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Review

The Microplastics Cycle: An In-Depth Look at a Complex Topic

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Abstract: Microplastics, or plastic particles smaller than 5 mm in size, have become ubiquitous in the environment, found in places ranging from remote deep ocean trenches to minute dust particulates. From the breakdown of larger plastic products and the release of synthetic clothing fibers, these particles enter the ecosystem and cycle through the various components including aquatic, terrestrial, and human systems. Due to their durability, capacity to adhere to other toxic compounds, and potential effects on humans and ecosystems, microplastics have recently risen to the forefront of environmental and health concerns. To address these critical issues, there has been a surge in research related to the microplastics cycle, examining where they originate, how and where they travel, and their environmental and human health impacts. Research on the microplastic cycle is often broken down into its various individual components such as sources, fate, and effect, and further scattered through the literature are focuses on specific environments such as land, oceans, and freshwater, as well as on human health. Here, we review the current state of the literature on the microplastic cycle across its various environmental reservoirs. In-depth examination of the microplastics cycle is necessary for understanding the scope of the problem and developing viable solutions or mitigation strategies, such as reducing plastic production and promoting recycling. Understanding the complex microplastics cycle is an urgent issue that necessitates multidisciplinary research and action.

Keywords: microplastics; plastic pollution; micro-particles; microbeads; plastic waste; persistence; contaminants; environmental impact; human health; food chain; ecosystems

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1. Introduction

The discovery of enormous plastic waste patches in the Pacific Ocean, comprising at least 79,000 tons of plastic and spanning an area of 1.6 million km^2, sparked an immense interest in microplastics [1]. Microplastics are minute fragments of plastic garbage that originate from the dumping and breakdown of consumer and industrial items. Plastics degrade to become microplastics and nanoplastics in many forms, including fibers, films, foams, and fragments, depending on soil moisture, temperature, pH, and the plastic's size, shape, molecular weight, and kind. These micro- and nanoplastics can serve as vectors for toxic metals, pathogens, organic contaminants, and antibiotic resistant genes [2–5]. Microplastics are derived from several sources, including bigger plastic trash that degrades into ever-smaller fragments. In addition, microbeads, a form of microplastic, are extremely small bits of synthetic polyethylene plastic that are added as exfoliants to some soaps and personal care products. The majority of plastic waste ends up in aquatic bodies [6–8], in part because microscopic particles readily slip past most water filtering systems and wind up in rivers, oceans, and lakes, presenting a hazard to aquatic ecosystems. When researchers realized the sheer quantity and ubiquitous nature of plastics in the environment, and their potential to become microplastics, the necessity for and attention to addressing microplastics skyrocketed. Thus, microplastics are now a significant focus of research. Despite a recent surge in research on microplastics, it remains a relatively new area of study, with only a rudimentary understanding on their fate and effect in the environment.

Additionally, there is a lack of consensus, yet an identified need, regarding standardized methods for monitoring, collecting, and quantifying microplastics from the environment (e.g., soil, sediment, water, biota). Eventually, standardized field and laboratory techniques will allow for global comparisons of the amount of microplastics in the environment, which is the first step in determining the eventual distribution, and the consequences of this debris. Plastic litter, like climate change and persistent organic pollutants, is yet another troubling example of human impacts on the global biosphere. According to Villarrubia-Gómez et al. [9], marine plastic pollution is irreversible and pervasive on a global scale. Therefore, it meets two of the three requirements for a global threshold hazard, except that the disruptive effect is not identified until it is a global problem [10].

In the realm of microplastics research, the majority of published studies, comprising 61% of the corpus, have been dedicated to investigations within the marine environment. Conversely, only 39% of these studies have focused on the freshwater environment. Utilizing the comprehensive Web of Science Core Collection database, our search strategy entailed querying for the keyword "microplastics" within the title, abstract, author-defined keywords, and keywords. Our search spanned up to the year 2022, encompassing a substantial compilation of 11,947 research papers. As illustrated in Figure 1, the trajectory of publications on microplastics exhibits a remarkable and consistent upward trend over the years, demonstrating a substantial surge from 1986 to 2022. While numerous papers have been published on the examination and assessment of microplastic levels in water sources, these studies often indicate that the detected quantities may not have a significant impact on the metabolism of biological organisms. What is even more intriguing is the question of whether this relatively low quantity of microplastics can indeed make a substantial difference over the long term. Many of the research findings related to the impact of microplastic contamination on aquatic organisms tend to focus on short-term effects.

