgent need.

2. Materials and Methods

2.1. Data Source

A structured bibliometric approach or citation network analysis (CNA) is an objective way to capture research that shows knowledge proliferation over time. Establishing a research scope based on keyword selection is a more accurate evaluation than a traditional literature review [39].

Bibliometric analysis requires obtaining and analysing data on a specific topic or a range of issues. The data were captured through the Web of Science (WOS) in November 2022. The following search criteria were used. TS refers to the topic fields, which include titles, abstracts, keywords, and indexing. "TS = (microplastic*) AND TS = (microfibre* or microfiber* or fibre* or fiber*) AND TS = (textile* or clothing* or apparel* or fashion*) and Environmental Sciences or Engineering Environmental or Marine Freshwater Biology or Water Resources or Materials Science Textiles or Multidisciplinary Sciences or Polymer Science or Green Sustainable Science Technology or Engineering Chemical or Toxicology (Web of Science Categories) and Review Article or Proceeding Paper or Correction or Early Access or Editorial Material or Meeting Abstract (Exclude–Document Types) and 7.70 Thermodynamics or 3.87 Paper and Wood Materials Science or 3.32 Entomology or 6.73 Social Psychology or 2.74 Photocatalysts or 7.139 Energy and Fuels (Exclude–Citation Topics Meso) and Energy Fuels or Food Science Technology or Education Educational Research or Fisheries or Public Environmental Occupational Health or Meteorology Atmospheric Sciences or Oceanography or Toxicology or Microbiology (Exclude–Research Areas) and 3.60.1998 Pfos (Exclude–Citation Topics Micro) and Chinese (Exclude–Languages)". In total, 219 articles were identified. Figure 3 shows a flowchart summarising the identification, screening and bibliometric analysis used.

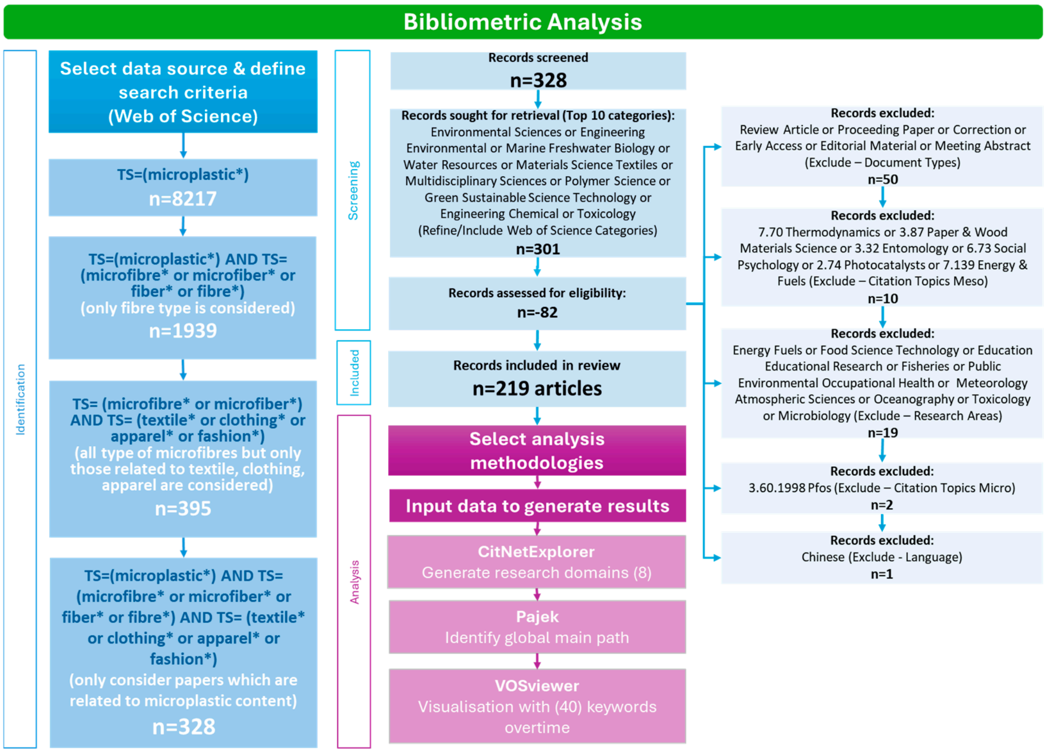

Figure 3. Flowchart of the bibliometric analysis showing the identification, screening and bibliometric analysis used. (* stands for wildcard which means include variants).

As microfibres have been developed in the industry since the 1970s, there were over 6246 papers related to this agenda, too many to be considered for a literature review. If the focus on microplastics and fibres was not specific to textiles and clothing, 1939 papers were available. We refined the parameters to be more specific and aligned them with the objectives of identifying opportunities from a sector perspective. In the early stage of knowledge development, this topic proliferated with research based on MPs without focusing on fibres, which were subsequently found to be the most substantial form. Therefore, instead of searching for keywords in the abstract, it was kept to the whole content, which resulted in 69 more papers, as these were critical papers. The results are summarised in Table 1.

Table 1. List of keyword research results from Web of Science in November 2022. (* stands for wildcard which means include variants).

Keywords	No of Articles
TS = (microplastic*)	8217
TS = (microplastic*) AND TS = (microfibre* or microfiber* or fibre* or fiber*)	1939
TS = (microfibre* or microfiber*) AND TS = (textile* or clothing* or apparel* or fashion*)	395
TS = (microplastic*) AND TS= (microfibre* or microfiber* or fibre* or fiber*) AND TS = (textile* or clothing* or apparel* or fashion*)	219

From the WOS, the graph in Figure 4 illustrates that there have been few published studies in the research domain since 2011, and a significant growth in numbers and citations since 2019. Data were exported and analysed using WOS, Microsoft Excel 365, CitNetExplorer 1.0.0, Pajek 5.16 and VOSviewer 1.6.18.

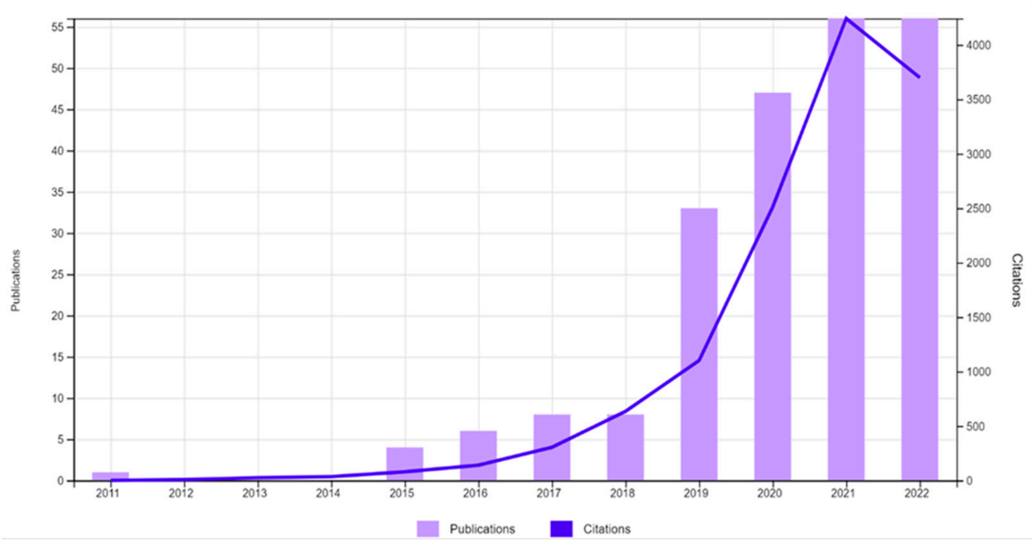

Figure 4. Times cited and the distribution of publications over time (2011–2022) were generated from the Web of Science using the search keywords listed in Table 1. (The Citation Report graphic is derived from the Clarivate Web of Science, Copyright: Clarivate 2022. All rights reserved. Date of search: November 2022).

