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MDPI

Systematic Review

Application and Efficacy of Management Interventions for the Control of Microplastics in Freshwater Bodies: A Systematic Review

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Abstract: This systematic review represents one of the first attempts to compare the efficacy of the full suite of management interventions developed to control (prevent or remove) microplastics (MPs) in freshwater bodies, both man-made and natural. The review also traces the evolution of research on the topic in relation to the timing of key policy and regulatory events and investigates whether interventions are being applied within regions and freshwater bodies that represent concerns in terms of MP pollution. The review incorporated bibliometric analysis and meta-analysis of 124 original research articles published on the topic between 2012 and April 2023. To supplement the key findings, data were extracted from 129 review articles on the major knowledge gaps and recommendations. The number of articles on the topic increased with each year, coinciding with a range of global policy commitments to sustainability and mitigating plastic pollution. The majority of the studies focused on MPs in general, rather than any particular particle shape or polymer type, and were conducted at wastewater/sludge treatment plants. Upstream interventions accounted for the majority of studies reviewed (91.1%). A smaller proportion (4.8%) of studies involved reduction in production and physical removal at the point of production (1.6%); treatment-related objectives such as removal through filtration and separation and the combination of these with other technologies in hybrid systems were dominant. Of the physical, chemical and biological methods/technologies (and combinations thereof) employed, physical types (particularly membrane filtration) were most common. The majority of the studies within the wastewater/sludge, stormwater and in situ water/sediment categories exhibited removal efficacies >90%. Although new interventions are constantly being developed under laboratory conditions, their scalability and suitability across different settings are uncertain. Downstream interventions lack sustainability without effective upstream interventions. Though in situ methods are technically achievable, they may not be feasible in resource-limited settings.

Keywords: microplastics; freshwater; treatment efficacy; intervention; mitigation

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1. Introduction

Microplastics (MPs) are emerging environmental pollutants that are ubiquitous in aquatic environments (freshwater and marine). MP pollution has raised much concern globally and consequently spurred voluminous studies on the prevalence, characterization, fate, impacts and removal of MPs [1–3]. The phenomenon of MP pollution in aquatic environments reflects a much bigger challenge, namely, the global plastic waste burden, which was placed at 275 million tons (Mt) in 2010, of which 31.9 Mt were estimated to be mismanaged plastics that enter the environment [4]. In 2015, Jambeck et al. [4] approximated 8% (8 Mt) of the total plastics used globally to eventually enter the ocean via rivers, surface run-offs and other means. Furthermore, in 2017, Geyer et al. [5] approximated 12,000 Mt of plastics to have escaped from the waste management cycle and entered landfills or the environment directly over the last 50 years. After macroplastic debris enters the aquatic environment, it can undergo biological (degradation by microorganisms), mechanical (erosion, abrasion) and chemical (photo-oxidation, hydrolysis) modifications [6]. These modifications collectively lead to the weathering and the fragmentation of macroplastic debris into smaller and more abundant pieces (5 mm), what we refer to as secondary MPs [7]. In addition to the formation of MPs from the breaking down of the macroplastics, a large amount of plastics is manufactured as MPs (microfibers and microbeads), known as primary MPs, and used in various products, particularly in cosmetic products and textiles, and manufacturing processes [8,9].

Primary MPs are synthetic polymer particles produced as small-sized beads or pellets for further processing or addition to goods to act as 'scrubbers' in cosmetics and household cleaners, as industrial abrasives for sandblasting, or to manufacture feedstock pellets [8]. These particles (pellets and beads) are transported into water systems and then into natural rivers, eventually entering the ocean [9]. Secondary sources of MPs come about as a result of the unintentional introduction of plastic particles into water bodies from macroplastic pollution; macroplastics break down into MPs as discussed earlier [6]. Synthetic textiles and clothing are also significant sources of MPs because laundry physical and chemical abrasion leads to the production of smaller microfibers [10] which can enter the environment, particularly waterways (lakes, reservoirs, ponds, rivers, streams, wetlands), through the inappropriate/untreated release of wastewater [11].

The first comprehensive overview of the state of waste management globally in the 21st century [12] highlighted that waste management is still a challenge which is predicted to intensify given that the global quantity of mismanaged plastic waste has been projected to increase to 155–265 Mt per year in 2060, in comparison to 60–99 Mt in 2015 [13]. In commenting on the global waste management challenge in general, Wilson and Velis [12:1049] raised an important point: "Effective technologies required to 'solve' the waste problem are largely already available, and have been much written about". Waste management decisions may, therefore, need to focus on the implementation and suitability of waste management strategies, and, in the case of plastics, this needs to incorporate strategies (technologies/methods) for both (1) better management of the macroplastic waste that could potentially produce MPs and (2) the control (removal and degradation) of MPs after they enter water in the built and natural environment. However, this is not a simple task, given that decisions on the selection of strategies to control MP pollution are complicated by the fact that MPs are highly variable in terms of type, abundance, source and fate [3,14–16]. While there is a comprehensive summary of the sources of MPs to the environment [17], the multiplicity of MP sources has created a host of potential fates, hazards and remediation options that have been documented within freshwater bodies [18–20], though not as extensively as in marine environments [3].

Within a catchment, pollutants such as MPs can move across (out of or into) multiple compartments, accumulate in certain compartments and even return to previous compartments. Efforts to manage and enhance the built environment and water resources through strategies such as stormwater infrastructure and the creation of green infrastructure further complicate the movement and distribution patterns of MPs within a catchment. Freshwater bodies that are found to contain MPs include groundwater, freshwater lakes, rivers, dams [3] and both constructed and temporary wetlands [21]. Microplastics are most common in urban freshwater sources but have also been found in remote locations such as high-altitude streams [22]. The factors that could influence their relative concentration/distribution (vertical and horizontal) in freshwater bodies include the source inputs, duration of input and type of material (including size, shape and density), as well as transport mechanisms which are in turn influenced by hydrodynamic elements such as turbulence, turbidity and climatic conditions [19,21]. For example, water flow [3] and rainfall have been shown to influence the input and concentration of MPs in freshwater environments and bring about seasonal variations in concentrations [3]. Retention of particles in these riverine environments is also governed by the presence or absence of aquatic and fringing vegetation, as they may serve to trap particles in the higher reaches if present [23], which has pointed to the value of ecological infrastructure in managing MPs [24,25].

A major consideration when selecting interventions for the prevention and removal of MPs is the impacts that one seeks to mitigate. The nature of these impacts will dictate whether an established or bespoke intervention or combination of interventions is needed [26,27]. These impacts include reduced environmental quality [3,18,25] and negative impacts on aquatic organisms. A review of these impacts on organisms is beyond the scope of the current review but it is worth mentioning that they can be direct in the form of gut blockage [28,29] or indirect by vectoring other sorbed pollutants such as organic contaminants, heavy metals and microbial pathogens [30–32] that threaten the lives of biota [33–35]. In terms of their impacts on water and sediment quality, inherent plastic monomers and additive compounds that aid plastic function can be leached out over time [34]. In light of the above, the suite of MP pollution control interventions employed in any catchment compartment should ideally accommodate for the variety of impacts these plastic particles could have within the compartment(s) under consideration and the downstream water bodies.

Making decisions on the suitability of MP pollution control interventions for freshwater systems requires careful consideration of the location where they are to be applied and, more specifically, the catchment features. On this note, the definition of a catchment in the Anthropocene now accommodates the built environment as part of catchments, particularly in urban areas where stormwater runoff from buildings and roads [36], and other infrastructure such as wastewater treatment plants (WWTPs) [37,38] and ponds and reservoirs [39,40], can all receive and release MPs into natural water bodies, particularly freshwater systems such as rivers [41,42]. This threat has spurred increased implementation/commitment to policies, treaties and/or regulations focused on controlling MP pollution globally [43–45]. This increased interest in controlling MP pollution, together with the multiplicity, complexity and variability of the factors that contribute to the prevalence and fate of MPs in aquatic environments in general, has led to diversification in the types of interventions (e.g., source control) and associated technologies/methods (e.g., membrane filtration) used.

