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Review

Microplastic Pollution: Threats and Impacts on Global Marine Ecosystems

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Abstract: This study investigates the scope of global marine microplastic pollution and its implications on marine ecosystems and human health. We first delve into how plastic enters the ocean, with an emphasis on the accumulation of plastic along coastlines, particularly the formation and impact of the Great Pacific Garbage Patch (GPGP). Through a concentration map of marine microplastics across five continents, the global distribution of microplastic pollution is revealed. Furthermore, the effects of microplastics on marine wildlife are explored, as well as their potential entry into the human food chain, posing potential public health risks. The results of our research underscore the serious threats of microplastic pollution to global marine ecosystems and human health, emphasizing the need for more scientific research and policy measures to address this challenge.

Keywords: ecosystem impacts; Great Pacific Garbage Patch; marine microplastic pollution; plastic accumulation; wildlife impacts

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1. Introduction

Plastic pollution is one of the most pervasive and persistent threats to the global environment, especially to the marine ecosystems that cover more than 70% of the Earth's surface and support a rich biodiversity of life [1–3]. The production and consumption of plastics are up to 300 million tons per year [4]. Due to the low recovery rates and high cost of plastic recycles [5], at least 10% of plastic waste enters the marine environment, which causes serious plastics pollution around the world, especially microplastics [6,7]. Also, the lifecycle of plastics spans from creation, production and post-consumption disposal, through stages like collection, sorting, and recycling, with some plastic waste entering the ocean due to inadequate management, as well as carried by wind and water currents [8].

Among the various forms of plastic pollution, microplastics (plastic particles < 5 mm) have received increasing attention in recent years due to their widespread occurrence, high durability, and potential impacts on marine organisms and human health [9–11]. Microplastics, characterized by a diversity in size, shape, density, and polymer type, are emerging pollutants in the environment (Figure 1). The complexity of these micro and nanoplastics not only poses challenges for chemical identification and quantification but also necessitates the use of advanced analytical methods. Therefore, understanding the properties of different plastics is essential for comprehending the behaviors of microplastics [12–14].