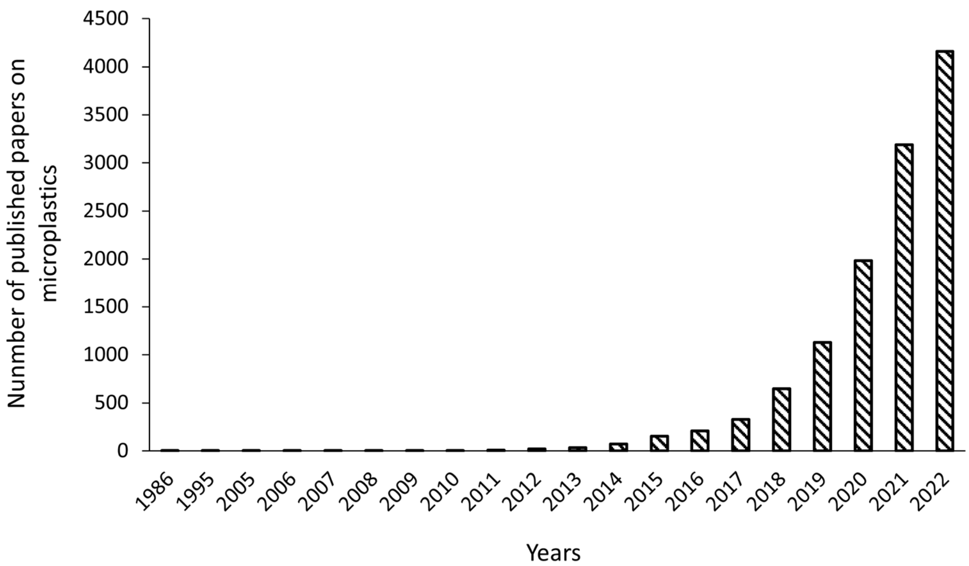

Figure 1. Temporal evolution of microplastics research publications (1986–2022), illustrating a sustained increase in research publications dedicated to microplastics over this period, highlighting a substantial surge in scientific interest.

2. The Microplastics Cycle

To comprehend the whole life cycle of microplastics, it is essential to understand their entry points into the environment, the course they follow, and the transformations they undergo. The microplastics cycle was first defined as a novel concept and model for comprehending the consequences of plastic contamination on ecosystems as a whole [11]. Recognizing that plastic pollution is now a part of the biogeochemical cycle is important in developing risk assessment and mitigation measures, as well as related standardizing research methods, to address the global scale of this environmental problem [11]. Recent studies have highlighted the approach to understand the life cycle of plastics [12–14]. This approach involves the comprehensive monitoring of plastics throughout their entire lifecycle, from creation to disposal, recycling, and their ultimate interaction with humans through polluted air, water, and seafood. This holistic strategy encompasses the entire journey of plastics, which also includes the prediction and modeling of potential threat of microplastics to humans [15], and their interaction with emerging contaminants, including pharmaceuticals [16], etc. Despite the presence of alternative models that focus on specific microplastic timelines, this complete and integrated approach has yet to receive widespread acceptance [17].

In some recent investigations, researchers have concentrated on examining the complete lifecycle of plastics [18–20]. This approach, often described as the 'cradle to the grave' perspective, involves tracing plastic materials from their initial use, through their disposal into the environment (such as landfills, recycling, and processing), and continues to follow their fate and transport through the various ecosystem components, up to and including human exposure via air, drinking water, and food. However, it is crucial to note that even after discarding plastics, they remain in transport. They continue to traverse various ecosystem components, ultimately leading to human exposure.

2.1. Microplastics in Land

Plastics have become prevalent, in part due to their portability, durability, light weight, and low cost, and the diversity of uses within residential, medical, and industrial settings [21]. Despite the fact that the design and manufacturing of microplastics and majority of its uses occurs on land, the research on the impact of plastic waste and microplastics on soil and landfills is considerably less extensive than that on water sources. (In 2022, 499 papers published on microplastics related to soil, sludge, compost, and land fill, among the total 2402 microplastic research articles. Using the Web of Science database, an extensive search was conducted employing the keywords 'microplastics and landfills', 'microplastics and sludge', and 'microplastics and compost' in the title, abstract, author keywords, and keywords plus fields). Plastics and microplastics captured in the soil may undergo multiple transformations, including degradation, before reaching water sources [22,23]; however, these transformations vary depending on a variety of factors such as temperature, rainfall, soil type, type of microbes in soil, chemical composition of soil, etc. [24,25]. In light of this, it is crucial to comprehend the plastics and microplastics present in landfills and soil, as well as their repercussions on soil and ecosystems.