Traditionally, environmental management interventions include pollution control measures (which include implementing regulations and technologies to reduce or eliminate harmful emissions and pollutants into the air, water and soil), habitat conservation and restoration (protecting and restoring natural habitats to preserve biodiversity and ecosystem functions), sustainable resource management (i.e., promoting the sustainable and responsible use of natural resources to ensure their long-term availability and encouraging responsible consumption and waste management) and environmental education and awareness [3,46]. Solutions for MP pollution include interventions that prevent the release of plastics to the environment during their life cycle and physical methods of recovering or removing MPs from the natural environment (e.g., using pumps, mesh nets and other capturing devices) [3]. Strategies to recover or remove MPs have been extensively reviewed [38,47–50] but focus largely on those associated with wastewater treatment [11,51–54] or on specific types of interventions such as bioremediation [55]. Reviews on interventions to prevent the release of plastics to the environment focus largely on policies and regulations [43–45] or source control [25] and rarely focus specifically on freshwater. Reviews that do focus on MP removal in freshwater environments e.g., [56,57] either do not compare the relative efficacy of the variety of prevention and removal interventions that have been applied, or focus exclusively on chemical, biological and physical methods. The systematic review on management interventions for the control of MP pollution in freshwater bodies undertaken here, therefore, represents one of the first attempts to compare the efficacy of the full suite of interventions that have been developed to control (prevent or remove) MPs in freshwater bodies, both man-made and natural, based on the contemporary understanding of what constitutes a catchment. The review addresses the following research questions:

- What are the temporal, geographic and thematic trends in research on the application of interventions to prevent or remove MPs in freshwater bodies?
- How do these research trends relate to the policy and regulatory evolution of microplastic pollution control?
- What types of MPs and which catchment compartments represent research priorities?
- What types of interventions and combinations thereof are being prioritized (i.e., what are the comparative levels of uptake of different interventions), and where?
- What are the comparative levels of efficacy of the different interventions, and which combinations appear to be most effective?

We believe that the comparative approach adopted in this review can aid management decisions on MP pollution control in freshwater bodies, particularly in terms of the selection of fit-for-purpose and efficacious intervention types and appropriate methods/technologies. The knowledge gaps identified and recommendations made will help move research on MP pollution into a solution-oriented paradigm.

2. Methodology

Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA, 2020) guidelines were followed to document the literature review [58]. The PRISMA method provides a comprehensive set of guidelines for conducting systematic reviews [59,60], which were applied as shown in the PRISMA flow chart (Figure 1). The results of the identification, screening and inclusion process are described below.

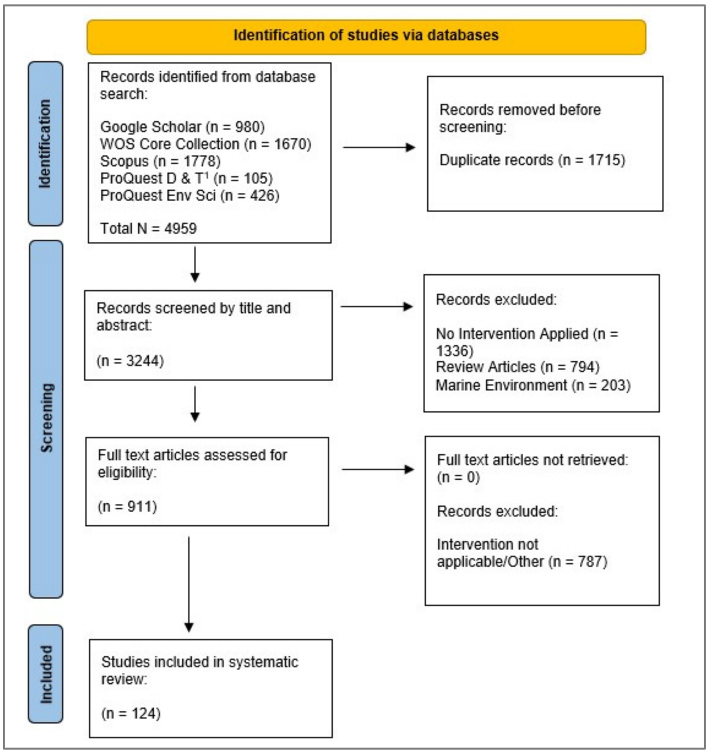

Figure 1. PRISMA flow chart showing steps and article counts at the various stages of the review process [[1] Database: ProQuest Dissertations and Theses Global and Environmental Science].

2.1. Search Strategy, Eligibility & Inclusion

A search strategy was devised to cover the three main topics: MPs, freshwater and management/mitigation. The full search strategy, which included multiple search strings and five databases, is presented in Appendix A. Google Scholar, Web of Science Core Collection (Clarivate Analytics, London, UK) and Scopus (Elsevier, Amsterdam, The Netherlands) were searched on 27 April 2023. Dissertations & Theses Global and Environmental Science, both on the ProQuest platform, were searched on 28 April 2023. All searches except for Google Scholar were limited to the period 2012 to April 2023. For studies to meet the inclusion criteria, they had to be peer-reviewed, original research articles or book chapters or dissertations published in English from 2012 to April 2023, and, most importantly, had to report on the application of an intervention to control MP pollution in a freshwater body/system/habitat. Studies were excluded if they reported on MPs in the marine environment, nanoplastics or macroplastics, or if they represented conference proceedings or review articles. Studies were imported into Rayyan [61] and assessed for eligibility by two independent reviewers. Any conflict based on the inclusion and exclusion criteria was marked and resolved by discussion with the entire research team. The initial search identified peer-reviewed articles on the control, mitigation, prevention and management of MP pollution in freshwater systems and identified 3244 articles after de-duplication. Of these 3244 articles, 911 were deemed suitable for a full-text review after title and abstract screening. Of these 911 articles, only 124 were found to involve the application of an intervention to control MP pollution in a freshwater system and subsequent assessment of efficacy—our primary criterion for inclusion after full-text screening.

In addition to the systematic literature review, we extracted data on the major recommendations and knowledge gaps on controlling MP pollution in freshwater bodies from a selection of review articles. From the original search of 3244 articles used for the systematic review, 794 review articles were screened, yielding 129 articles that were deemed suitable for inclusion after a full-text screening based on the fact that they contained specific recommendations and identified knowledge gaps related to controlling MP pollution in freshwater bodies or aquatic habitats in general.

2.2. Data Extraction & Management

The abstracts for all records identified via the initial search (n = 3244) were retrieved and imported into Rayyan [61] for screening. The 3244 records were then screened (two independent reviewers per article) using the title and abstract, and separated into three categories: 'include', 'exclude' and 'maybe'. The 'maybe' category served as the holding folder for review articles, which were subjected to a separate data extraction and analysis process (described below) by two independent reviewers per article, separate from the 124 original research articles ultimately included in the systematic review. The full text of all articles identified for inclusion was obtained, and the text was critiqued for eligibility by two independent reviewers per article as shown in the PRISMA flow diagram. Any conflicts were identified by Rayyan. All identified conflicts were resolved by discussion between the reviewers. If a resolution could not be obtained, then the article was assessed and discussed by the entire research team.

Using a modified data extraction spreadsheet created in Excel (see Supplementary File S1), two independent reviewers extracted data on the following for each of the 124 articles included in the systematic review: full citation, article country of origin, MP types, type(s) of intervention, objective(s) of intervention, method/technology employed, location/habitat/environment in which the intervention was applied and efficacy (based on percentage removal/reduction). If multiple interventions were reported in a single article, then data were extracted for each type of intervention separately. Additionally, recommendations and knowledge gaps on the subject were extracted from 129 review articles into an Excel spreadsheet and used for the supplemental analysis.

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It should be noted that this review process was subjected to multistage quality checks. As mentioned above, during the screening and full-text review phases, a minimum of two authors were assigned to each record. In cases where both authors yielded different results/outcomes, a third author examined the record and served as an arbitrator. Authors' profiles and disciplinary focus differed, resulting in a multidisciplinary group of reviewers, which ensured the reduction of bias.

2.3. Data Analysis

Data on MPs type and the number, type, objective, methods/technologies and efficacy(ies) of the interventions were coded based on predefined categories to generate a comparative matrix (Supplementary File S1). These data were disaggregated into the main thematic areas by crosstabulations (SPSS, Version 27). Publication dates were analyzed. The citation and keyword network analyses were generated in VOSViewer version 1.6.19, a tool for blending and visualizing bibliometric networks based on citation and journal data extracted from a robust body of scientific literature [62]. Recommendations and knowledge gaps extracted from the review articles were arranged thematically and scored for frequency (i.e., how many articles they appeared in). Using the frequencies, each theme was then ranked to identify the most frequent recommendations and knowledge gaps, and the top five for each category were selected for discussion.

3. Results & Discussion

The results of almost all the analyses described in this section were based on the database compiled for the study (Supplementary File S1), which contains data on the year in which the article was published; country where the intervention(s) was/were applied; the MP type(s) targeted (e.g., microbeads/pellets/nurdles); whether single or multiple interventions were applied; what type(s) of intervention(s) was/were applied (e.g., source control measures or wastewater/sludge treatment); what the objective of the intervention was (e.g., reduction in production or degradation); the method/technology (e.g., filtration or flocculation) employed; the location (habitat/environment/setting) where the intervention was applied (e.g., river/stream); and, finally, the normalized percentage efficacy of the intervention to allow for comparisons (given that the same method of quantification was used before and after application of each intervention). The database represents what we believe could be the beginnings of a decision-making tool for practitioners, managers and researchers to compare strategies for MP control in freshwater systems and access relevant literature on these strategies.