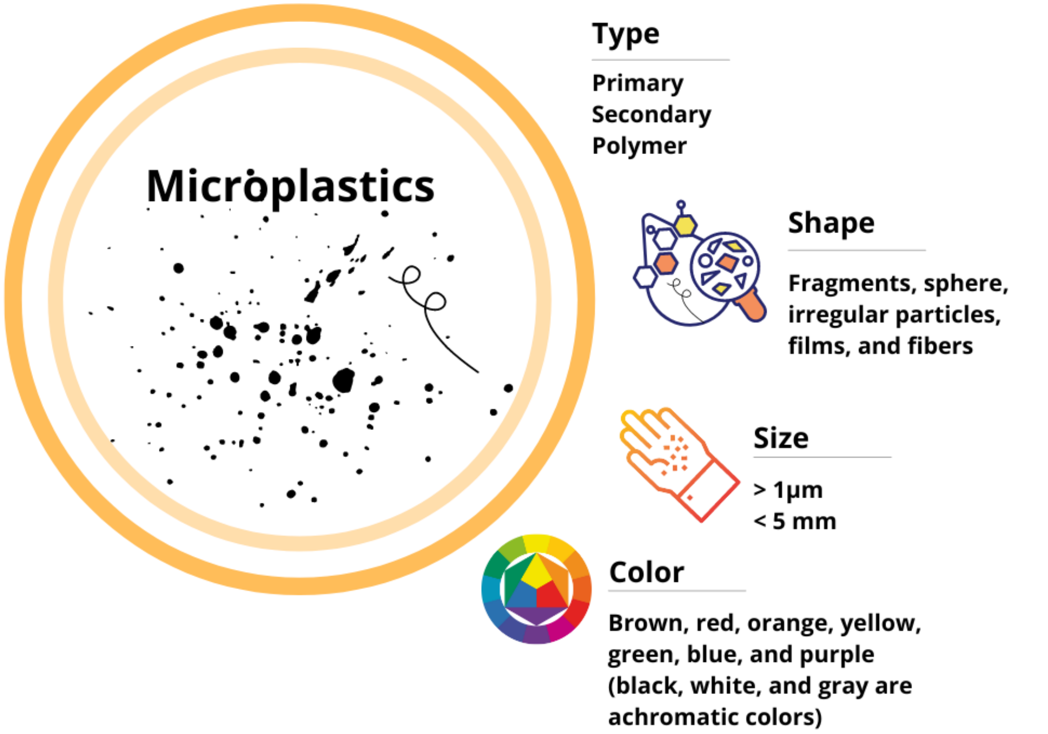

Figure 1. Microplastics exist in various sizes, shapes, polymer types, and colors. They are divided into primary and secondary microplastics. Primary microplastics are manufactured as small particles less than 5 mm, such as plastic resin pellets and microbeads. Secondary microplastics originate from larger plastic pieces, like the mechanical breaking of plastic. Polymer types include polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polyethylene terephthalate (PET), poly (methyl methacrylate) (PMMA), polyamide (PA), polylactide (PLA), polytetrafluoroethylene (PTFE). The shapes consist of fragments, spheres, irregular particles, films, and fibers, with sizes generally above 1 micron and below 5 mm [12,15–17]. Colors include brown, red, orange, yellow, green, blue, and purple, as well as achromatic colors like black, white, and gray [18].

Microplastics can enter the ocean from various sources, such as land-based activities (e.g., wastewater discharge, urban runoff, agricultural runoff), maritime activities (e.g., fishing, shipping, aquaculture), and natural processes (e.g., weathering, fragmentation) [19]. Once in the ocean, microplastics can be transported by currents and winds, accumulate in certain regions (e.g., coastlines, gyres), or sink to the seafloor [20]. Microplastics can also act as vectors for other pollutants, such as metals, organic contaminants, and pathogens, by adsorbing them from the surrounding water or releasing them from their own composition [21–23]. These pollutants can then be transferred to marine organisms that ingest microplastics, causing various adverse effects, such as inflammation, oxidative stress, endocrine disruption, and reduced growth and reproduction [24–27]. Moreover, microplastics can also enter the human food chain through the consumption of seafood or drinking water contaminated with microplastics, posing potential risks to human health [28]. Wright and Kelly (2017) also stated that plastic toxicity could occur due to the localized leaching of component monomers, endogenous additives, and adsorbed environmental pollutants [29].

There have been policies and mitigation measures to tackle with the global plastic production. The European Union has implemented the Single-Use Plastics Directive, which restricts and regulates single-use plastic products to curb their impact on the environment [30]. Extended Producer Responsibility (EPR) programs, such as those endorsed by the World Bank, hold producers accountable for managing the end-of-life waste of their products, fostering more sustainable design practices [31]. Plastic deposit and return schemes, exemplified by initiatives like the Plastic Soup Foundation's Plastic Bottle Deposit Scheme, incentivize recycling by offering refunds on returned plastic beverage containers [32]. International agreements like the Basel Convention, with its 2019 amendments, aim to better control the global movement of plastic waste and promote responsible disposal [33]. Grassroots movements, including Plastic Free July, encourage individuals to reduce their plastic consumption and raise awareness about the issue [34]. Research institutions are driving innovation in biodegradable plastics, recycling technologies, and plastic-eating enzymes. Moreover, educational campaigns run by organizations and governments play a vital role in informing the public about plastic pollution's consequences and inspiring behavior change. While this snapshot of policies and efforts is based on information available until September 2021, staying updated with reputable sources like governmental agencies, international organizations, and environmental NGOs is crucial to understand the evolving landscape of plastic pollution mitigation.

Therefore, it is imperative to understand the scope of global marine microplastic pollution and its implications for marine ecosystems and human health. In this study, the current state of knowledge on marine microplastic pollution focuses on four main aspects: (1) how plastic enters the ocean and accumulates along coastlines, particularly the formation and impact of the Great Pacific Garbage Patch; (2) how microplastics are distributed across different ocean basins and regions; (3) how microplastics affect marine wildlife at different trophic levels; and (4) how microplastics may pose public health risks through the human food chain. The results of our research will highlight the serious threats of microplastic pollution to global marine ecosystems and human health, and emphasize the need for more scientific research and policy measures to address this challenge.

2. Materials and Methods

We collected data on global marine microplastic from various sources, including public databases and academic studies. To estimate the pathway by which plastic enters the world's oceans, we adopted the platform of "Our World in Data" for data analysis. "Our World in Data" is a reputable and comprehensive database known for its credible and reliable information on a diverse range of global issues. With interactive visualizations and detailed articles, it offers a user-friendly platform for researchers, educators, and the public to explore and understand complex data. By providing open access to regularly updated information, the database promotes evidence-based insights and informed decision-making on critical global challenges [35].