The presence of microplastic (MP) particles has been detected in various commonly consumed items derived or processed on land, including sugar (0.44 particles/g), honey (0.10 particles/g), salt (0.11 particles/g), alcohol (32.27 particles/L), bottled water (94.37 particles/L), tap water (4.23 particles/L), and ambient air (9.80 particles/m^3) [26,27]. According to Banerjee and Shelver [28], there is an estimated annual deposition of a substantial amount of microplastics in North American agricultural soils, ranging from 44,000 to 300,000 tons. This expansion of focus to include agricultural contexts highlights the presence and potential impact of microplastics in these specific settings. European farmlands have been associated with a comparable estimate ranging from 63,000 to 430,000 tons, as reported by Nizzetto, Futter, et al. in 2016 [29]. These studies highlight just one route of exposure people have to microplastics as they move through the environment in the land, water, and air, and enter our food chain.

Furthermore, the potential for plants to concentrate plastic particles and then be ingested by animals adds another dimension to this intricate matter. The utilization of plastic film is a common technique in agriculture for the purpose of preserving fodder, which plays a crucial role in the diets of dairy and beef cattle [30]. Furthermore, it is common practice to encase hay bales with mesh or twine in order to maintain their shape. This practice involves the use of plastics, which are incorporated into feed preservation techniques for animals that are raised for food production. This method increases the likelihood of migration of microplastics or additives from feed packaging into animal feed.

It is worth mentioning that there have been documented cases in scientific research, where bisphenol products (BPs) have been detected in animal feed. These BPs are believed to originate from packing materials such as polypropylene (PP) and polyethylene (PE) [31]. The infiltration of polycyclic aromatic hydrocarbons (PAHs) into the solid feed of cows serves as a significant indication of the likelihood for these pollutants to permeate the milk generated by these livestock, as emphasized by Russo et al. [32].

The number of publications published by various nations on the same topics as those mentioned above is shown on the global map (Figure 2). Using the Web of Science Core Collection database, we combed through all 1405 papers published up to 2022. The search pattern included all conceivable permutations of the word associated with each of four land-related terms. The studies were combed for location and publication date information. China is, according to statistics, the leader in microplastics research connected to landfills, followed by the United States of America. It is noteworthy to observe that the number of published research papers on microplastics in soil has risen nearly 20-fold during the last five years.

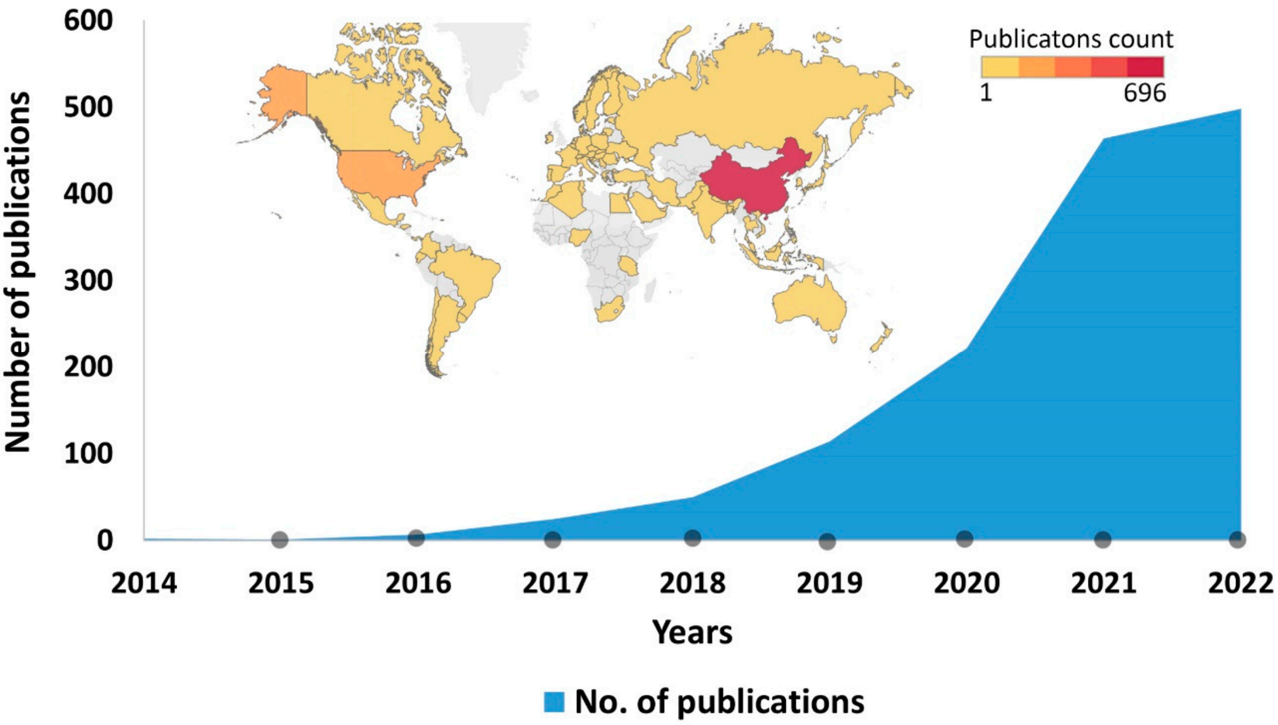

Figure 2. The graph shows the volume of research publications on microplastics in soil, sludge, compost, and landfills published throughout time. The number of publications published by various nations on the same topics as those mentioned above is shown on the global map.