3.1. Scope of Publications on MP Interventions in Freshwater Systems

Our initial search yielded a total of 3244 articles but only 124 papers [3,4,63–183] were ultimately selected for review based on the exclusion criteria. The initial search yield (based on title and abstract) is reflective of the overwhelming number of publications on MPs over the last decade [2,184], but the marked difference between the number of papers in the initial search yield and the final number of papers selected for review is possibly a consequence of an over-emphasis on MPs in the marine environment. For example, Blettler et al.'s [185] analysis of journal databases for publications over an unspecified duration until May 2018 showed 440 (~87%) marine MP studies that fulfilled their search criteria in comparison to only 64 (~13%) in freshwater habitats. When the authors expressed these numbers in terms of publication rate, they showed that publication rates of studies of plastics in the marine and freshwater environments were 41 and 7 papers per year, respectively. The underrepresentation of studies on the application of interventions for the management, prevention and mitigation of MP pollution in freshwater environments in the literature is of particular concern; for instance, in the present study, only 3.24% of the studies that met the initial search criteria (Figure 1) focused on the application of an intervention to manage, prevent or remove MPs in freshwater bodies.

All studies included in the systematic review [3,4,63–183] were published in 2016 or later, with an increase in the number of studies published each year, except in 2023. We believe that the 'false' decline in 2023 is simply a consequence of the analysis only including articles published up until April 2023. Therefore, while the set of articles analyzed for this paper represents a focused sample of research published on MPs, it can be inferred from this sample that the number of papers being published on MPs is continuously growing. In terms of the chosen timeline, 33.1% of publications used in this systematic review were generated in the year 2022. This is reflective of publication trends in the literature on MPs in general [2], where research on MP pollution is seen to have gained momentum after the publication of the global Paris Agreement (UNFCCC, 2015) and the listing of MPs as one of the top 10 environmental issues in 2014 (Figure 2). Even though our analysis begins in 2016, there may have been several factors promoting research on MP removal/degradation in freshwater systems before this timeframe. For example, the significant rise in publications may have been spurred by the global commitment to the Sustainable Development Goals (SDGs) in 2015. This thrust may have been sustained by subsequent events such as the G7 signing of the Ocean Plastic Charter in 2018 and China's release of a document strengthening plastic pollution control by its National Development and Reform Commission and Ministry of Energy in 2020.

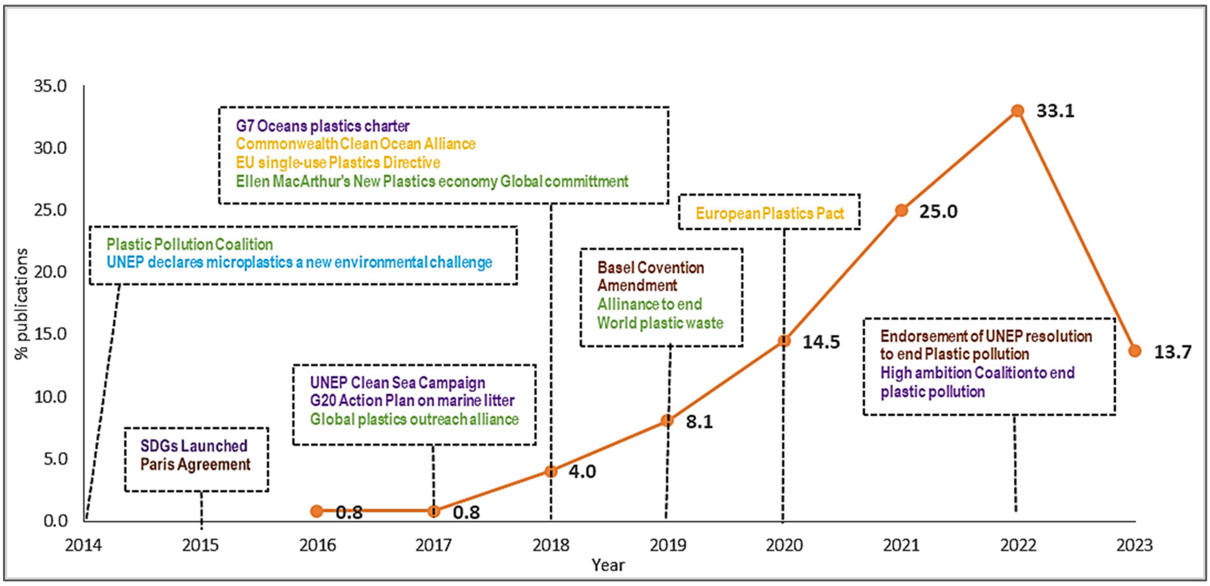

Figure 2. Timeline giving publications per year [3,4,63–183] and key events in the evolution of microplastic pollution control.

To truly appreciate this increased momentum, one has to only consider that our analysis showed the number of publications on the control of MPs in freshwater bodies to increase by 1700% between 2016 and 2020 and by 127.8% between 2020 and 2022. Similarly, Al et al. [2], in their bibliometric analysis of emerging trends in research on MP pollution in the post-Paris Agreement and post-COVID-19 pandemic world, showed that the number of articles in 2020 increased by 1770.0% relative to 2015. Based on the trends they observed, Ali et al. [2] predicted a much higher number by the end of 2021. The trends we see here in terms of the increase in the number of studies on management interventions for MP pollution control in freshwater bodies are also very likely due to the increased generation and access to published research on MPs, as evidenced by an analysis by Sorensen and Jovanović [184] which showed that the number of MP publications increased by 2323.1% in 2019 relative to 2009. Furthermore, their analysis showed that 2019 was the year with the highest total number of citations (42,000 citations), followed by 2018 (25,000 citations) and 2017 (13,000 citations). However, in comparison, freshwater interventions for MP control remains under-researched across most of the world when compared to research on marine systems. This may change in the foreseeable future, given the endorsement of the first-ever legally binding UNEP resolution to end plastic pollution in 2022 and the continuous improvement in detection methods [186].

The minimum number of co-occurrences between the keywords was set at five, which produced a total of 53 keywords (Figure 3). In Figure 3, the larger the 'dot 'underneath the keyword, the more often the keyword occurs, and, based on this, the top keywords include microplastics, pollution, particles, fate, removal and identification. There are four clusters of keywords indicated in red, green, blue and yellow. The blue cluster reveals themes of pollution, particles and identification, with a focus on fibers, debris, WWTPs and sewage sludge. The red cluster includes MPs, marine environment and sediments with a variety of other terms like degradation and biodegradation coagulation, polymers, drinking water, polyethylene and polystyrene. The green cluster represents not only fate and wastewater-related keywords but also the natural environment with terms like fish and river. A small yellow cluster includes the removal and activated-sludge process. This cluster analysis reflects the importance of the types of data extracted from the 124 selected articles: The blue cluster highlighted the need to discriminate among the types of particles targeted across different studies; the red cluster highlighted the need to extract data on the methods/technologies used; the blue and green clusters highlighted the importance of looking at the application of interventions upstream (e.g., wastewater/sludge treatment plants (upstream) and downstream (e.g., rivers); the yellow cluster highlighted the importance of interventions focused on the removal of MPs (Figure 3). Numerous articles have pointed towards the importance of considering the type(s) of MP targeted, the source of the MPs and the method/technology used for their removal/degradation/reduction when designing MP control interventions for freshwater systems [49,170,187].

The article with the highest number of citations was Carr [71], with 1043 citations (Figure 4). This paper discussed MPs in wastewater treatment plants. Other articles with 200 or more citations include Auta [65,66] discussing microbial MP degradation, as well as Edo [81], Conley [75] and Lv [119] discussing WWTPs. These results highlight the emphasis placed on interventions focused on the removal of MPs from wastewater (i.e., upstream interventions) globally, a trend evidenced by the large number of articles on wastewater treatment in this study (74.2%) and the voluminous number of articles on the removal of MPs from wastewater/sludge reviewed elsewhere [37,38,51].

The publications reviewed in this paper reflect studies on the application of interventions to control MP pollution in freshwater bodies from across the globe; however, the majority of articles originate in the People's Republic of China, the United States of America and Australia (Supplementary File S1). Likewise, articles with the highest citations were also from the People's Republic of China and the United States of America, each with two distinct authors contributing to the metric (Supplementary File S1). The possible reasons for this geographical bias are discussed in Section 3.3, where we examine the geographic patterns in terms of the application of interventions for the control of MPs in freshwater bodies. However, it should be mentioned that these two nations host several premier academic institutions that have been driving the research agenda on environmental pollution for many years. Moreover, they have been actively involved in developing and lobbying for improved policies and regulations for MP pollution, specifically along the MP pollution control timeline shown in Figure 2.