2.2. Methodology

CNA aims to identify research domains, evaluate research traditions, and map changing paradigms [40]. The concept of CNA is that citation networks constitute a theory of connections between articles and systematic channels, transforming scientific knowledge, particularly when developing the main path [41]. Researchers in the same field tend to cite each other and add new knowledge to their latest research. Thus, the advancing knowledge in a particular research field will continue to grow [40].

CitNetExplorer is software that maps the topmost cited publications in the database. All non-matching cited references were excluded to ensure that every citation in the database in CitNetExplorer could be matched with a publication. A resolution for clustering of 2.00 with a minimum of ten citations and merging of small clusters was selected, and the analysis generated eight clusters with six publications that did not belong to a cluster. Clustering is used to identify the number of research domains [42].

According to Van Eck and Waltman [43], circles indicate publications, curved lines indicate citation relations, and the vertical axis represents time in visualisation. The proximity of publications in the citation network determines publication locations in the horizontal direction. The closer the two publications are to each other, the closer they are positioned in the horizontal direction. The citation score is the number of citations of a publication received from other physical publications in the WOS Database. The core publication has citation relations with at least ten different publications. The longest path was the longest knowledge network developed during the study period. Therefore, the core publication and longest path were also generated for evaluation, in addition to a complete network cluster analysis.

Pajek is software for analysing and visualising large networks (networks containing up to one billion vertices) [44]. This was applied to determine the global main path in the acyclic citation network using a traversal weight scheme to examine the research domain's most significant knowledge dissemination.

Publications assigned to the same cluster tend to be closely related to the citation networks. Each cluster was reviewed and assigned to a research domain. The longest path analysis from CitiNetExplorer and the main path analysis from Pajek were used to identify the key contributors to the leading articles.

VOSviewer is software that analyses publication data to create network maps. It creates distance-based visualisation, in which more closely related terms are closer to the visual display [42]. This software was used to map the co-occurrence of all keywords in publications. Full counting was performed to ensure that each keyword had the same weight as all the other keywords, regardless of the number of keywords per document. The minimum occurrence requirement for a keyword to be included in the map was selected as 40. Only the top 40 keywords on the map are included.

3. Results

3.1. Publication Profile

Table 2 shows that the environmental science communities continue to drive major studies. Five of the top ten journals comprised 53% (116) of the total environmental science or pollution research publications, and 13% (29) were from chemical and polymer disciplines. Again, such small numbers affirm that MPFs/MFs are less focused subjects.

Table 2. Number of publications by top 10 journals.

Name of Journal	No of Publications	%
Science of the Total Environment	34	16%
Environmental Pollution	27	12%
Marine Pollution Bulletin	22	10%
Environmental Science Technology	15	7%
Environmental Science and Pollution Research	14	6%
Chemosphere	9	4%
Journal of Hazardous Materials	8	4%
PLoS ONE	6	3%
Frontiers in Marine Science	4	2%
Polymers	4	2%

Table 3 illustrates that over 70% (155) of the articles from the top ten countries were from developed countries in the USA and Europe. China is the largest producer of textiles and clothing in the world. Although it had the highest number of publications, it accounted for only 15% (n = 34) of the total publications. This may explain why the research was highly skewed toward the usage phase of textiles in garment laundry. From Table 4, the largest cluster generated by CitNetExplorer was assigned to the research domain of domestic laundry and drying, with 85 publications, constituting 39% of the total.

Table 3. Distribution of articles by top 10 countries.

Publication Countries	No of Publications	%
People's Republic of China	36	16%
USA	34	16%
England	27	12%
Italy	26	12%
Canada	15	7%
Germany	12	5%
Spain	12	5%
Switzerland	11	5%
Australia	9	4%
Finland	9	4%

Table 4. CitNetExplorer-generated clusters and the number of publications in each cluster.

Group No	Colour	No of Publications	Research Domains
0	NA	6	Scattered Samples
1	Blue	85	Domestic laundry and drying
2	Green	28	Test methodology
3	Purple	22	Aquatic ecosystem
4	Orange	21	Atmosphere environment
5	Yellow	19	Wastewater source
6	Brown	17	Abundance and distribution
7	Pink	11	Terrestrial ecosystem
8	Light Blue	10	Hazardous nature

3.2. *Citation Network*

Figure 5 shows the cluster analysis of all 219 publications imported from WOS. Eight clusters were found with 1483 citation links, and six papers did not belong to any cluster. The colours and breakdown of each cluster are summarised in Table 4. The research domains were allocated according to their content by evaluating each cluster relationship. The details of each cluster are discussed in Section 3.4.

As shown in Figure 6, there were 153 core publications with 1363 citation links. From the longest path analysis between Browne et al. [1] and Volgare et al. [45], there were 17 publications with 92 citation links, all of which were built on MPFs/MFs released from domestic laundry with different textile and laundry parameters, and the uptake of MPFs from aquatic organisms. In addition to MPFs from polyester, Zambrano et al. [46] raised concerns regarding MFs, including from cotton and rayon. Kärkkäinen et al. [16] expanded the MPF release to include tumble drying. Two articles proliferated and were not found in the main path. De Falco et al. [47] shared the potential of using pectin finishes to reduce MPF release, and Herweyers et al. [48] attempted to evaluate MPF/MF pollution from a consumer perspective.

In Figure 7 of the global main path, Rochman et al. [49] diverted from Browne [50] to assess MPs/MPFs ingested by fishes and bivalves. This study highlights the potential of MPs/MPFs for human consumption, such as from seafood. Instead of studying the release of MPFs from textiles, Talvitie et al. [51] continued to dive deeper and found direct evidence that WWTPs are a point source of MPs/MPFs released into aquatic environments. Pirc et al. [52] focused on MPF emissions from different textile and laundry parameters.