We quantitatively analyzed surface plastic mass and qualitatively analyzed pathways, locations (e.g., shoreline, coastal, offshore), or geographic regions by ocean basin using data from [20,36]. Plastics persist for decades and accumulate on our shorelines, coastal, and offshore; and the global mass budget for positively buoyant macroplastic debris in the ocean using data from previous studies were investigated [37]. Sources of plastic in the GPGP, distinguishing by plastic use and particle size, were also analyzed. Plastic sources are measured in mass (in tonnes) [35,38]. To estimate the concentration of marine microplastics in Asia, Africa, South America, North America and Europe in the past five years, we used the "NOAA/NCEI Microplastics Database" [39] for data analysis and visualization. We also review the literature to investigate the impact of microplastics on marine ecosystems.

3. Results

3.1. The Pathway by Which Plastic Enters the World's Oceans

We have analyzed the journey of plastic waste from its creation to its entry into the ocean (Figure 2). Plastic waste is mainly generated from production processes and post-consumption disposal. After stages such as collection, sorting, and recycling, some of it enters the environment due to inadequate management and subsequently reaches the ocean through wind and water currents. The percentages in the diagram indicate the proportion of plastic waste lost at each stage, reflecting the mechanism and scale of marine plastic pollution. (Results were analyzed by Our World in Data based on the original study of [20,36] from plastic waste generation rates, coastal population sizes, and waste management practices by country.).

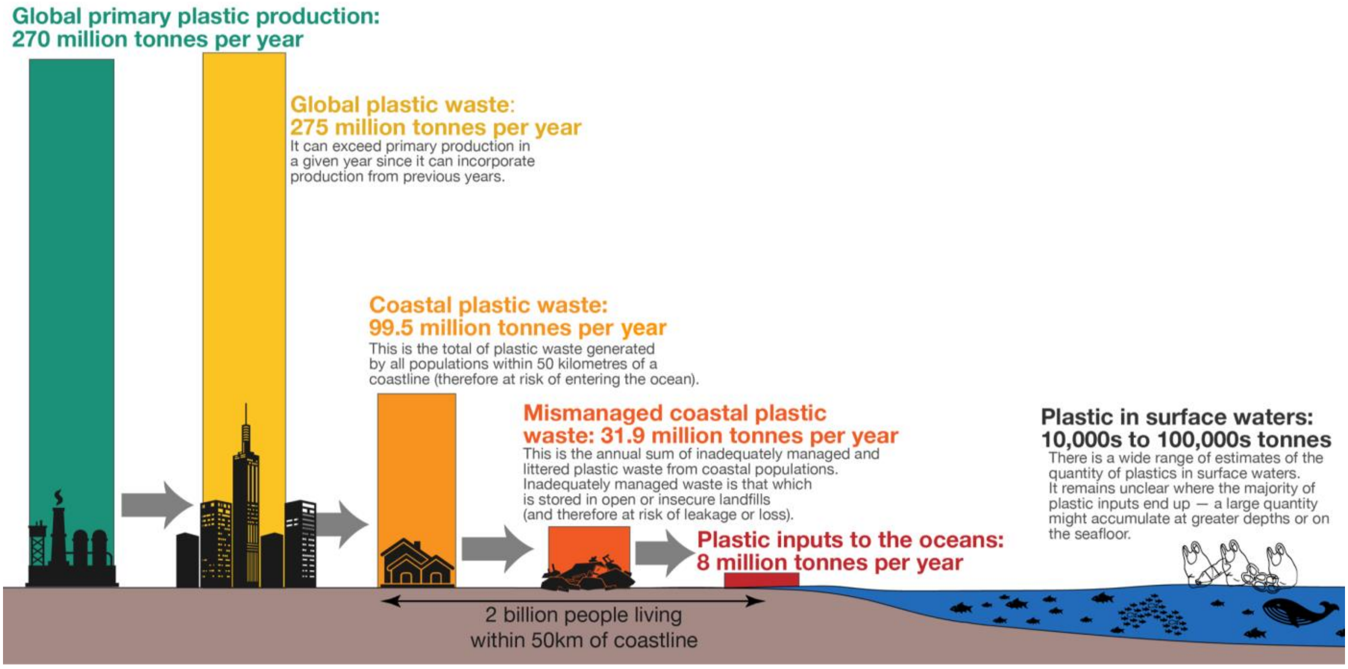

Figure 2. The pathway by which plastic enters the world's oceans. (Results were analyzed by Our World in Data (https://ourworldindata.org/plastic-pollution#where-does-our-plastic-accumulate-in-the-ocean-and-what-does-that-mean-for-the-future, accessed on 18 June 2023) based on the original study of [20,36] based on plastic waste generation rates, coastal population sizes, and waste management practices by country).