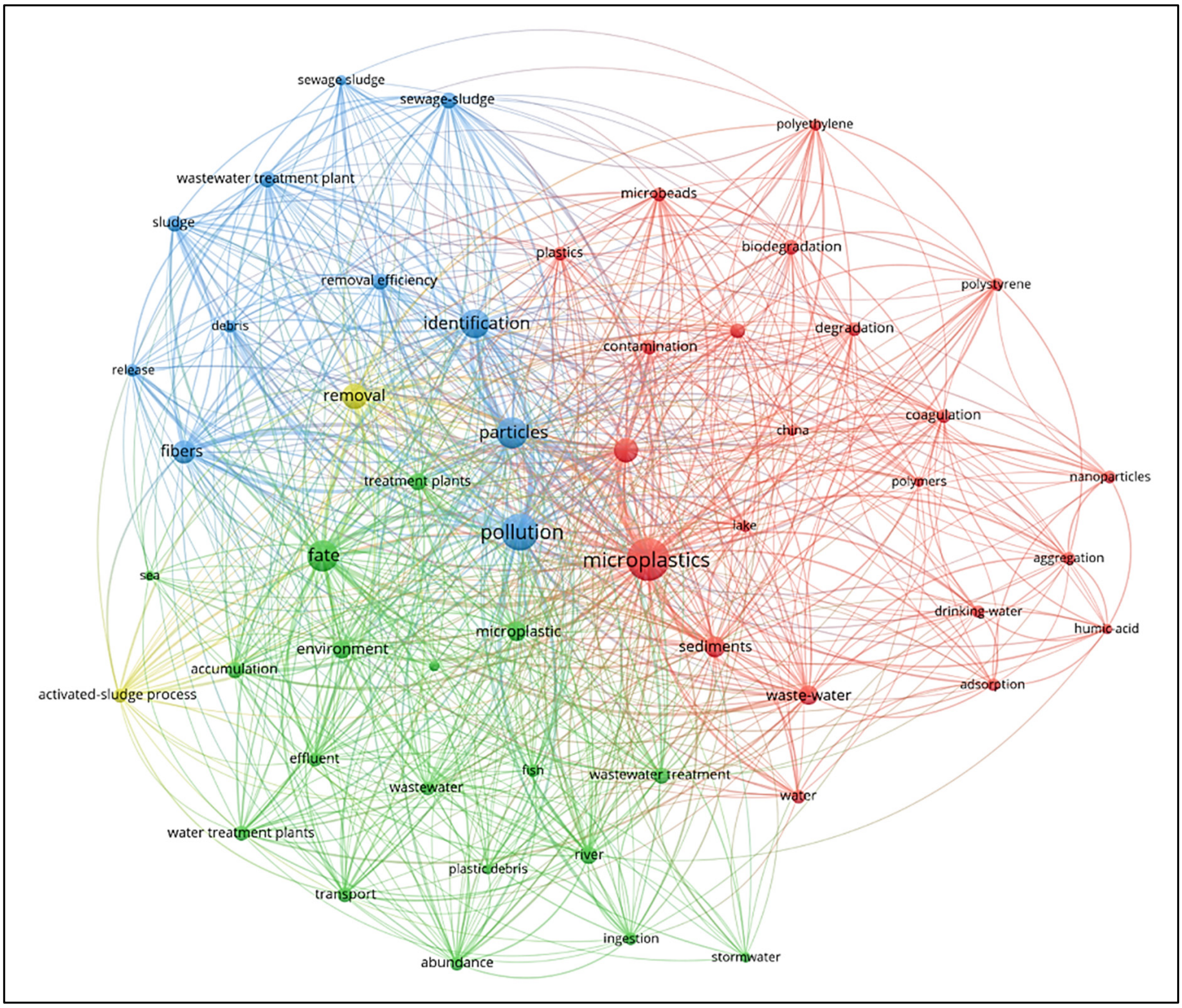

Figure 3. Map of the network of co-occurring keywords from the included articles [3,4,63–183] generated in the visualization software VOSViewer version 1.6.19 (n = 124).

3.2. Location of Studies

A country-level classification shows that 36.3% of the publications were conducted in China, while USA (8%), Germany and UK (5.7%), Australia and Thailand (4%), India (3.2%) and Canada, Denmark, Iran, Malaysia, Spain and Sweden (2.4%) comprised the main geographic focus. Further analysis revealed that the research foci varied across these main countries (Table 1): China, Germany and the UK produced publications across several categories of interventions while countries such as the USA and India focused on wastewater/ sludge, bioremediation and stormwater treatment interventions (Table 1). Evidently, publications on wastewater/sludge treatments were the dominant research focus in terms of intervention type, with China contributing 29.8% of the articles in this category.

However, more important in this systematic review is habitat/environment/setting in which these interventions were applied, as this will help shed light on the catchment compartments that are being prioritized and the degree to which interventions are being applied in real-world settings. Of the 18 potential habitat/environment/setting types used to extract the data (see Supplementary File S1), nine were represented in the articles reviewed here (Figure 5). As expected, a large proportion of the studies were conducted at treatment plants (36.3%). However, it was interesting to note that the majority of the studies (44.4%) were conducted ex situ, under laboratory conditions, aiming to develop or refine interventions. These two locations were followed by constructed/natural wetlands in terms of frequency, with a handful of studies (8.8%) taking place in real-world settings such as stormwater drainage, roads/streets/highways and households/homes [86]. Importantly, none of the studies reviewed were applied at the catchment scale and there were no studies on other freshwater catchment compartments known to be impacted by MPs, such as lakes and dams, that met the search criteria. Even though this suggests that future research should aim to close these gaps in terms of under-researched catchment compartments, they may also point to the fact that the freshwater systems that are currently the foci of research in the field (e.g., rivers/streams, stormwater systems and WWTPs), represent the major threats/priorities. The results also suggest that new methods are constantly being developed and refined under laboratory conditions before they are implemented (at scale) in situ [112]. However, many of these lab-based studies use manufactured MPs [99,171,176] and appear to ignore weathering/aging effects and diversity in MPs (shape and polymer types) that exist in natural settings [132]. This can result in the development of interventions that are not fit-for-purpose (i.e., not scalable and/or inefficient in situ).

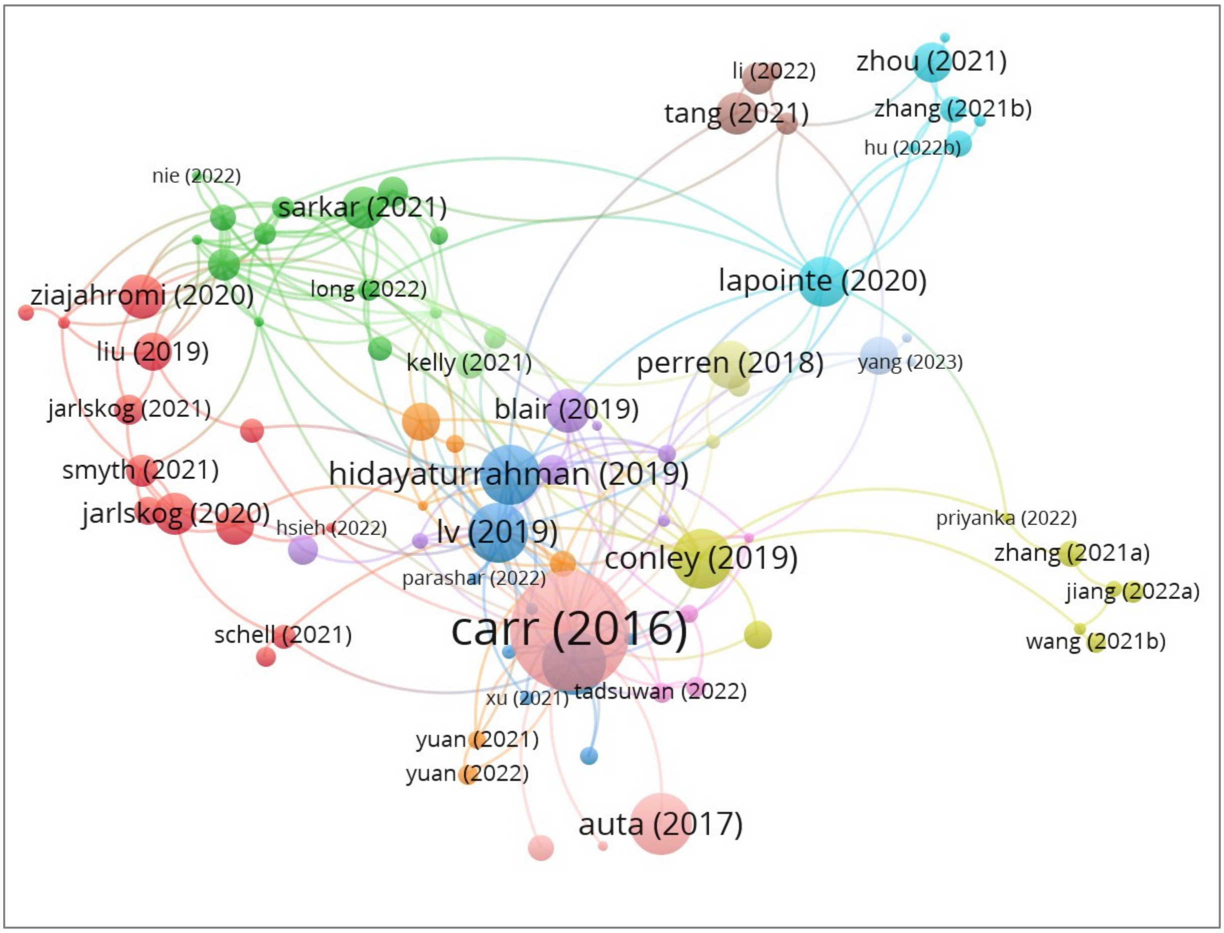

Figure 4. Results of citation analysis (up until July 2023) of the included articles [3,4,63–183] generated in VOSViewer (n = 124).