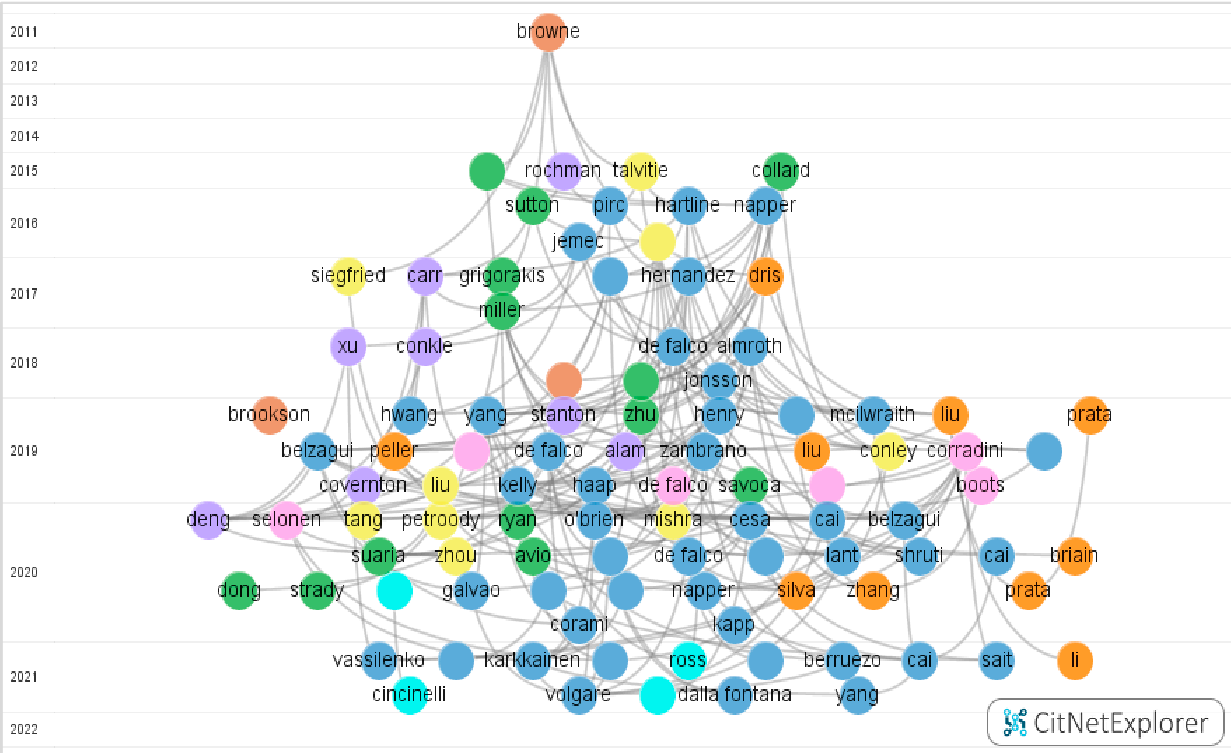

Figure 5. Full citation network generated by cluster analysis. (Research domain clusters are coloured according to Table 4).

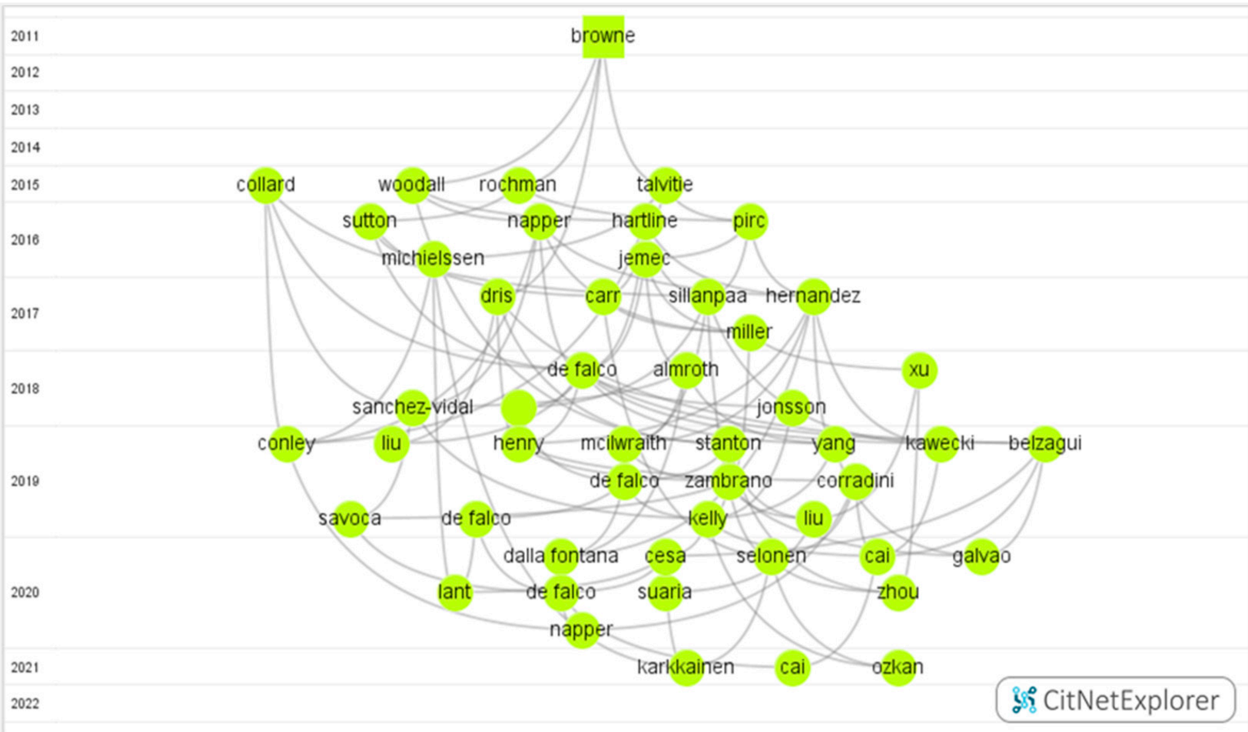

Figure 6. Citation network by core publication analysis.

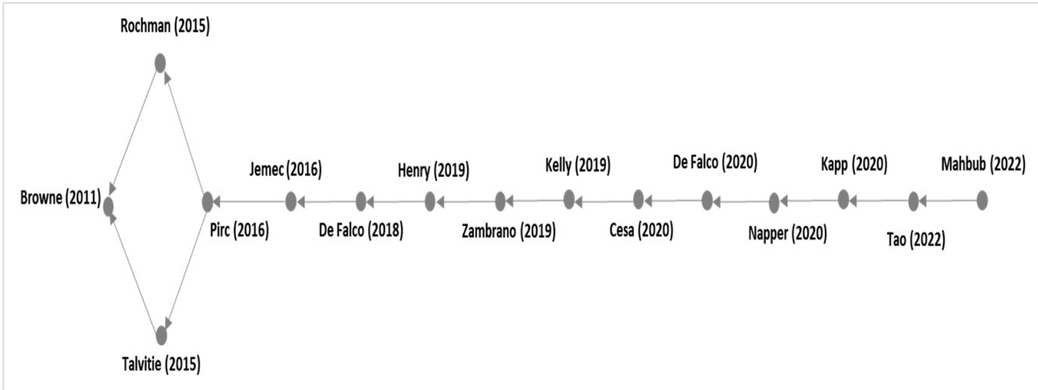

Figure 7. The global main path was generated using Pajek.

3.3. Connection between Keywords

Figure 8 shows that MPFs/MFs have originated as a branch of MP research with a long history. However, the scope has broadened to cover more comprehensive fibres, including natural and semi-synthetic fibres [46]. Since then, more papers have reported the release or shedding from these non-synthetic sources using the fibre type as a function of the test parameters [53]. The dynamics of the problem have shifted from MP pollution to the more significant issue of fibre fragmentation from the most commonly used textile materials (polyester and cotton) and their applications in the last few years.