3.2. Where Plastic Accumulates in the Ocean

Based on global plastic production data, data on emissions of different types and ages of plastic into the ocean, and transport and degradation rates, the amount and age of plastic in different marine environments were mapped, creating a global ocean plastic model [37] (Figure 3). This model quantifies the accumulation of plastic in the ocean, including coastlines, coastal areas and areas far from the coast, maps the amount and age of plastic in different marine environments, and visualizes the accumulation of plastic in different environments in the ocean [35].

3.3. The 'Great Pacific Garbage Patch' (GPGP)

The Sources of plastics to the GPGP, differentiated by plastic use (foamed material, pre-production plastic pellets, hard plastic, plastic sheet and film, plastic lines, ropes and fishing nets) and particle size (diameter from 0.05 cm to >50 cm) (Figure 4). Plastic sources are measured by mass in tonnes. Data is based on collections of GPGP plastics in the year 2015 (results were analyzed by Our World in Data (https://ourworldindata.org/plastic-pollution#the-great-pacific-garbage-patch-gpgp, accessed on 30 August 2023) [35]), based on the original study of [38].

3.4. Concentration Maps of Marine Microplastics on Five Continents over the Past Five Years

The concentration map of marine microplastics in the past five years was also investigated based on a previous study [39] (Figure 5). The visualized map portal contains information on microplastics concentrations (reported in particles/m^3), from June 2018 to June 2023, latitude and longitude where data was collected. Results revealed that marine microplastic concentrations are mostly in medium range (0.005–1 pieces/m^3) around the five continents. Very High or High concentrations were observed around North America and the North shore of Asia.