Table 1. Intervention types researched by top-producing countries (n = 124) [3,4,63–183].

Country *	1	2	3	4	5
China	3.2	29.8	2.4	-	0.8
USA	-	5.7	-	2.4	-
Germany	0.8	4	-	0.8	-
UK	0.8	4	.8	-	-
Australia	-	4	-	-	-
Thailand	-	4	-	-	-
India	-	2.4	0.8	-	-

1 = Source Control; 2 = Wastewater/Sludge treatment; 3 = Bioremediation; 4 = Stormwater treatment; 5 = In-situ sediment/water treatment; * Only showing results for the main countries contributing to research highlighted in the systematic review.

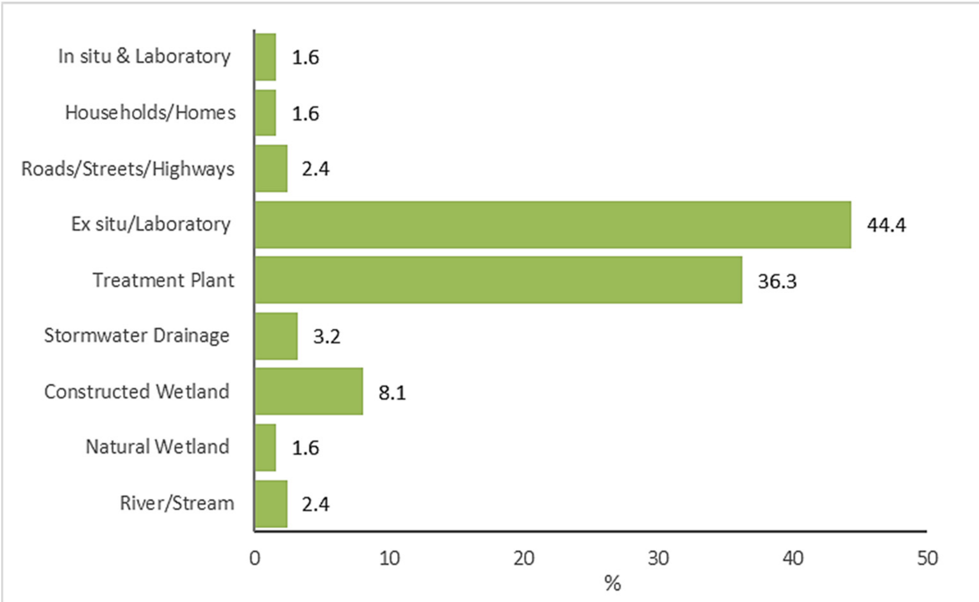

Figure 5. Habitat/environment/setting in which interventions were applied [3,4,63–183] (n = 124; Multiple entries observed in some records).

3.3. Types of MP

Of the 124 studies reviewed, the majority (89.5%) focused on interventions targeting MPs in general rather than any particle shape (fibers, films, foams and fragments) or polymer type (polyethylene, polypropylene, polystyrene, polyamide, polyester and acrylic). There was a small proportion of studies that focused on microbead and microfiber removal (~4.8% each). Fibers are the most dominant group of MPs, especially in urban landscapes and originate from the washing of clothes/textiles [180,188]. Microbeads have also been identified as a major threat to many aquatic environments, given their widespread use in cosmetics and personal care products [8,189]. These MP prevalence patterns do not appear to be reflected in the literature on interventions to control MP pollution, though. For example, there was a very limited focus on interventions designed to capture microfibers using laundry technologies [120] and microbeads [127] specifically. Targeted interventions such as these do not seem to be the norm since the size, ubiquity and indiscriminate release of MPs into freshwater environments would make such an approach unnecessary and/or ineffective in most instances [190].

3.4. Type and Application of Interventions for Freshwater Systems

Based on the logic of process principles, by reducing the loss of plastics to the environment, the input of MPs into freshwater environments could be subsequently reduced. Solutions that focus on the prevention of plastics release to the environment during their life cycle can be termed 'upstream solutions', while 'downstream solutions' refer to the physical methods of recovering or removing MPs from the natural (freshwater) environment (e.g., using pumps, mesh nets and other capturing devices) [3]. Our review revealed a suite of upstream and downstream solutions (termed 'interventions' henceforth) that could be discriminated at the highest level in terms of 'intervention type' using the following typology (Supplementary File S1):

(1) Source control—measures to prevent MPs from coming into contact with (stormwater) runoff in natural and/or built environments; this includes clean technologies—any technology-based process, product or service that reduces/prevents MP inputs into the environment [74];
(2) Wastewater/sludge treatment—physical water treatment, biological water treatment, chemical treatment, and sludge treatment aimed at removing MPs and other pollutants [113];
(3) Bioremediation—use of either naturally occurring or deliberately introduced microorganisms or other forms of life to consume and break down MPs, to clean up a chronically or episodically polluted site [77];
(4) Stormwater treatment—the installation of structural controls primarily designed to remove MPs from stormwater runoff before this water is released into natural freshwater bodies [86];
(5) In situ water/sediment treatment—the physical removal of MPs from water or sediment in a natural freshwater body [99].

It was clear that the majority of the studies reviewed (95.2%) involved a singular intervention type, with only 4.8% of the studies involving a combination of interventions. Upstream interventions, namely wastewater/sludge, source control and stormwater interventions (collectively 91.1%) appear to be the dominant approaches adopted, with downstream interventions (bioremediation and in situ water/sediment interventions) accounting for a total of 12 studies reviewed. Wong et al. [3], in their review of the prevalence, fates, impacts and sustainable solutions to MPs in freshwater and terrestrial environments, observed that downstream solutions lack sustainability without effective upstream solutions. Though physical (e.g., mesh nets, pumps and other capturing devices) [100] and microbe-based [142] methods of recovering or removing MPs from freshwater bodies are technically achievable, they are often not logistically feasible due to the large number of MPs that are constantly entering these environments. Given that these methods require the installation of infrastructure or the introduction of foreign organisms, they also have the potential to disrupt local ecosystems.

In terms of the ultimate objective(s) of the interventions, a very small proportion of the studies involved reduction in MP production and physical removal at the point of production [120]; far more emphasis seems to be placed on treatment-related objectives such as removal through filtration and separation, capture and attachment and a combination of these technologies in hybrid systems (Table 2). However, it should be noted that interventions that involve the actual degradation of MPs appear to be uncommon (only 8.1% of the studies investigated). Interventions that involved the use of biodegradation were limited [126,159]. Similarly, research on bioplastics was limited [163], pointing to the technical challenges associated with this type of research: the rate at which bioplastics degrade is affected by different environmental conditions such as temperature, moisture, pH, oxygen content and, importantly, the availability of microorganisms [191]. The aquatic environment appears to be less suited than the terrestrial one for the degradation of bioplastics due to the lower availability of diverse microorganisms that enable higher biodegradability as compared to other environments such as soil [3].

Table 2. Description of ultimate objective(s) of the interventions/studies investigated (*n* = 124) [3,4,63–183].

Intervention Objective	% of the Articles Reviewed
Reduction in production	4.8
Removal–Filtration & Separation	21.6
Removal–Capture & Surface attachment	16.1
Removal–hybrid	48.4
Degradation	8.1
Physical removal at production	1.6

The high frequency of removal through the use of a combination of technologies (60; labeled 'Removal–hybrid' in Table 2) is a consequence of the fact that studies dealing with WWTPs constituted the majority (74.2%) of the articles reviewed here. This sampling bias, which was unavoidable as it reflects the literature on the subject over the last decade (evidenced by multiple reviews) [38,192], influenced other trends that emerged in our data analysis which are discussed later in this paper. This is largely because WWTPs are viewed as perhaps the most important source control points within catchments since they represent the solution in cases where they are efficient but quickly turn into problems when they experience failures and/or are based on inefficient technologies/methods [193].