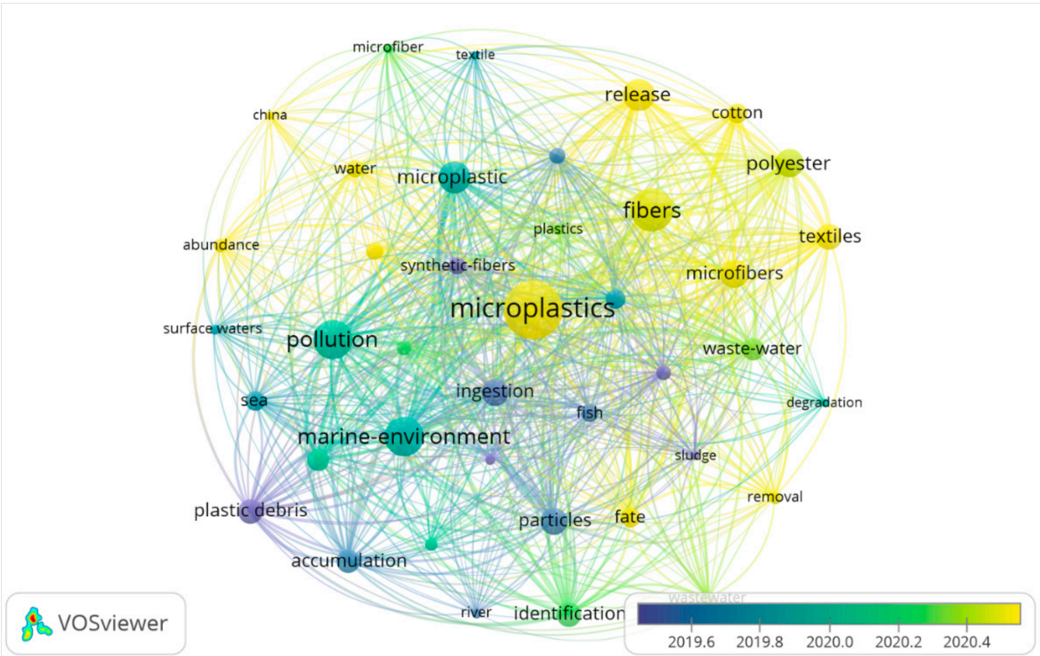

Figure 8. Overlay visualisation result by 40 keywords co-occurrence generated from VOSviewer.

Although studies have shown that textile finishing agents have prolonged their biodegradability from 85% to 75% [54], merging non-synthetic, natural, and semi-synthetic fibres in one piece has increased the challenges and made the problem more difficult to unravel. This requires a more complex system approach across the entire textile value chain as it becomes challenging to differentiate between accountabilities and responsibilities in the complex chain. Nonetheless, this may hinder using more sustainable bio-based synthetic materials as they are exposed to a similar MF fragmentation issue. Therefore, it is crucial to develop methodologies to differentiate common textile materials and their blends to find appropriate solutions for different fibre compositions and reduce their release into the environment. Although natural or semi-synthetic materials can behave differently depending on their degradability and the chemicals added, generalising natural MFs with MPFs is not recommended as it may hamper the resolution of MPF pollution.

De Falco et al. [47] raised concerns about MPF release from washing, and evaluated other laundry and textile parameters that impact the release quantity. Domestic washing was concluded to be the source of the MFs released into the ocean via wastewater treatment plants. De Falco et al. [55] demonstrated for the first time that the immediate release of MFs from clothing to air during wearing is equally as important as when released into the waterway from washing. Attention has also shifted from the aquatic environment to the terrestrial, as a proliferation of studies has raised similar concerns about airborne MFs in indoor and outdoor environments with additional releases from electronic dryers [56]. This can potentially outweigh aquatic emissions, notably if the retention rate of WWTP is improved. In addition, the concentration of MFs in sludge will increase, polluting terrestrial ecosystems.

It is also not difficult to recognise that China has become one of the most researched countries, as most polyester fibres are produced in this region [57]. The ability to initiate remedial action at an early stage of the production process should be more effective, as some studies have found that the emission quantity from industrial WWTPs can be up to a thousand times greater than that from municipal WWTPs [36,58]. Therefore, the ability to mitigate at the production stage is a more impactful mitigation approach than to do so during its use and disperses in diversified pathways.

3.4. Summary of Each Research Domain

3.4.1. Domestic Laundry and Drying

This research domain has the largest group of publications and citation links in CNA. The global main path was first introduced by Browne et al. [1], who reported that more than 1900 fibres were released per garment per wash. This was followed by Pirc et al. [52], who first stated that the release of MFs was 3.5 times higher from tumble drying.

Several studies have reviewed the shedding of MFs during the usage phase. Fabrics and garments are washed under different conditions, such as with different detergents, temperatures, and machines. Variations in the sampling methods, testing methodologies, and reporting units employed in numerous studies make it difficult to compare the results. The impacts are summarised in Table 5.

Front-load washing machines reduce MF release because their mechanical actions are less severe. This reduction can be by up to seven times [59]. Most studies have found a decreasing trend in the release of fibres by sequential washing [16,53]. Washing load is considered to be one of the most influential factors in fibre release. On the other hand, textile parameters are expected to play a critical role. Limited studies are available for reference in development, although it is known that more compact structures, higher twists, and long filaments can reduce MF release. However, this information is more complex to translate to textile design without reporting more details and comparing meaningful parameters in different production processes. Rathinamoorthy and Balasaraswathi [60] also identified that, among all laundry parameters, water volume was the most influential on MF release, followed by washing duration, mechanical agitation, and temperature. Therefore, a full load can maintain the water-to-fabric ratio at a minimum level, which is the most effective setting to reduce fibre shedding during washing, which was also shown by the results of Kelly et al. [61].

Table 5. Summary of effect on MPF/MF release from domestic laundry and drying from selected articles.

Parameters	Articles	Effect on MPF/MF Release
Textile Parameters		
Structure	[62]	Increase with loose construction
	[55]	Reduce with compact to loose structure
	[63]	Reduce as interlacing coefficient and weft density increase
Composition	[64]	Recycled polyester > virgin polyester
	[65]	Acrylic > polyester > nylon
Spinning method	[66]	Ring > rotor or air-jet
Yarn twist	[62]	Reduce with higher twist
	[67]	Spun > non-twist filament > hard-twist filament
	[55]	Reduce with a higher twist
Fibre length	[55]	Reduce with continuous filament over short staples
	[53]	Increased release with shorter irregular fibres
	[68]	Reduce from staple to textured filament.
Finishing	[47]	Reduce with a pectin-based finish
	[66]	The processed surface can produce five times more
Cutting	[66]	Scissor-cut 3–31 times higher than laser-cut
Washing and Drying Parameters		
Machine type	[59]	The top load releases seven times more than the front load
Subsequent washes	[52]	Successive washes decrease emissions
	[69]	Reduce and typically stabilise from the 4th and 5th cycle
	[61]	Reduce after 4 cycles
	[53]	Reduce after the peak at 3rd cycle
	[17]	Reduce and stabilise from 5th cycle
	[67]	Reduce
	[68]	Reduce significantly from 5th cycle
	[70]	Reduce and stabilise at the 7th cycle
Water volume-to-fabric ratio/washing load decrease	[61]	Increase as the most influential factor
	[45]	Increase by five times
	[60]	Increase as the most influential factor
Washing temperature	[46]	Increase with temperature
	[61]	No significant effect between 15 and 30 °C and increase at 60 °C
	[71]	Increase with temperature
	[70]	1.8 times more if the temperature is increased from 20 to 40 °C
Washing and drying time	[61]	No impact if the increase is from 15 to 60 min
	[71]	Increase with duration and spin speed
	[70]	Increase if duration increases from 30 to 60 min

Table 5. *Cont.*

Parameters	Articles	Effect on MPF/MF Release
Using detergent and softener	[52]	Reduce (both detergent and softener)
	[72]	Reduce (softener only)
	[46]	Increase (detergent only)
	[61]	No effect (detergent only)
	[53]	Reduce (detergent only)
	[73]	No significant impact (both detergent and softener)
	[71]	Increase (detergent and conditioner)
	[74]	Reduce (softener only)
	[70]	Increase (detergent only)

Both McIlwraith et al. [75] and Napper et al. [76] proved that mitigation devices had some impact on reducing fibre release in the washing process, and the Lint LUV-R filter was the best performer, with a retention rate of approximately 80%. The remaining devices had significantly lower rates (approximately 30%). Herweyers et al. confirmed that further education is required if these devices are introduced to consumers. They must be user-friendly and easy for consumers to understand how they can make an impact, so as to secure long-term behavioural changes [48].