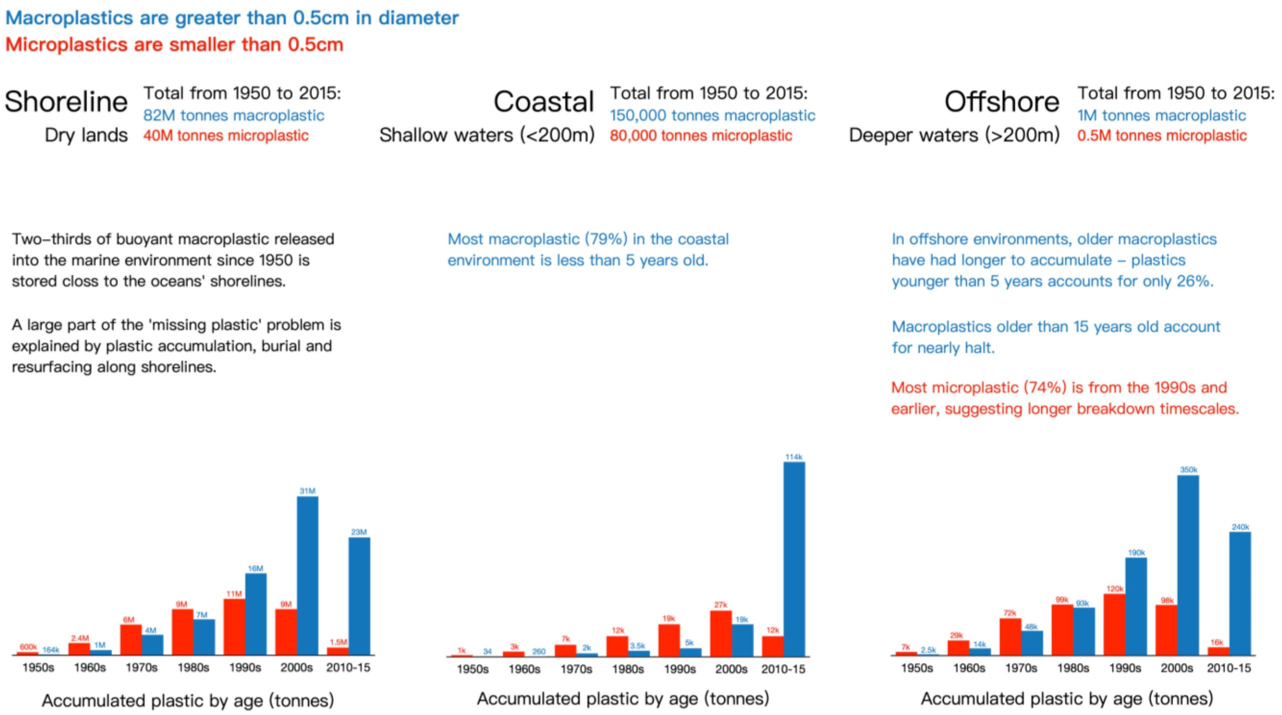

Figure 3. Plastics persist for decades and accumulate on our shorelines, coastal, and offshore. (Results were analyzed by Our World in Data (https://ourworldindata.org/plastic-pollution#plastics-persist-for-decades-and-accumulate-on-our-shorelines [35], accessed on 18 June 2023) based on the original study of Lebreton et al. (2019). A global mass budget for positively buoyant macroplastic debris in the ocean [37].).

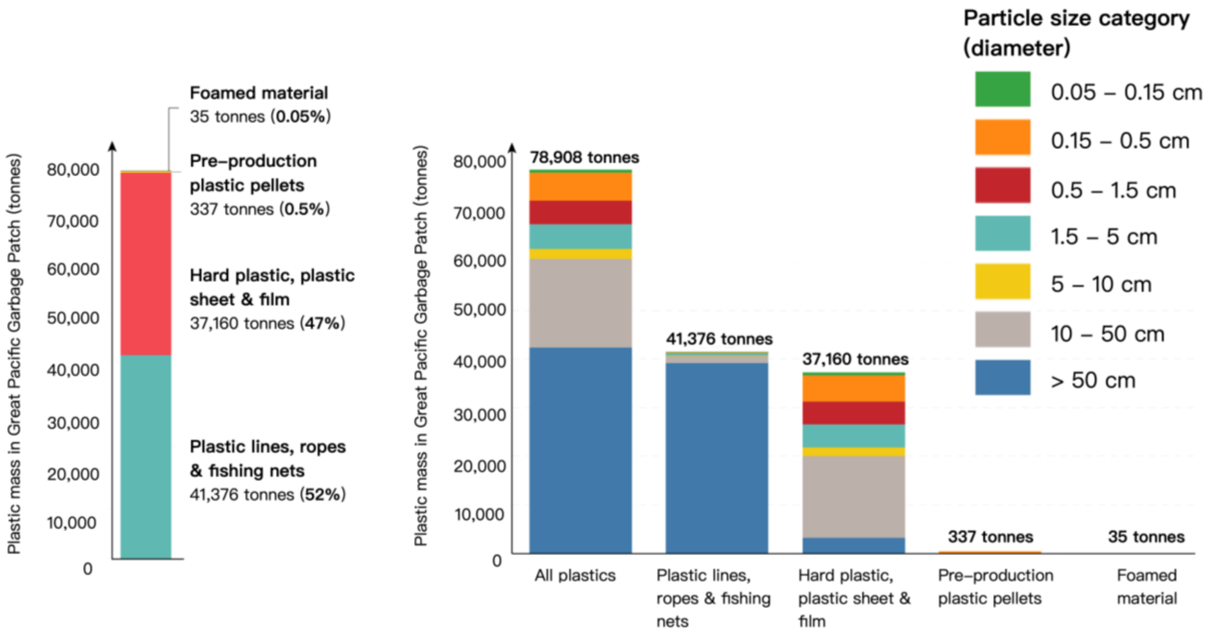

Figure 4. Great Pacific Garbage Patch (GPGP) plastic sources. (Results were analyzed by Our World in Data (https://ourworldindata.org/plastic-pollution#the-great-pacific-garbage-patch-gpgp, accessed on 18 June 2023) [35]) based on the original study of [38].