Our analysis revealed that a wide range of techniques/methods are being employed/ explored for controlling MP pollution in freshwater bodies (Table 3). A brief description of the technologies that were identified in the systematic review is given below. However, it should be noted that this list is not exhaustive and some of these technologies are evolving very rapidly, with a single method/technology sometimes displaying multiple design, application and combination variations, so we have also highlighted articles that offer a more detailed technical description of these technologies.

Table 3. Description of technologies adopted for MP control in freshwater systems (*n* = 124) [3,4,63–183].

MP Control	Descriptions	Citation/s	% of Articles Reviewed
Filtration membrane	Using different types of membrane filters to remove MPs during water treatment.	[50,123,147]	36.3
Constructed/natural wetland	Using natural or engineered (constructed) wetland systems to capture and remove MPs from wastewater and non-point source pollution. These include various designs of constructed wetlands, with a variety of materials and plants.	[70,74,132,156,181,182]	15.3
Coagulation/electrocoagulation	Using different types of coagulants such as polyacrylamide (PAM) and alum, or electrical charge to allow MPs in water to form an agglomeration. The coagulation is followed by flocculation and then settling (sedimentation) of the particles, after which they are physically removed.	[26,63,82,104,109,127]	15.3

Table 3. *Cont.*

MP Control	Descriptions	Citation/s	% of Articles Reviewed
Flocculation and sedimentation	Using flocculation of MPs, followed by their sedimentation, and then physical removal of the particles during water treatment. Various types of chemical coagulants and/or electrocoagulation have been used to speed up the natural flocculation and sedimentation process.	[109,111,128]	15.3
Adsorption	Utilizing different types of sorbents (e.g., activated carbon, biochar, zeolites, sponges) or electrical charges to facilitate sorption of MPs onto these particles, followed by their sedimentation and physical removal.	[48,172]	6.5
Magnetization	Utilizing magnetisms (e.g., via binding with nano-Fe_3O_4 particles) to magnetize the hydrophobic surface of MPs, followed by their separation and removal under the influence of a magnetic field.	[141,148]	2.4
Micromachines	Utilizing novel approaches like microscale particles with magnetic properties, e.g., magnetic field, to create a continuous motion to facilitate transportation and then separation/removal of MPs in aquatic environments [48]. Micromachines can also include utilizing a bubble barrier device to collect [175] and surface-functionalize microbubbles to accumulate and remove MPs in aquatic systems [176].	[48,175,176]	0.8
Superhydrophobic materials	Using various chemicals, with superhydrophobic surfaces, to functionalize MP surfaces which results in a change in the surface chemistry of the particle, facilitating removal (e.g., via sorption, flocculation and sedimentation).	[63] and references therein	1.6
Microorganism aggregation	Using microorganisms (e.g., micro-algae and bacterial films) to facilitate aggregation (via biofilm formation) of MPs in aquatic/treatment systems, which increases the density and promotes sedimentation of particles for ultimate physical removal.	[63,76,77]	4.0

Table 3. *Cont.*

MP Control	Descriptions	Citation/s	% of Articles Reviewed
Photocatalytic	Using light irradiation to excite photocatalysts, a pair of electrons and holes are produced in the redox reaction, and then this process degrades MPs into smaller inorganic molecules, such as carbon dioxide and water.	[47]	0.8
Microorganism degradation	Using microorganisms (e.g., bacteria) to physically degrade MPs as natural and/or engineered remediation of MPs in aquatic systems.	[48] and references therein [65,66]	10.5
Thermal degradation	Using various thermal processes, often hydrothermal hydrolysis combined with the use of various chemical treatments (e.g., Thermal Fenton Reaction), to remove MPs in water bodies or WWTPs.	[72,93]	4.0
Oxidation ditch	Exposing MPs to an oxidizing environment enriched with bacteria (e.g., during activated sludge system in WWTPs) increases their oxidation, which will increase their hydrophilicity. The increased hydrophilicity of MPs assists with their removal via froth flotation in the presence of cationic and anionic surfactants.	[90,100]	8.9
Sedimentation	Removal of MPs from aquatic systems (including WWTPs) via vertical sinking (often combined with coagulation and flocculation) and deposition onto the bottom, which can be followed by physical removal.	[26,48,63]	6.5
Mechanical manual removal	Mechanical/manual removal of MPs via flotation, sedimentation and filtration, using various filtration techniques such as screening, sand/membrane filtration and reverse osmosis.	[26,48]	4.0
Agglomeration	Natural and/or enhanced (using chemical and/or electrical coagulation) aggregation of MPs into a large mass. The agglomerated particles are larger and thus sink and accumulate on the bottom, after which they can be physically removed.	[88,89,139]	1.6

Table 3. *Cont.*

MP Control	Descriptions	Citation/s	% of Articles Reviewed
Sand filtration column	Using a sand filtration system that traps MPs between sand grains is often enhanced with the addition of various filtration aids such as biochar.	[26] and references therein [92]	1.6
Laundry technology	Using various technologies in washing machines (e.g., filtration system or removable fiber attracting innovations as part of the wash) for source control of MPs.	[79,120,121]	0.8

Based on the descriptions given above, our analysis revealed physical methods to be the most widely used, including membrane filtration, separation via phyto-capture, grit/primary sedimentation, density separation, coagulation and flocculation and combinations thereof. This finding is supported by other recent reviews [194] and is largely a consequence of the dominance of wastewater/sludge treatment-related studies in the dataset, as discussed earlier. Membrane filtration, for example, is the most frequent technology/method employed in wastewater/sludge treatment but is almost always used in combination with other methods (as evidenced by other reviews [52,195]), most frequently coagulation/electrocoagulation, the combination of flocculation and sedimentation and oxidation ditch. The employment of other technologies traditionally associated with wastewater/sludge treatment, such as adsorption, magnetization, superhydrophobic, thermal degradation, and agglomeration, appears to be less frequent (all between 1.6–5.6%). Technologies/methods that involved microorganisms either for aggregation or degradation of MPs (14.5% in total) and the use of constructed/natural wetlands (15.3%) for separation were less frequent than traditional physical methods/technologies. However, it should be noted that both microorganisms and wetlands were observed to be applied in isolation or integrated into wastewater/sludge treatment plants. More rudimentary (combination of sand filtration and sedimentation, and sedimentation in isolation) and highly technological (micromachines) methods/techniques were recorded, but these were less frequently used (all $\leq$ 6.5%).

3.5. Levels of Efficacy across Interventions

When efficacy was assessed within each category, we noted that the majority of the studies within the wastewater/sludge, stormwater and in situ water/sediment interventions all exhibited reported efficacies of >90% (Table 4). Furthermore, though a significant proportion of studies in the wastewater/sludge category (19.8%) exhibited efficacies of 76–90%, efficacies for this intervention type were spread across the lower, middle and upper ranges. This can be attributed to variations in the number of treatment steps, type and operating conditions of treatment technologies and, possibly, differences in the age and/or quality of facilities within and across different studies. Similarly, efficacies for studies within the bioremediation category were spread across the lower and upper ranges; the majority (30%) of these studies exhibited efficacies <25%. In this case, differences in the efficacy of any biological solution can be expected given that changes in climatic/environmental conditions acting on aquatic environments cannot be controlled/accommodated for and most often influence the performance/physiology of the organisms used.

Table 4. Comparison of MP prevention/removal efficacy rates (%) across intervention types [3,4,63–183].

Type of Intervention	<25%	26–50%	51–75%	76–90%	>90%	Effective: Rate Not Disclosed
Source control (*n* = 14)	-	-	14.3	21.4	14.3	50.0
Wastewater/sludge treatment (*n* = 91)	4.4	1.1	12.1	19.8	41.8	20.9
Bioremediation (*n* = 10)	30.0	10.0	-	20	10.0	30.0
Stormwater treatment (*n* = 7)	-	-	14.3	14.3	42.6	28.6
In situ water/sediment treatment (*n* = 2)	50.0	-	-	-	50.0	-
Total (*n* = 124)	7.4	1.6	11.3	19.4	36.3	25.1

Efficacies for studies in the source control category were spread across the upper three ranges (51–75, 76–90 and >90%) but the design of these studies often did not require the quantification of efficacy, which may explain why efficacy was not reported in 50% of the studies of this type. Other intervention categories included a significant number of studies where the intervention was reported to be effective, but the efficacy rate was not reported (20.9–50%); in total, 25.1% of the 124 studies reviewed did not report efficacy. Importantly, when data for all intervention types were pooled for analysis, 55.7% of the studies reviewed exhibited efficacies >76%, of which 36.3% exhibited efficacies >90% (Table 4).