Owing to the vast variations in textile materials, there is an inevitably considerable variation between the sample specimens used, which makes comparisons inconclusive. Researchers from non-textiles backgrounds may collaborate with industry or academic disciplines to support the selection of fabrics that have an enormous impact and for which detailed textile parameters can be provided.

3.4.2. Test Methodology

Measuring and identifying microplastics is difficult because of inconsistent sampling and quantification methods, resulting in challenges in comparing data and estimating their prevalence [35,77]. For many years, the characterisation of polymers has relied on optical spectroscopy to provide information on polymeric materials' identity and chemical composition. One major finding is that relying solely on microscopic visual identification of MPs or MFs is inaccurate; each particle must be confirmed as plastic using techniques capable of tackling small particle sizes, such as micro-Fourier-transform infrared microscopy (μFTIR), micro-Raman(μRaman), Pyrolysis Gas Chromatography/Mass Spectrometry(Py-GC/MS), and High-Performance Liquid Chromatography(HLPC) [78]. However, μFTIR and μRaman are the most commonly used techniques and are highly recommended for characterising MPs, with similar performance, especially in wastewater samples [78,79]. Raman spectroscopy is a laser-based method that provides better resolution than infrared spectroscopy. This is well suited when the process requires focusing on small regions of a sample. It can also address the identification of MPs as small as 1 μm. The Raman spectrum yielded similar but complementary information to that obtained by FTIR. To establish a standardised method for the qualitative analysis and characterisation of MPs, both instruments can be effectively combined with optical microscopy [80]. However, its high cost and time requirements render it unscalable.

However, a few commercial standards have been published for quantifying MFs from domestic washing. They are published by the Microfibre Consortium [81], AATCC [30], and ISO [31] (which are under development). They are remarkably similar and consistent; therefore, the results are likely comparable. The minor difference is that the TMC method requires eight specimens but no blank test. In comparison, the AATCC provides two options for pretreatment and drying: detergent and wash temperature, as per the label.

The AATCC and ISO standards are less sophisticated versions of the TMC standards, and require only four sample specimens.

Adopting new test methods will require industry collaboration, which can be accelerated by stakeholder pressure and regulatory interventions to introduce aligned measures. Currently, most identification methods are based on MPs and laboratory scales, with MPFs being a subgroup of MPs. This requires scalable investment and the ability to include non-synthetic fibres. However, current commercialised standards do not consider the influence of other particle contaminants, differentiation of fibre types, and length distribution. The accuracy and reliability of the control parameters are yet to be improved. This relies on specific polymer characteristics not possessed by natural fibres. Some test protocols entail using solvents to remove contaminants that can dissolve or remove organic matter, including natural fibres. Therefore, in developing a methodology, it is essential to include fibre types commonly used by the textile industry.

3.4.3. Aquatic Ecosystem

Pollution in aquatic ecosystems is the first concern regarding the release of MPs/MPFs/MFs into the environment. Indeed, there is compelling evidence that their impact was previously underestimated because 300 μm sieves were used in the sampling process, and most later studies confirmed the most prevalent length to be <100 μm. According to Conkle et al. [82], approximately 80% of previously published papers did not account for MP size <300 μm. The discrepancies can be as high as one to four orders of magnitude when a sieve <100 μm is used [83]. Therefore, earlier studies using coarse sieves for sampling underestimated MP prevalence.

MPFs have been found in almost every marine habitat's seawater and sediments. In a review by Gago et al. [84], the most abundant fibre length of surface water was established as 500–1000 μm and up to 4750 μm. In sub-surface waters, this was found to be 1–5 mm, with the most abundant fibres in sediment ranging in size between 800 and 1000 μm, consistent with those found in WWTPs and domestic laundry studies. MPs and MPFs can be viewed as unavoidable byproducts of contemporary lifestyles which can be transmitted directly to oceans, rivers, and lakes without assistance from WWTPs [85]. Nevertheless, a Great Lakes study revealed that the estimate for MPFs in aquatic environments was disproportionately higher than the concentrations found in wastewater effluents [86]. As a result, research into aquatic environments may consider a more balanced approach of using a smaller sample volume, like Barrows et al. [87], instead of coarse sieves and a large volume sample size, which may result in underestimation.

3.4.4. Atmospheric Environment

MPFs are ubiquitous, but their long-term effects on human health and the environment are poorly understood. Dris et al. [88] first reported the concentration of 1.0 and 60.0 fibres/m^3 and 0.3 and 1.5 fibres/m^3 in indoor and outdoor air, respectively. Most were natural or cellulosic, which is unsurprising because they are short, staple fibres and are more vulnerable to breakage and fallout during use and wear. Studies of long-term exposure to UV radiation from sunlight and fluctuations in ambient temperature have proven that textiles break down and release MFs into the atmosphere [89].

It is generally believed that the most consequential shedding of clothing fibres occurs during laundering. However, this assumption may need to be revised as it only accounts for some products. Non-laundered fabrics such as flags and sails also undergo predictable disintegration, with associated fibre losses over time [85]. Fibres were also readily noticeable on clothing closets, floors, display monitors, and other undisturbed indoor surfaces. In later studies, there have been emerging discussions on their fate in the air we breathe, the dust we inhale at home, the water we drink, and other elements of our being and environment. Liu et al. [89] and Zhang et al. [90] suggested that textile clothes and soft furnishings are likely to be the major sources of airborne MPs in indoor environments. Over 60% of MPs were MPFs, which could be an essential source of MP pollution.

However, the concentration of MPFs or MFs largely varies between indoor and outdoor environments in different regions, as reported by [19,34,89,91]. Clothing and textile furniture are the dominant sources [92]. However, differences in lifestyle and the use of textile-derived products are expected to be the main reasons for the variations in indoor environments. At the same time, the distribution in the outdoor environment is vastly influenced by wind, airflow, and other factors, such as consumption habits, socioeconomic status, traffic, and urbanisation [93].

Most airborne fibres in various studies [19,91,94] were below 1000 µm, posing an inhalation risk to humans. More recently, it was demonstrated that MPFs in the atmosphere may cause issues related to inhalation and their presence in human lungs [24].

Nevertheless, the airborne MF phenomenon requires strict contamination control from sampling to the point of the experiment. This is particularly important because the potential presence of airborne MFs, such as from researchers' clothing or other textile materials, can significantly impact the experiment's outcome. Therefore, it is essential to implement effective control procedures to minimise contamination.

3.4.5. Wastewater Source

Doubtlessly, wastewater is a well-known source of microplastic fibres released into the aquatic environment. It is accepted that laundering fabrics leads to abrasion and wear of textiles, leading to fibre-shedding and their subsequent release within effluent from washing machines through sewage effluent. Browne et al. [1] reported that the proportions of polyester and acrylic fibres in sewage effluent resemble those of MPs found worldwide contaminating sediments. This was interpreted as an indication that at least some of the MFs in the marine environment originated from textile washing, with WWTPs acting as pathways.

WWTPs as pathways for MP release have drawn attention recently, with an exponentially growing number of related publications in the last few years [95]. Mintenig et al. [96] suggested that WWTPs could be a sink and a source of MPs and thus play an essential role in MP pollution. There is strong evidence that MPs/MPFs can easily bypass WWTP filtration and other solid separation processes, which are not designed for such a purpose [97–99]. Magnusson and Norén [100] and Talvitie et al. [101] demonstrated that the supply of MPs from WWTP effluents to the aquatic environment may be substantial because of the enormous volume discharged daily.

In the study by Conley et al. [96], MPF removal efficiency was reported at 80.2–97.2%, which is relatively high but still significantly less than the total MPs. Talvitie et al. [102] suggested that advanced wastewater treatment (e.g., a membrane bioreactor) can improve the removal efficiency of small-sized MPs (<100 µm). This was further supported by Ziajahromi et al. [98], who found that fibres were the dominant MPs detected in most effluent samples and were not completely removed even after advanced treatment processes.