The problem associated with plastics intensifies as land-based plastics undergo aging. Physical, chemical, and biological reactions generate microplastics from waste plastics. According to recent study by Yu, Wu, et al. [33], carbonyl groups are produced in preference to hydroxyl groups, resulting in an increase in the hydrophilicity of waste plastics as landfills age. Therefore, microplastics may attract microorganisms from landfills and sewage systems. Also, metals (e.g., Al, Fe, Ca, Ti, Ni) may be released from plastic additives in discarded plastics [33]. Microplastics are capable of absorbing hazardous compounds from the environment [34–36]; hence, microplastics may function as a vector for these toxic chemicals, and microplastics can introduce these toxic chemicals into the food chain [37]. In Kilponen's [38] study, an investigation was carried out to assess the presence of microplastics in a stream located in close proximity to a landfill that had been inactive for over three decades. The study exclusively focused on the detection of microplastics larger than 1 mm. The results indicated the presence of microplastics in the stream, confirming that even though the landfill had been closed for three decades, it continued to release microplastics into the environment. It is plausible that aged plastics within the landfill were undergoing degradation, transforming into microplastics that were subsequently leached into the river water. Given that the analysis was limited to particles larger than 1 mm, it is reasonable to assume that there may be an even greater quantity of smaller-sized microplastics present than what was initially determined. As a result, it is evident that the long-term impact of plastics and microplastics on the environment remains significant, even when strict monitoring and control measures are promptly implemented.

Primarily, the introduction of plastics into the soil occurs through municipal landfills designated for solid waste disposal. These landfills serve as repositories for various plastic items, which can inadvertently release microplastics over time due to degradation and environmental weathering. To address this issue, landfill leachate treatment systems have been established. These systems play a crucial role in recovering microplastics and, potentially, repurposing the polymers into valuable products. However, it is essential to recognize that collecting microplastics from these treatment facilities is a formidable task due to the small size and diverse nature of microplastics. Additionally, the transformations that microplastics undergo at different stages within these systems are intricate. From their initial introduction into landfills to their potential release into the environment through leachate, microplastics can experience a series of physical, chemical, and biological changes. These transformations are influenced by factors such as environmental conditions, polymer types, and the duration of exposure within the landfill. Given the complexity of this process and the challenges associated with collecting microplastics from treatment plants, further exploration and comprehensive research are necessary to gain a more profound understanding of the fate and behavior of microplastics in landfill environments and beyond [39]. Microplastics, tiny plastic particles under 5 mm in size, present complex challenges in landfill environments [40]. Wind and mechanical activity in landfills disperse microplastics into the air, potentially inhaled by nearby residents, posing health risks [41]. Landfills attract wildlife seeking food, with animals ingesting plastic waste, introducing microplastics into their systems. This interaction raises ecological concerns and potential food chain contamination. Leachate, liquid draining from landfills, carries microplastics into nearby water bodies, contributing to aquatic contamination and endangering aquatic life [42]. As plastics degrade in landfills, hazardous chemicals can seep into soil and groundwater, increasing environmental contamination [43,44]. Additionally, leachate from microplastics can enhance antibiotic resistance gene propagation and pathogen enrichment on polystyrene microplastics [45].

When plastic degrades aerobically in landfills, microbes can colonize them, releasing enzymes by the colonized bacteria that further break down the plastics into smaller low molecular weight particles [46]. Microbes break down microplastics even more in anaerobic conditions by taking electrons from sulfate, nitrate, iron, carbon dioxide, and manganese. This makes methane and hydrogen sulfide, in addition to water, carbon dioxide, and microbial mass, which comes from aerobic digestion (taking electrons from oxygen) [47,48].