When we compare the level of efficacy of different interventions in terms of their main objective, it was evident that the removal of MPs using hybrid systems, which refer to wastewater/sludge treatment plants, was the most effective, with 50.8% of the studies in this category displaying efficacy rates of >90% and 16.9% of studies reporting rates of between 75–90% (Table 5). Other reviews [192,196] have also concluded that during the wastewater/sludge treatment process, most of the MPs are removed. Systems that employed a grease-skimming method during the preliminary treatment process seemed to have a large proportion of MPs removed from the treatment process, while filtration and membrane technologies seemed to be the most effective during the final stages of treatment [192]. While other reviews have shown that high efficacy rates for wastewater [51,196] and sludge [197] treatment plants are common, it should be said that very few of these treatment plants remove MPs with 100% efficacy, which implies that treatment plants are also a significant secondary source of MPs [194]. WWTPs have for some time now been recognized as perhaps one of the most significant sources of MP pollution globally [193,198,199]. Closer analysis of the wastewater-related studies suggests that the high levels of efficacy can be attributed to significant advances in membrane technologies such as ultrafiltration (UF), microfiltration, reverse osmosis and membrane bioreactors over the last decade [50,147] and the adoption of other treatment technologies/methods such as the combination of a porous membrane with a biological process [49,200]. These supplemental/alternate wastewater treatment options have been born of necessity. One of the major drawbacks of membrane filtration is the fouling phenomenon which is the result of the adsorption of particles on the membrane surface. This fouling leads to reduced membrane filtration performance and consequently higher energy costs, operation time and maintenance [201]. Also, the efficacy of WWTPs is based on the systematic and accurate detection of MPs to keep track of how effectively the treatment process is in removing MP particles [192]; in this regard, during the screening of articles for our review, we encountered a large number of studies on MP detection methods/technologies.

Table 5. Comparison of MP prevention/removal efficacy rates across intervention objectives (in %) [3,4,63–183].

Intervention Objective	<25%	26–50%	51–75%	76–90%	>90%	Effective: Rate Not Disclosed
Reduction in production (*n* = 6)	-	-	1.7	33.3	1.7	33.3
Removal–Filtration & separation (*n* = 26)	7.7	-	26.9	15.4	26.9	23.1
Removal–Capture & surface attachment (*n* = 21)	4.8	9.5	4.8	28.6	28.6	23.8
Removal–hybrid (*n* = 59)	3.4	-	8.5	16.9	50.8	20.3
Degradation (*n* = 10)	30.0	-	-	20.0	10.0	40.0
Physical removal at point of production (*n* = 2)	-	-	-	-	-	100.0
Total (*n* = 124)	5.6	1.6	11.3	19.4	36.3	24.2

Even though studies on interventions with other objectives, specifically reduction in production, removal–filtration and separation and removal–capture and surface attachment and degradation, comprised a far smaller proportion of the studies reviewed, there were a significant number of reports within these categories where efficacy rates were between 75–90% and even >90% (Table 5). Additionally, 33.3% of the studies that had the objective of reduction in production reported efficacies of between 76–90%. It was also apparent that MPs of higher density can be removed effectively by coagulation, flocculation and then sedimentation (a finding supported by other review articles [22]).

Studies focused on the removal of MPs at the point of production were the exception, with efficacy rates not being reported for both the studies reviewed. On this note, it was worrying that 24.2% of the studies investigated (including all categories in the table below) indicated that the intervention was effective but did not report an efficacy rate; most notable was the 40% of studies on degradation that did not report levels of efficacy. In terms of the lowest levels of efficacy, interventions that focused on degradation (30%) appeared to be by far the least effective.

As mentioned earlier, our review revealed a wide variety of technologies/methods (*n* = 18) that have been applied/investigated to control MP pollution of freshwater bodies. However, the frequency with which these methods/technologies are used independently and/or in combination with each other varies widely (Table 6), necessitating careful interpretation of their efficacy. For example, 100% of the studies involving the independent use of CSA–micromachines, CSA–superhydrophobic, CSA–adsorption, agglomeration, sand filtration column and laundry technologies/methods exhibited efficacies of 100%; however, all these categories were represented by just 1–4 articles. Similarly, a significant proportion of the studies that involved the independent use of sedimentation, agglomeration and thermal degradation reported efficacies of >50% but these categories were represented by 2–3 articles. When we look at the technologies/methods that were used more frequently, either independently and/or in combination, the following stand out in terms of significantly high levels of efficacy: Filtration–membrane was used in a total of 42 studies and 72.4% of these exhibited efficacies >76%; separation–constructed/natural wetlands was a feature of 16 studies, of which 50.1% exhibited efficacies >76%; CSA–coagulation/electrocoagulation, CSA–flocculation & sedimentation and microorganism degradation were all featured in 5–9 studies, with 40–66.6% of these exhibiting efficacies >76%. The pros and cons of membrane filtration technologies have already been discussed above but it is worth noting that an oxidation ditch was used eight times in combination with a filtration membrane, pointing to the efficiency of this combination in the hybrid systems used in wastewater/sludge treatment. Our review also revealed some very novel approaches to microorganism-aided degradation of MPs [142,145], which is encouraging despite the relatively lower efficacies.

Table 6. Comparison of MP prevention/removal efficacy rates (%) across intervention methods/technologies applied independently and/or in combination (*n* = 124) [3,4,63–183].

Method/Technology	<25%	26–50%	51–75%	76–90%	>90%	Effective: Rate Not Disclosed
1 (*n* =29)	-	-	10.3	17.2	51.7	20.7
1,11 (*n* = 2)	-	-	-	-	50.0	50.0
1,13 (*n* = 4)	-	-	-	-	75.0	25.0
1,13,14 (*n* = 1)	-	-	-	-	-	100.0
1,13,14,15 (*n* = 1)	-	-	100.0	-	-	-
1,14 (*n* = 2)	-	-	-	50.0	50.0	-
1,2 (*n* = 2)	-	-	100.0	-	-	-
1,2,4,9,11,14 (*n* = 1)	-	-	-	-	-	100.0
1,3,4,13 (*n* = 1)	-	-	-	-	100.0	-
1,4 (*n* = 3)	-	-	33.3	-	33.3	33.3
1,4,11,13 (*n* = 1)	-	-	-	100	-	-
1,4,13 (*n* = 2)	-	-	-	50	50	-
1,4,13,14 (*n* = 1)	-	-	-	100	-	-
1,9,13 (*n* = 1)	-	-	-	-	100	-
2 (*n* = 16)	12.5	-	18.8	18.8	31.3	18.8
2,3,6 (*n* = 1)	-	-	-	100	0	0
3 (*n* = 9)	22.2	-	11.1	22.2	33.3	11.1
3,4 (*n* = 4)	25	-	-	25	50	-
3,4,5,11 (*n* = 1)	-	-	-	-	-	100
3,5 (*n* = 1)	-	-	-	100	-	-
3,6(*n* = 1)	-	-	-	100	-	-
4 (*n* = 5)	-	-	-	60	40	-
5 (*n* = 3)	-	-	-	-	33.3	66.7
5,12 *n* = 1)	-	-	-	-	100	-
6 (*n* = 2)	-	-	-	50	-	50
6,12 (*n* = 1)	-	-	-	-	100	0
7 (*n* = 1)	-	-	-	-	100	-
8 (*n* = 2)	-	-	-	-	100	-
9 (*n* = 2)	-	100	-	-	-	-
11(*n* = 8)	37.5	-	-	12.5	-	50
12 (*n* = 3)	-	-	-	33.3	-	
13 (*n* = 2)	-	-	50	-	-	50
14 (*n* = 4)	-	-	25	-	-	75
15 (*n* = 2)	-	-	-	-	-	100
16 (*n* = 2)	-	-	-	-	100	-
17 (*n* = 1)	-	-	-	-	-	100
18 (*n* = 1)	-	-	100	-	-	-

1 = Filtration-membrane; 2 = Separation-constructed/natural wetland; 3 = Coagulation/electrocoagulation; 4 = Flocculation & sedimentation; 5 = Adsorption; 6 = Magnetization; 7 = Micromachines; 8 = Superhydrophobic; 9 = Microorganism aggregation; 10 = Photocatalytic degradation; 11 = Microorganism degradation; 12 = Thermal degradation; 13 = Oxidation ditch; 14 = Sedimentation; 15 = Mechanical manual removal; 16 = Agglomeration; 17 = Sand filtration column; 18 = Laundry technology.

The results described above confirm that filtration technologies such as UF, sand filtration and granular filtration are the most popular choices—no doubt related to their effective, economic and energy-efficient application in WWTPs of different sizes [53,192]. In most cases in the articles reviewed here, the WWTP-related studies employed membrane bioreactor technologies, which is not surprising since membrane bioreactors have become the most popular and most effective (usually >99% removal rate) treatment technology among all of the biological treatment methods for MP removal [71]. Similarly, the combination of filtration with other biological treatment methods (e.g., activated sludge process, aerobic digestion, anaerobic digestion, biological degradation and constructed wetlands) was more common than combinations with chemical methods (e.g., oxidation, photo-oxidation, photo-catalytic degradation, coagulation, Fenton, photo-Fenton and acid–alkali treatment). Electrochemical methods such as electrocoagulation [127] and electro-Fenton processes [93] have added a new dimension to chemical methods to improve their efficiency but were less frequently combined with other technologies. It was also interesting to note that pyrolysis and co-pyrolysis technologies which were touted as promising approaches for MP removal over the last decade based on their extra advantages of low-cost fuel production [202,203] were virtually absent from the technology/method combinations identified in this review.