WWTPs in developed countries are believed to be more efficient. For example, Mintenig et al. [96] showed a removal efficiency of 98% for MFs after advanced filtration in a German WWTP. Whereas, in developing economies, WWTPs usually have lower standards because of inadequate sewage infrastructure. In 2014, China alone accounted for 69% of all polyester fibre production globally, with the combined output of China, India, and Southeast Asia representing over 80% of the global total [13]. Nevertheless, developing countries produce and consume a higher proportion of synthetic textile materials, at 62.7% compared to 48.2% in developed countries [9]. Developing countries tend not to have commonly available tertiary treatment standards, which is of greater concern.

Xu et al. [28] measured MPFs directly discharged from textile mills to an industrial WWTP that collects effluents from mills in the region for treatment before their discharge to the aquatic environment. This is a typical textile industrial CETP with a daily treatment capacity of 30,000 tons in the same region where the present study was conducted. This plant receives production wastewater from 33 printing and dyeing mills in a textile industrial park, accounting for approximately 95% of the influent. The average abundance of

MFs, both natural and synthetic, was reported as 334.1 (±24.3) items/L in the influent before being reduced to 16.3 (±1.2) items/L in the final effluent, with a retention efficiency of 95.1%.

When comparing industrial textile effluents from Xu et al. [28] and municipal effluents from Yang et al. [103] and Lv et al. [104] in China, there were 28–1310 times more MFs discharged directly in concentrated effluent to aquatic environments from industrial sources than from municipal WWTPs. The scale of textile effluents is vast, as it is one of the highest water-use industries globally [105] and is considered the second largest consumer and polluter of clean water [10]. Once discharged, no practical solution exists to remove it from freshwater and the ocean. It is essential to avoid discharging MPFs/MFs to aquatic environments, as there is no alternative way to remediate them. Therefore, it is imperative to take immediate action to control the release of wastewater. The magnitude of this pathway suggests that it is of primary importance and high priority. Regulators should be informed and educated without delay.

3.4.6. Abundance and Distribution

Estimating MPF pollution globally with many unknown factors and uncertainties is challenging, which explains the discrepancies between studies. These uncertainties can be either structural (related to the understanding of the mechanisms and pathways of leakage) or data-related (associated with the availability of reliable datasets, which are particularly difficult to obtain in certain countries) [106]. The predominant global estimates of MPF leakage are listed in Table 6.

Table 6. Global microfibres release yearly estimates from listed sources.

Estimates (Weight)	Source of References
190,000 tonnes/year	[107]
525,000 tonnes/year	[9]
260,000 tonnes/year	[108]
280,000 tonnes/year	[109]

Boucher and Billard [98] defined the leakage of primary MPs as a function of loss and release rates. Therefore, the loss rate measures the quantity of MPFs lost from a specific activity such as domestic washing, and the data are usually more accessible. The release rate estimates the fraction of this loss reaching the ocean, which is not captured in waste treatment plants or other infrastructure. This leads to significant uncertainties owing to the high complexity of release pathways. The estimation often requires validation from field studies, which require further improvement. Perhaps the latest estimate by Belzagui et al. [109] was closer to the true scenario for release based on domestic laundry, as the estimation model considered extended parameters such as the volume of laundry effluents, percentage of municipal water that has been treated, type of water treatment applied, and proportion of front- versus top-loading washing machines.

Owing to their high density, MPFs are the most prevalent MPs in the natural environment, particularly in sediment and surface water. Miller et al. [110] and Dris et al. [111] identified both synthetic and non-synthetic fibres in freshwater and Lusher et al. [112] identified them in the gastrointestinal tracts of fish. Surprisingly, despite synthetic fibre production surpassing natural fibre production for over a decade, a few studies [73,113] have found that natural MFs are more abundant than synthetic ones. Apart from this, other sources show that MFs are more diverse during the use phase through the air system, with some findings suggesting that MFs from natural sources are even higher density [111].

The most commonly detected polymers are polyesters (PES), polyamides (PA), and polyethylene (PE). The fibre types examined could have been more consistent in different studies. Ziajahromi et al.'s [98] findings resemble the global fibre production market, with polyester as the most significant contributor. Fishing nets, ropes, and gears are potential sources of MPF pollution. The main concern regarding the use or abandonment of fishing gear is that it is a source of secondary MP pollution. Generally, it is perceived that ropes discarded following their use in fishing activities and marine transportation are the primary source of MPFs following weathering and breakdown of material over time [114–116].

The MPFs shed during washing vary from 11.9 to 17.7 µm in diameter and 5.0 to 7.8 mm in length across polyester, polyester/cotton blends, and acrylic. They typically range in diameter from 6 to 175 µm [117]. The most common fibre lengths found in marine environments are 100–1500 µm [87] and in wastewater treatment plants (WWTPs) are 100–1000 µm [118]. The size range of <500 µm was dominated by surface waste, whereas 500–5000 µm was dominated by sediments [119].

Assessing the worldwide impact of MPF contamination is complex due to various unknown factors and uncertainties. Thus, there may be divergent findings from different studies. As textile materials are diversified, more accurate estimates require a deeper understanding of the relationship between textile parameters and their fragmentation performance over the entire product life cycle. For example, industrial wet processing factories which discharge through industrial WWTPs can potentially release higher amounts of MPFs than municipal WWTPs with input from domestic washing [58,120]. This can contribute to significantly more releases than in the current estimation. In addition, more recent studies claim that terrestrial pathways from the use of electronic dryers can contribute more MFs than the aquatic pathway [15,111]. Considering these additional sources and pathways is crucial for comprehensively assessing the global abundance of MFs.

3.4.7. Terrestrial Ecosystem

Synthetic fibres have been reported in municipal sewage sludge in soil. They can be dated back to the studies of Habib et al. [121] and Zubris and Richards [122], which indicated fibre presence in wastewater and its diverging pathways. Fibres within the sludge material cannot biodegrade quickly in nature and can persist for more than 15 years in the soil. Such pollutants in the soil can be retained in terrestrial environments or eventually enter marine environments via runoff.

Because of its nutritional and organic content, sludge produced from WWTPs is still used as a fertiliser in the agricultural field. Most of the MPFs found in WWTPs were retained in sludge [101]. WWTPs are not designed to filter out MPs/MPFs [123]. According to Corradini et al. [124], MPs were found at 18–49 particles/g, and the majority were fibres, accounting for 90% of sludge and 97% of soil.

Evidence of MPs'/MPFs' impact on soil ecosystem functioning and soil stability is varied. Owing to the presence of MPs and the size distribution of water-stable soil aggregates, evidence showed that fewer seeds germinated. The experiment using MPs and MPFs to grow the Lolium Perenne plant showed reduced shoot height [125]. Prendergast-miller et al. [126] studied polyester MFs in the litter-feeding earthworm Lumbricus Terrestris. They showed that they were not fatal but caused transcriptional responses related to general stress, and there was evidence of a change in casting behaviour. On the other hand, textiles treated with silver nanoparticles released into wastewater and sludge are further transported to the soil and may cause reproductive impairment in earthworms [127]. In addition, shorter microplastic fibres can enter the terrestrial food chain via ingestion by soil vertebrates [128].