2.2. Microplastics in Freshwater

Regardless of where they are used, plastic products used both on land and water can introduce microplastics into freshwater bodies [49,50]. Even the primary microplastics designed for use in terrestrial systems, including medicine, industry, home, recreation, etc., have the potential to progressively break down into microplastics and reach freshwater sources. Plastics undergo degradation in the soil and end up in rivers and lakes as microplastics [51]. Or they enter aquatic bodies as macroplastics, and are later transformed into microplastics [52]. After use, many plastics designed for use in the water are typically discarded into water sources. As stated above, most of the microplastics originated from production, and use on land can ultimately transverse wastewater treatment plants (WWTPs) [53,54]. Microplastics can invade freshwater bodies through treated waters, since there is currently no effective method or procedure for eliminating microplastics [55]. Current methods used to intercept microplastics within WWTPs typically involve several key strategies, including physical separation [56] and filtration [57]. Although these methods hold promise for mitigating microplastic contamination, there are obstacles to their practical application. To address these obstacles and improve the viability of microplastic interception, researchers are developing cost-effective and flexible advanced treatment processes, such as magnetic seed filtration [58], magnetic micro-submarines [58], and photocatalytic micromotors [59]. Membrane bioreactors coupled with activated carbon filters [60] hold promise for enhancing the efficacy of microplastic removal. Following processing from WWTPs, solid wastes, often contaminated with microplastics, separated by the WWTP (i.e., sludge), are sometimes utilized for agricultural fertilization [61,62]. Precipitation (i.e., rain, snow) and wind, however, can transport the microplastics to freshwater bodies [62]. Microplastics have been identified in plastic landfill leachate [41].

With the help of the Web of Science Core Collection database, we went through all 2249 publications, using key words (freshwater, river, and lake) that had been published up to that year (2022) to identify research on microplastic in surface water (i.e., lakes, rivers, oceans). The location and publication years were obtained from the research. The data suggest that China is the global leader in research on microplastics on freshwater ecosystems, followed by the United States (Figure 3). Over the last five years, there has been a near ninefold increase in the number of published research publications on microplastics in water.

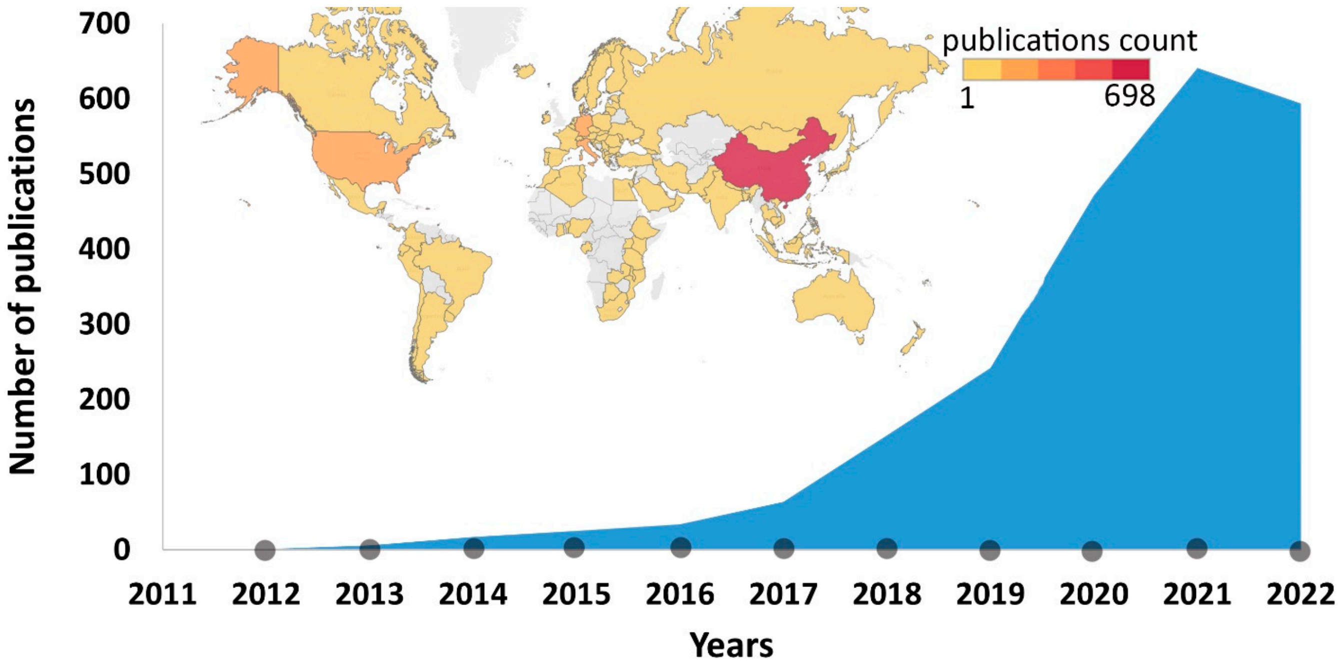

Figure 3. The graph shows the volume of research publications on microplastics related to freshwater, rivers, lakes, ponds, etc., published from 2011 to 2022. The number of publications published by various nations on the same topics as those mentioned above is shown on the global map.