3.6. Overview of Knowledge Gaps & Recommendations Extracted from Review Articles

To supplement the results of the systematic review, the recommendations and knowledge gaps were extracted from 129 review articles and subjected to thematic analysis which showed that these could be separated into the following categories: source control, wastewater and sludge treatments, bioremediation, stormwater treatment, behavior, education and awareness, and policy and regulatory frameworks (Table 7). However, there was sufficient overlap across categories for us to generate a set of overarching recommendations and knowledge gaps (five each, Table 7) based on the frequency of occurrence across the articles reviewed.

Table 7. Top five recommendations and knowledge gaps on management interventions for controlling MP pollution in freshwater bodies, ranked in descending frequency (F) of occurrence across 129 review articles published between 2012 and 2023 [1,3,11,14–16,18–20,25–27,36,38,41,43,45,47–56,189,192–200,204–296].

Rank	Knowledge Gaps	F (n = 129)	Citations
1	Data on sources, diversity, transport and fates of MPs, particularly within developing countries.	30	[3,20,27,45,49,56,189,198,205,206,209, 215,218,219,223,226,234,235,238–240, 244,248,277,278,280,282,286,290,292]
2	Exposure pathways and biological/toxicological effects of MPs for humans and environments.	24	[14,15,20,26,49,51,213,215,218,220,222, 224,229,231,237,242,278,284,285,289, 290,292–294]
3	Standardized MP analytical methods: Quantification and characterization.	24	[15,16,18,37,41,189,193,199,211,214, 219,220,222,227,233,246,254,255,264, 274,280,283,289,293]
4	MP weathering, degradation and removal (e.g., via biodegradation).	12	[1,49,50,53,195,196,246,247,262,266, 272,274]
5	Abilities of MP to interact with and eventually release associated pollutants.	7	[3,197,217,221,225,226,252]
	Recommendations		
1	Develop standardized detection and analytical methods to study and monitor MPs.	37	[14,26,27,49,50,56,189,192,197,199, 204–206,208,209,215,225–227,234,235,239,240,242–244,251,252, 255,256,268,282,284,288,294–296]
2	Conduct more research on sources, transport pathways, fates, trophic interactions, toxicity, removal (e.g., biodegradation, electrocoagulation) and ecological impacts of MPs.	28	[16,25,36,47,49,52,53,189,205–207,209,212,216–223,226,231,238,239,243,258,295]
3	Implement comprehensive policies/legislation/regulations at local, national and international levels to prevent or remove MPs, and foster research collaboration and cooperation.	24	[14–16,18,41,193,216,219,224,227,229, 230,232–234,242,277–279,290–294]

Table 7. *Cont.*

Rank	Knowledge Gaps	F (n = 129)	Citations
4	Conduct extensive public education, training and awareness programs on MP pollution mitigation.	16	[18,51,204,223,229,231,233,242,244, 245,267,279,282,283,285,292]
5	Optimize secondary and tertiary MP treatments (e.g., with membrane bioreactors) at wastewater/sludge treatment plants.	12	[11,51,53,195,200,237,248,251,252,255, 257,258]

In terms of knowledge gaps, it appears that the application and efficacy of interventions could benefit from increased availability of data on sources, diversity, transport and fates of MPs, particularly within developing countries. Fit-for-purpose interventions could also be designed if exposure pathways and biological/toxicological effects of MPs for humans and environments are better characterized. In general, interventions need to be informed by/based on more robust and standardized MP analytical methods (for quantification and characterization). Management interventions appear to be hampered by insufficient knowledge of MP weathering, degradation, removal (e.g., via biodegradation) and the abilities of MPs to act as vectors of other pollutants.

Based on the 129 review articles included in the analysis, the major recommendations largely speak to the knowledge gaps identified in that they call for the development of standardized detection and analytical methods to study and monitor MPs and generate more data on sources, transport pathways, fate, trophic interactions, toxicity, removal (e.g., biodegradation, electrocoagulation) and ecological impacts of MPs. Additionally, the risks posed by WWTPs need to be addressed by optimizing or improving secondary and trtiary (e.g., with membrane bioreactors) MP treatments at wastewater/sludge treatment plants. Importantly, the recommendations do speak to the need to bring about behavioral change for reduced plastic use, improved plastic waste management and mitigation of MP pollution through the implementation of comprehensive policies/legislation/regulations, research collaboration and cooperation, and extensive public education, training and awareness raising (Table 7).

4. Concluding Remarks & Recommendations

To protect freshwater bodies from MP pollution, we must seek to develop and implement fit-for-purpose interventions. This can best be achieved by an evidence-based approach toward intervention design, selection and implementation. Irrespective of the intervention(s) selected, they must strike the balance between resource availability and environmental sensitivity. On this note, lab-based studies aimed at developing management interventions need to be more environmentally relevant and focus on treatment technologies that can be taken to scale in both the developed and developing world. Highly effective technologies used for the removal of MPs at wastewater/sludge treatment plants such as UF are a case in point; these must be made more accessible and affordable to developing countries [10].

To better protect freshwater bodies from MP pollution, we must increase awareness around the fact that ecosystems and human systems are connected within a catchment (though not always at the primary level), which implies that what happens in one compartment in terms of MP pollution can have knock-on effects on others. These knock-on effects can be accommodated when management interventions for MP pollution are planned and implemented at the catchment scale using participatory approaches such as catchment management forums.

Reducing the discharge of MPs from WWTPs into freshwater systems represents an immediate priority. Though wastewater, and, by implication, the MPs that cannot be removed, may be transferred to marine environments by deep sea discharge, it is now well-established in the literature that WWTPs represent the dominant discharge pathway of MPs into freshwater environments [56,151,193,239]. In fact, Wang et al. [239] reported that 85% of the studies they reviewed on discharge pathways into freshwater ecosystems involved discharge from WWTPs.

New interventions are constantly being developed and refined under laboratory conditions but their scalability and suitability across different settings are uncertain. For improved efficacy, the application of these interventions must also be strategically tailored to local hydrogeological and climatic conditions. Downstream interventions are not sustainable without effective upstream interventions. Though in situ methods are technically achievable, they may not be feasible in resource-limited settings. On this note, although it did not emerge as part of the findings of this study, cost-benefit comparisons of the different types of interventions reviewed here represent a major knowledge gap that should be addressed in future studies. These types of analyses are a major consideration, and, in resource-limited settings, perhaps the basis, for management decisions related to pollution control.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w16010176/s1, Supplementary File S1: Meta-data on interventions applied to freshwater bodies extracted from 124 articles included in the systematic review.

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Appendix A Search Strategies

Google Scholar
Limits: None
Microplastic* AND (freshwater OR river* OR wetland* OR estuar* OR catchment* OR drainage OR basin* OR reservoir* OR stream*) AND (intervention* OR manage* OR mitigation OR *remediation OR reduction OR treatment OR removal OR regulation* OR law* OR polic*)

Web of Science Core Collection (Clarivate Analytics)
Limits: 2012–2023
(microplastic* OR microbead*) AND (freshwater OR river* OR wetland* OR estuar* OR catchment* OR drainage OR basin* OR reservoir* OR stream* OR lake* OR pond* OR “inland water bod*” OR dam OR bay* OR lagoon*) AND (intervention* OR manage* OR mitigation OR *remediation OR reduction* OR treat* OR removal OR regulation* OR law* OR policy OR policies OR “land use” OR prevent*)

Scopus
Limits: 2012–2023
(TITLE-ABS-KEY ((microplastic* OR microbead*)) AND TITLE-ABS-KEY ((freshwater OR river* OR wetland* OR estuar* OR catchment* OR drainage OR basin* OR reservoir* OR stream* OR lake* OR pond* OR “inland water bod*” OR dam OR bay* OR lagoon*)) AND TITLE-ABS-KEY ((intervention* OR manage* OR mitigation OR *remediation OR reduction* OR treat* OR removal OR regulation* OR law* OR policy OR policies OR “land use” OR prevent*))) AND PUBYEAR > 2011 AND PUBYEAR < 2024

Dissertations and Theses Global (ProQuest) and Environmental Science (ProQuest)
Limits: 2012–2023

noft ((microplastic* OR microbead*)) AND noft ((freshwater OR river* OR wetland* OR estuar* OR catchment* OR drainage OR basin* OR reservoir* OR stream* OR lake* OR pond* OR "inland water bod*" OR dam OR bay* OR lagoon*)) AND noft ((intervention* OR manage* OR mitigation OR remediation OR reduction* OR treat* OR removal OR regulation* OR law* OR policy OR policies OR "land use" OR prevent*))

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