A more recent estimate by Gavigan et al. [129] suggested that after emissions from apparel washing between 1950 and 2016, waterbodies would have received 2.9 Mt of MPFs. In contrast, terrestrial environments and landfills receive almost 2.5 Mt. The quantity was nearly as large (and increasing) in terrestrial areas and landfills. Improved wastewater treatment can shift the MPF emissions from water bodies to terrestrial environments. Further examination is necessary to fully understand the transfer of MPFs and the potential consequences of such transfers, particularly when implementing WWTP retention improvements to mitigate this issue. It is essential to ensure that this strategy does not simply shift the problem from aquatic to terrestrial environments.

3.4.8. Hazardous Risk

The concerns regarding MPFs compared to cellulosic fibres, typically those from cotton and considered a pollution issue, are mainly because polymers are not easily degraded or decomposed in the natural environment [130]. Once created, they can persist for hundreds of years and are transferred between different media, resulting in a bioaccumulation effect. Another concern is that there are thousands of types of chemicals added to the textile production process to provide specific functionalities and durability that depend on the intended product applications and are frequently identified in marine environments, which leach out and transfer to aquatic organisms [131]. Several studies have reported that MPFs transfer contaminants, such as plasticisers [132], dyes [133], polycyclic aromatic hydrocarbons, and polychlorinated biphenyls [134]. MPFs can contaminate deep sea organisms via various physical, chemical, and biological pathways [12].

Several studies have documented that marine MPs were covered by biofilm communities [135,136]. These organic layers likely acted as reservoirs for hazardous substances such as persistent organic pollutants (POPs). In addition, this prolongs degradation, as biofilms can form a protective layer against UV radiation [137]. Furthermore, MPs/MPFs can function as vehicles to carry harmful pathogenic microorganisms and parasites from stable biofilms on their surfaces when exposed to wastewater. Their surfaces provide habitats for microbial colonisation and biofilm formation, allowing the migration of opportunistic pathogens and invasive species [135,138].

Fibrous MPFs may be more harmful than their spherical counterparts, causing cancer, scarring, and harm to marine life [139]. Many aquatic species ingested MPFs/MFs, leading to entanglement, slowed growth, and diminished feeding and reproduction [140,141]. The vast presence of MPFs/MFs in the marine environment has supported evidence that biota has ingested them directly or potentially along the food chain. They were present in mussels [142], oysters [143], sea urchins [144], sea cucumbers [145], fish, shrimp, shellfish [49,146], and even in deep sea organisms [138]. More recent studies have reported oxidative stress responses in clams [147] and others, and cellular disturbances and thermal stress responses in mussels [148]. Moreover, the large surface area of MPFs means that environmental pollutants may be absorbed onto the surface of the particles, with the potential to be transferred into body tissues once ingested [149,150]. These contaminated residues can adsorb and concentrate organic pollutants that may be ingested by marine fauna, which can be subsequently transferred to the food chain and potentially reach humans [14,22,151,152].

The release of MPFs from drying clothes could represent a source of airborne MPFs. Recently, increasing evidence of the presence of MPFs in the atmosphere has been reported [153,154]. The flying MPFs inhaled by humans are deposited in the lung tissue and may lead to tumours. Several studies have shown that respiratory inflammation, pulmonary fibrosis, and cancer can also be caused by regular and prolonged exposures [85].

There have been growing concerns that natural fibre sources also contributed to the issue, not to a lesser extent [68]. This may be because of the faster degradation rate and metabolites available in the marine environment [46,155]. In addition, the higher biodegradability of natural fibres may also result in a higher chance of releasing chemical additives [156]. Environmental concerns regarding natural and synthetic fibres also differ owing to their chemical pollutant sorption behaviours. They possess different fibre surface properties and chemical bonds which control sorption behaviours, such as electronegativity, making the adsorption of natural fibres on cationic surfactants relatively higher than on synthetic fibres [46,62]. The difference in surface attractions showed the potential for different threads to play distinct roles in hazardous chemical sorption and fate. Therefore, shifting from synthetic fibres to natural fibres from this perspective does not appear to solve the pollution issue. The use of less and more sustainable, non-toxic, and nonpersistent chemicals is believed to be a more holistic approach. Perhaps further research should evaluate this in greater detail to find a non-regrettable option for different hazardous impacts from various types of fibres.

4. Opportunities

Research on MPFs/MFs associated with textile materials has been a prominent area of focus since 2011. This subject gained more attention in 2019, reaching 61 studies in 2022. Despite some advancements, this field is still in its nascent stages, necessitating additional research, particularly a systematic approach to sampling, methodology, and reporting standards that can be applied. Below is a list of priorities with actions that are recommended to leverage and accelerate progress.

4.1. Interdisciplinary Collaboration

Plastics are used in a vast number of products. Further studies and resources are being employed to address MP pollution. Since MPs and MPFs have similar chemical structures, the knowledge gained from MP studies is expected to be referenced, especially regarding ecological impact and toxicity. However, there is an expectation to report MPFs/MFs in more detail regarding textile parameters [4], so that the information can be comparable and reproducible. Nonetheless, it should only partially depart from the MP mainstream because they have larger communities and stakeholders in the textile sector to leverage their knowledge, resources, and solutions. MPF studies can also tap into MP studies through collaborations between academic disciplines. Textile and polymer science researchers should be desperate to collaborate with ecologists and toxicologists to determine the life cycle impact of MPFs/MFs [53].

Solutions for improving the effectiveness of washing practices require a multifaceted approach involving collaborations with washing machine manufacturers, wastewater treatment facility builders, and promotion of responsible consumer washing habits. This involves engagement beyond primary research communities in the current subject, including exploring new technologies, implementing stricter regulations, and educating the public.

4.2. Textile Parameters

Textile production uses materials with unique compositions, structures, and properties to cater to specific aesthetic and functional demands. Therefore, without considering critical specification parameters, such as fibre count, yarn twist, fabric density, structure, and finishes, selecting fabrics at random can lead to inconclusive outcomes and hinder a comprehensive understanding of fibre fragmentation [157].

A better understanding of textile manufacturing processes that result in the increased release of MPFs/MFs could lead to the development of a textile process that reduces the release of MF fragments during domestic washing. For example, Pangaia partnered with MTIX using multiplexed laser surface enhancement (MLSE®) technology to modify fibre surfaces within a fabric to prevent microfibre shedding [158].

Regardless of the small size and shedding performance of MFs, they may not wholly resemble the same version, as they are much finer and more vulnerable. Fibre shedding is a well-known phenomenon in the textile industry, and there is a long history and set of control and effective reduction measures available for its use [148]. Therefore, remedial measures can be built on the existing knowledge of shedding.

A good practice guideline was published by [159], and reducing the MF release in the synthetic textile supply chain could be a starting point. However, it is more critical to begin referencing it and promote its adoption in the textile industry without further delay in waiting for the perfect version. Since it was prepared a few years ago, it can be updated with more refined details and parameters from the latest research.

4.3. Laundry Parameters

The laundry parameter studies concluded that the laundry setting plays a critical role in reducing MF release. Consumers are advised to wash in cold water and with fewer cycles and launder clothes when necessary and in full loads [73,160], which indirectly extends the lifetime of a garment irrespective of conflicting parameters when using detergents and softeners. This requires changing consumer behaviour when purchasing and caring for clothes. Switching to milder washing and drying conditions can be the most cost-effective solution because it merely involves changing the existing machine settings, consequently reducing energy.

Most consumers may find it more challenging to adapt to options that incur additional costs of purchasing a front-loading washing machines that generate fewer MFs or purchasing less high-quality clothing [13]. Indeed, manufacturers of washing machines, tumble dryers, detergents, and softeners should also contribute by improving their performance in releasing fewer MPFs/MFs and communicating their impact to consumers.