Microplastics can constitute a hazard to freshwater ecosystems, inflicting comparable physical and biophysiological harm, as in marine habitats [63]. Other than field experiments, the evidence on the relative effects of microplastics is often inconsistent with the concentrations of microplastics in water bodies [64]. Studies often employ a greater concentration of microplastics than is typically present in aquatic environments and focus on the impact on live organisms [64–66]. However, research indicates that the present amounts of microplastics have the potential to inflict significant harm to species over time. Another major concern associated with microplastics is that they concentrate other pollutants in water on their surface [67–69]. Microplastics supporting other contaminants may readily harm organisms and serve as a vector to move these other contaminants into the food web [70–72].

Transport of microplastics and other associated contaminants may be facilitated though biofilm growth on microplastics, and the subsequently mistaken for food. Several articles have identified that microplastics can serve as a substrate for biofilm formation [73]. When microplastics age, their surfaces roughen, creating increased crevices that can create a favorable habitat for biofilm development and other pollutants and pathogens to adhere [74,75]. Biofilms formed on microplastics can have a significant impact in the adhesion and concentration of pollutants [76]. Polyvinyl chloride plastics (PVC) with biofilms absorb approximately 50 percent more of the antibiotic norfloxacin than PVC without biofilms. Similarly, high density polyethylene (HDPE) and polyamide (PA) microplastics with biofilm absorbed 46 percent and 24 percent more norfloxacin, respectively, than HDPE and PE microplastics without biofilm [77]. Metal adsorption on microplastics depends heavily on intraparticle diffusion. In addition, a rise in temperature and a decrease in salinity boost the affinity of metals and microplastics [78]. Different kinds of microplastics and metals exhibit varying degrees of adherence. PE microplastics have a stronger affinity for metals than PS microplastics, whereas PP microplastics have an even greater attraction [79]. Furthermore, the adsorption of microplastics on metals varies, depending on the microplastics' particle size [79]. The surface carbonyl group of PS microplastics interacts with the biogeochemistry of silver to produce silver nanoparticles [80]. Additionally, viruses may also adhere to the surface of microplastics. However, the adsorption affinity of microplastics varies on their size and surface functional group [81].

The complexities of the degradation of plastics into microplastics, driven by microbes and biofilms, raises questions about the impact of these plastics on the microbes themselves and their integral role in the ecosystem. It also raises questions about the impact of these plastics, and their integral role in the ecosystem on the very microbes themselves and the wider ecological balance. In addition to interactions of microplastics and biofilms, several papers have identified interactions between microalgae and microplastics. Microalgae are at the base of the food chain, and subtle impacts to them may affect the whole food chain. Microplastics can inhibit the development of the microalgae *Chlorella pyrenoidosa*, modify oxidative stress, and compromise cell membrane integrity [82]. Microplastics can also inhibit the photosynthetic activity of *Chlorella vulgaris*. Microplastics also dramatically decreased peroxidase and glutathione reductase levels in *C. vulgaris*, while increasing superoxide dismutase levels [83]. Additionally, when organic pollutants such as amoxicillin, ibuprofen, sertraline, and simazine are adsorbed onto microplastics, the combined disruption of this combination has a substantial impact on the photosynthetic activity of *Scenedesmus armatus* [84]. Further concern is raised when examining the interactions specifically with cyanobacteria and microplastics. Gopalakrishnan and Kashian [85] found that microplastics exerted a dual effect on *Anabaena variabilis* growth, stimulating it at lower concentrations but inhibiting it at higher levels (>0.3 mg/mL) across a temperature range of 2.5–32.5 °C. As the concentration of microplastics increased, shading by the microplastics may have induced stress, which corresponded with an observed increase in extracellular polymeric substance (EPS) production by *A. variabilis*, which enhanced microplastic deposition. This complex interplay suggests that microplastics may play a role in cyanobacterial blooms, potentially impacting their deposition dynamics. In eutrophic reservoirs, microplastics can serve as vectors for potentially harmful cyanobacterial toxins, specifically microcystin-LR and microcystin-LF [86]. The interaction between cyanobacteria and calcium plays a crucial role in facilitating the sedimentation of microplastics within these ecosystems [87]. Moreover, naturally weathered microplastics have been observed to accumulate cyanobacterial toxins, thereby posing environmental concerns in eutrophic lakes [88]. Furthermore, microalgae can secrete EPS to avoid the combined toxic effects of cadmium [89]. Currently, researchers are concentrating on the characteristics of charged microplastics and nanoplastics. Positively charged nanoplastics with an amide group on the surface hindered the development of *M. aeruginosa* more than negatively charged nanoplastics with carboxyl groups on their surfaces [90]. Overall, there is a clear dose–response relationship between microplastics and their effect on the survival of microalgae.