4.4. Sustainable Chemicals

Although some studies have suggested that fibres from biomass can mitigate MF release, some people are still sceptical as they may persist after chemical treatment. It is widely understood that MPs/MPFs/MFs are considered a threat and risk to the ecosystem and human health due to contaminants [161]. Therefore, it is of higher importance to ban these hazardous chemicals and move to the use of natural or non-toxic substances in the production process, which can be more effective in reducing their toxicity and hazard risk than avoiding synthetic textiles.

However, it is necessary to distinguish the non-degradability of synthetic textiles, which can become vectors or carriers of other pathogens or pose a physical hazard to microorganisms, as this will take time to be resolved through sustainable chemistry. The outcome needs to be differentiated from that of natural fibres [101].

4.5. Renewable Materials and Circularity

Existing solutions are available to shift the use of renewable materials. A commercial example is Tandem Repeat Technologies, which uses genetic sequencing and synthetic biology to produce a new fibres based on a unique protein structure originally found in squid tentacles. In contrast, Natural Fibre Welding provides a sustainable and circular material that uses plants as a renewable resource.

Since the Earth's resources are finite, reducing, reusing, and repurposing with an extended product lifespan is still preferable. Although improving shedding performance can reduce MF emission quantity, reducing the use, production, and enhanced circularity of textile materials within the system can effectively reduce MF release, which addresses the root cause of pollution [153–155].

Currently, the lint filter is the most effective device. Yousef et al. [162] have provided new modelling to collect MFs and use them as a renewable energy source. This innovative development transforms MF waste into a new valuable energy resource capable of reducing the carbon footprint and has the potential to be scaled up.

4.6. Wastewater Treatment

As WWTPs are the major sinks and sources of MPs/MPFs/MFs, a higher retention rate using advanced treatment technology should considerably influence release reduction. However, proper sludge handling must be performed simultaneously to ensure that the problem is not transferred from aquatic to terrestrial environments. Although, practically, other advanced treatment technologies such as Membrane Bioreactor (MBR) and Zero Liquid Discharge (ZLD) are available in the industry to reduce water stress and pollution, they all involve significant investment and time for implementation [7].

Increasing recycled water within WWTPs and reducing wastewater discharge can be a quick fix. Innovations in dry finishing technologies, such as using carbon dioxide as a dyeing carrier, is cleaner than wet processing. This is also a new trend that can help resolve MFs and water pollution in one solution. Combining these benefits has multiple effects on accelerating the investment decisions. Lack of knowledge and test methodology, inability to include MPF requirements in sourcing policies from retailers, and limited financial incentives to invest are the most significant barriers to industrial transformation [156]. Apart from standardising the testing methodology, incentives such as green funds supporting the transformation to innovative technologies are essential to resolve MF discharge through the aquatic pathway.

4.7. Mitigation Devices

Several studies have evaluated mitigation devices, and non-profit organisations (NGOs) have been educating and promoting the use of mitigation devices and proper wash care at the consumer level [163,164]. However, these devices have gained little popularity [48], as some of them were less effective than they had thought, and the users found them difficult to recognise owing to their impact level.

Although these external devices are convenient, improper waste handling and disposal potentially mean that the disposal route of MFs is transferred from one end to another. Thus, they are still incapable of mitigating this issue. Washing machine manufacturers should have a role to play by building similar performance features into new models, making them more accessible and practical. It is essential to recognise that relying solely on these devices may not adequately reduce MF release from this source. Embracing sustainable washing habits, such as decreasing the frequency of washing and altering purchasing behaviours to acquire fewer but longer lasting garments, can result in a more impactful outcome.

4.8. Standardised Test Method

Developing methodologies that effectively measure MPF/MF release is necessary to evaluate solutions and enable science-based decisions. Effective and standardised methods can help regulatory bodies by holding all stakeholders accountable and defining the maximum thresholds for releasing MPFs/MFs into the environment, thus realistically stopping them. A more unified approach using AATCC TM212 [30], ISO/DIS 4484-1 [31], and the TMC method-2019 [81] is now available for the industry to evaluate MFs from laundry. There is continued demand to expand its scope to cover drying, air, wastewater, and sludge. Since synthetic and natural fibre impacts and toxicity mechanisms intrinsically differ, methods that can enumerate size and quantify separately when the materials are blended are also important.

The different reporting parameters and insufficient transparency of the methodologies used have hampered the progress of MP studies. A group of researchers has developed harmonised reporting guidelines [165]. A similar approach should also be followed in MPF/MF studies, alongside developing a standardised method to guide researchers and commercial practitioners and ensure that the results are comparable, reproducible, and reliable for estimating its impact and developing mitigation solutions. Furthermore, it can facilitate the implementation of regulatory measures.

4.9. Government Interventions

Global legislation to regulate MPFs is imperative; however, only a few regions have taken regulatory action. Currently, France is the front runner. In 2020, it was the first country to pass a law that required all new washing machines to have MF filters by 2025. Apart from taking responsibility for the producer scheme through legislative intervention, governments also need to improve their waste management and WWTP infrastructures, which requires large-scale investment [58,159]. On the other hand, funding research to accelerate knowledge and engage stakeholders is an inevitable action to support policy development, making them practical and pragmatic for implementation.

Moreover, providing education and information to the public is an indispensable part of government intervention. Educating consumers to take responsibility for reducing release in the usage phase must be targeted to reach decision makers who can make purchasing choices. Consumer behaviours are typically challenging to change, as they require a shift in values and beliefs, to understand their social responsibilities, and become part of the solution. Initiatives driven by civil societies that engage communities more effectively remain vital to continuing the shifting momentum [151,154].

Existing mitigation solutions are voluntary and market driven. Innovative technologies require financial investments to scale and make them affordable. Government intervention and investors in scaling are inevitable and often play a critical role in reaching the tipping point. Socioeconomic factors should not be excluded from resolving sustainability issues involving systematic change. In reality, some of the solutions are interdependent. For example, reducing synthetic fibres can increase the demand for natural fibres with a larger carbon footprint and competing land use and biomaterials in other systems. Therefore, wider stakeholder groups from cross-disciplines must collaborate to address this cross-disciplinary agenda and evaluate its impact on the complete lifecycle of related ecosystems to ensure that it does not negatively impact other industries or the socioeconomic system.

5. Conclusions

5.1. Limitations

Bibliometric analysis is generally viewed as a reliable method, but some degree of subjectivity remains when choosing articles based on specific keywords. While a set of 219 articles is adequate for conducting main path analysis, expanding the sample size can yield greater insights into emerging trends, particularly concerning less common keywords like "fibrous microplastics", "airborne microplastics", and "microfibre fragmentation" found in journal databases. This review used the WOS database, and it is recommended that other databases and non-traditional publications be included.

WOS consistently updates its database; data downloaded for a specific period maybe added to after a particular time. According to Pilkington and Meredith [166], CNA treats all citations as equally important irrespective of the significance of their citation or utility type. Consequently, the research trends were more robust than the specific numbers per group. Negative citation is unavoidable, but it is rare and insignificant.

5.2. Outlook

The success of the industry relies on practising sustainable solutions throughout a product's life cycle [167]; however, these solutions cannot be isolated because there has been a systematic change from low technology to an industry that depends on innovation and sophisticated knowledge of the impact of MPFs/MFs on the environment, human health, and socioeconomic aspects. Furthermore, this depends on the capability of stakeholders to work together in a collaborative approach.

The bibliometric analysis used in this review has enabled the systematic utilisation of publications from all science areas, likely to influence multidisciplinary research topics and reach a broader audience. Moreover, it is remarkably applicable in the study of MPFs/MF, as it is more of an interdisciplinary subject of interest requiring a collaborative approach to accelerate progress.

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