2.3. Microplastics in Oceans

Much of the research on plastic pollution in marine systems has focused on ocean surface waters [91], but recent studies have expanded to examine microplastics at the ocean's depths, so existing knowledge disproportionally favors surface water. Approximately 18% of the plastic identified in marine habitats comes from fisheries and sectors associated with fishing [92]. The broad use of plastic items as direct replacements for metal and mechanical components in the fishing and allied industries is the primary factor for their prevalence in marine systems [93]. Additionally, aquaculture increases or introduces many plastics into the marine ecosystem [94]. Comparing wild and farm-raised or cultured mussels, for instance, the amount of microplastic debris in farmed mussels is substantially greater than that in mussels captured in the wild, away from the farming facilities. This rise in plastic debris in cultivated mussels is mostly due to the use of PP plastic lines in mussel farming [95]. Additionally, beach plastic litter is a significant contributor to plastics and microplastics entering marine habitats. Approximately 50 percent of beach litter is composed of plastic [96]. These plastics may either immediately enter the sea or ocean as plastics, or degrade on the beach and enter the marine ecosystem as microplastics. Vectors that contribute to the movement of microplastics into the marine environment include wind, rain, streams, and rivers, and also illegal waste dumping.

Research on microplastics in marine settings has been widely published. We quantified this using the Web of Science Core Collection database to search through all 3616 publications that had been published up to 2022. The search strategy encompassed all permutations of the term 'microplastics' in conjunction with each of the three related phrases: 'ocean', 'marine', and 'sea' (Figure 4). Locations and published years were culled from the research. The data suggests that China is the global leader in publishing on the effects of microplastics on marine ecosystems, followed by the United States (Figure 3). Over the past five years, academic articles on microplastics in marine environments have surged to approximately four times their previous numbers.

Microplastics' age in the marine environment has a substantial bearing on their effects and problems [97]. As microplastics spend more time in the environment, the possibility that microorganisms, invertebrates, and vertebrates they interact with, grows [98,99]. In addition, the longer the time period, the higher the likelihood of organic or microbiological deposition on microplates due to surface roughness [100] and/or ionic group changes [97]. Biofilms made up of organic components, microorganisms, and algae are rich in microplastics that have disintegrated over time. When this occurs, the substance may readily enter the food chain, since the microorganisms and algae in the biofilm serve as food for certain groups of species [101]. Copepods typically consume microplastics that have been in the environment longer, because these older plastics develop a biofilm of natural microbes, which contains similar prey and emits chemicals that make the particles more enticing as food [101]. Additionally, recent research has delved into the potential of plastics to serve as a carbon source for microorganisms, which can further boost biofilm development [102]. Consequently, microplastics create localized micro-hotspots characterized by heightened microbial activity, thereby instigating alterations in carbon cycling dynamics. Therefore, the longer that microplastics remain in the environment, the greater the likelihood that they will enter the food chain.

Vertical transport, which refers to the movement of microplastics from the surface (floating) to the bottom of the sea or ocean, is a growing area of study in the field of microplastics. Research has identified several variables that contribute to this phenomenon. Generally, microplastics sink when their specific gravity exceeds that of seawater, which is 1.03 g/cm^3 [103]. Despite the fact that microplastics have a low specific gravity in general, some additives added to plastics to make them acceptable for certain applications have rendered their buoyancy unstable and caused them to sink as a result of an increase in specific gravity [104]. Additionally, microplastics that enter the sea or ocean with a lower specific gravity than water begin to sink with age, owing to many causes such as fouling by biofilm, microorganisms, organic pollutants, etc. [105]. Although specific gravity is a crucial factor in the fluctuating buoyancy of microplastics, other conditions may cause them to sink. As microplastics descend, they can adhere to aquatic vegetation like eelgrass, a process facilitated by the formation of biofilm. Two predominant epiphytic bacteria were identified as the key microorganisms within the biofilm, facilitating the adherence of microplastics to the grass (Vibrio and Exiguobacterium) [106]. The disintegration rate, nutritional alterations, and potential interactions of microplastics with specific species as they enter the food chain vary significantly, depending on factors such as environmental conditions, particle size, and chemical composition. As a consequence of photodegradation by sunlight, microplastics that are still in suspension break down at a considerably quicker pace than those that have settled to the bottom [107].

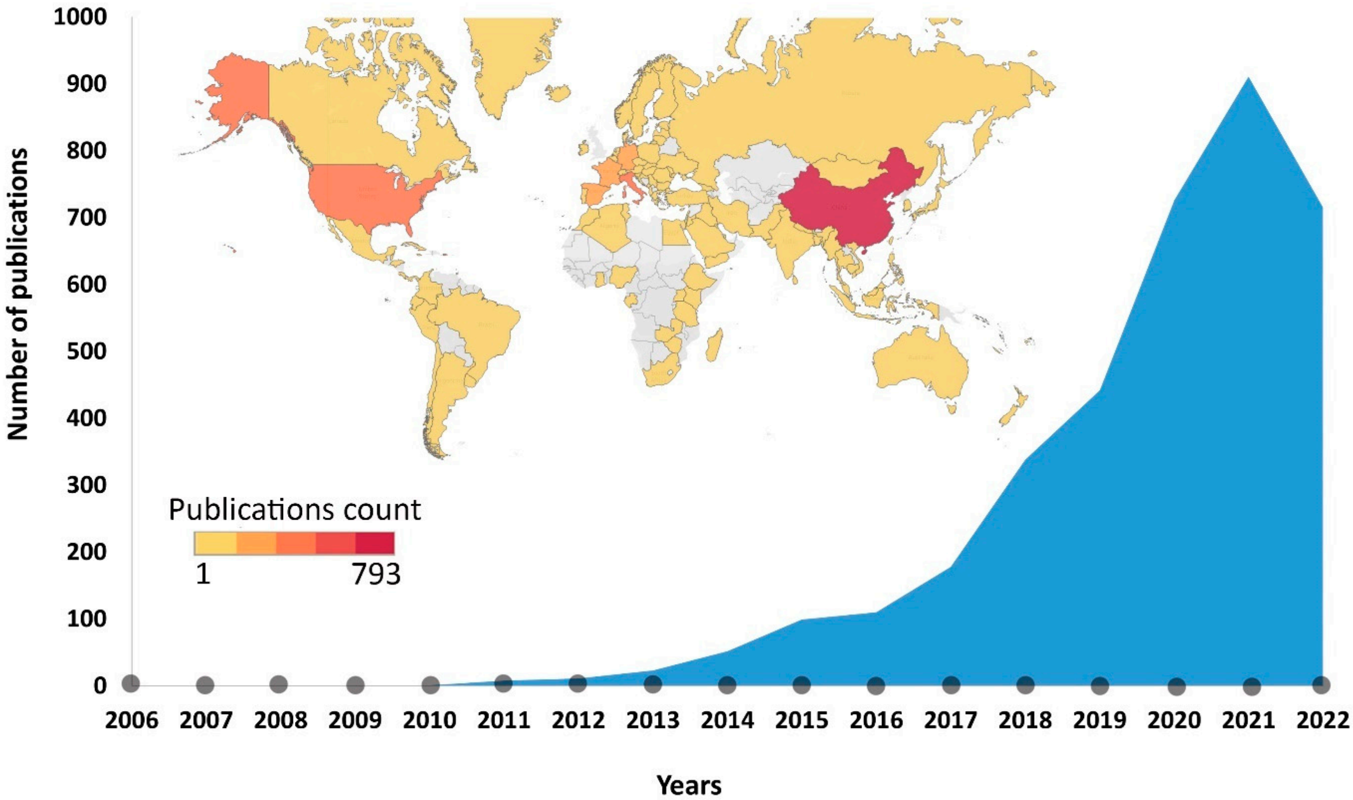

Figure 4. The graph shows the volume of research publications on microplastics related to oceans, seas, marine environments, etc., published over time. The number of publications published by various nations on the same topics as those mentioned above is shown on the global map.

3. Conclusions

Comprehending the microplastic cycle necessitates interdisciplinary research, bringing together the realms of biophysics, ecology, and chemistry. These disciplines collectively unravel the intricate web of physical processes governing particle behavior, chemical interactions, and the dynamic interplay of biological systems. By weaving these threads together, we gain a holistic understanding of how microplastics' fate and impacts are shaped. From the physical and chemical breakdown of larger plastic products to the shedding of synthetic clothing fibers, microplastics are pervasive, and their persistence, ability to absorb and transport harmful contaminants, and potential effects on human health and the environment are a growing concern. Microplastics' origins, pathways, and environmental effects are the subject of extensive research. Research findings highlight the severity of the problem due to microplastics, and the urgent need for measures to restrict the production and distribution of microplastics, increase their recovery and recycling, and encourage the development of viable substitutes. Due to the inherent complexity of this issue, it is essential to have clear guidelines and policies in place at every stage of the microplastics life cycle, to help mitigate and minimize inputs and impacts in the environment.

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