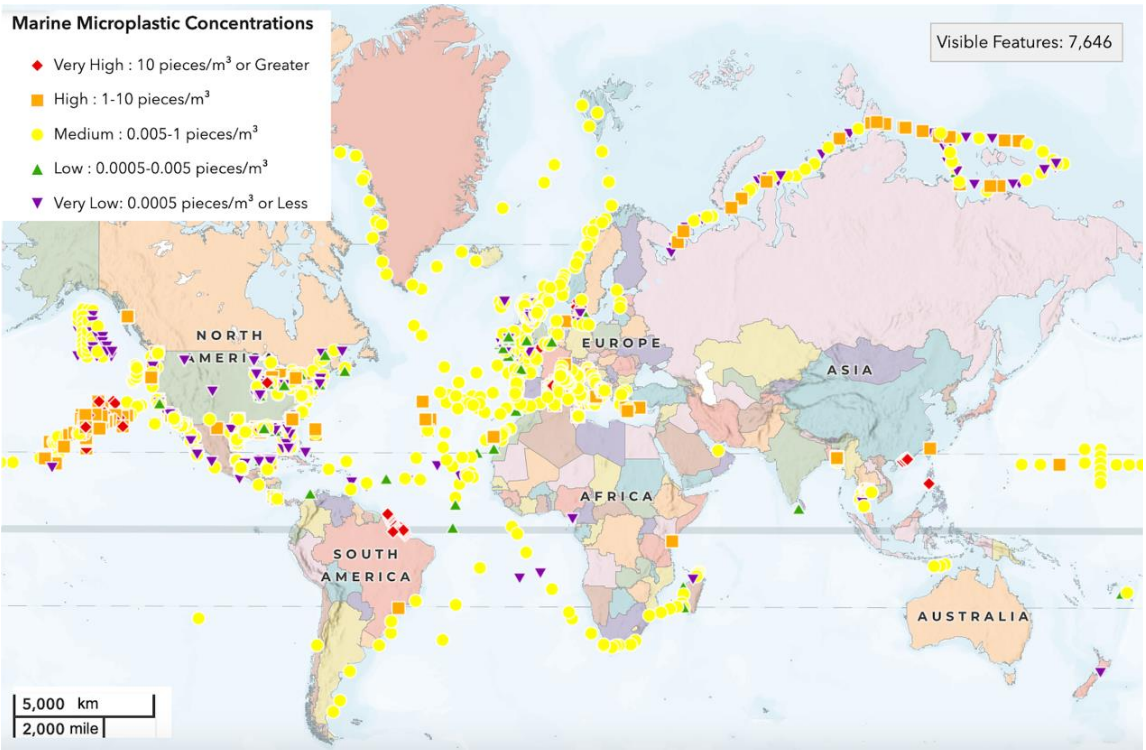

Figure 5. Concentration map of marine microplastics in the past five years. (Results were analyzed from NOAA/NCEI Microplastics Database (https://experience.arcgis.com/experience/b296879cc1984fda833a8acc93e31476, accessed on 18 June 2023) [39]). The visualization of marine microplastic concentrations includes 7646 features are represented by different shapes and colors (a red rhombus signifies very high concentrations (10 pieces/m^3 or greater), an orange square indicates high concentrations (1–10 pieces/m^3), a yellow circle stands for medium concentrations (0.005–1 pieces/m^3), a green triangle represents low concentrations (0.0005–0.005 pieces/m^3), and a purple inverted triangle denotes very low concentrations (0.0005 pieces/m^3 or less).

Concentration map of marine microplastics in Asia is illustrated in Figure 6. Most areas are with medium concentration, and some areas of the South China Sea and the Gulf of Thailand and Look ng Maynila have very high concentrations. The visualized map portal represents the concentrations of marine microplastics over the last five years (from June 2018 to June 2023), reported in particles/m^3 and marked according to the latitude and longitude where data was collected. These concentrations are depicted by different shapes and colors for clarity and ease of interpretation.

Figure 7 displays the concentration map of marine microplastics in Africa. Most areas have moderate concentrations, and parts of the North Atlantic and Mediterranean regions have high concentrations.

The concentration map of marine microplastics in South America was also explored (Figure 8). Most areas are with medium concentrations, and some in the northern waters of Brazil have very high concentrations of microplastics.

The concentration map of marine microplastics in North America was further investigated (Figure 9). Most areas are below the medium concentration of yellow, the Great Lakes region, a small part of the western and southern coasts, the North Atlantic and the North Pacific have high orange concentrations, and some parts of the North Pacific have red marks with very high concentrations.

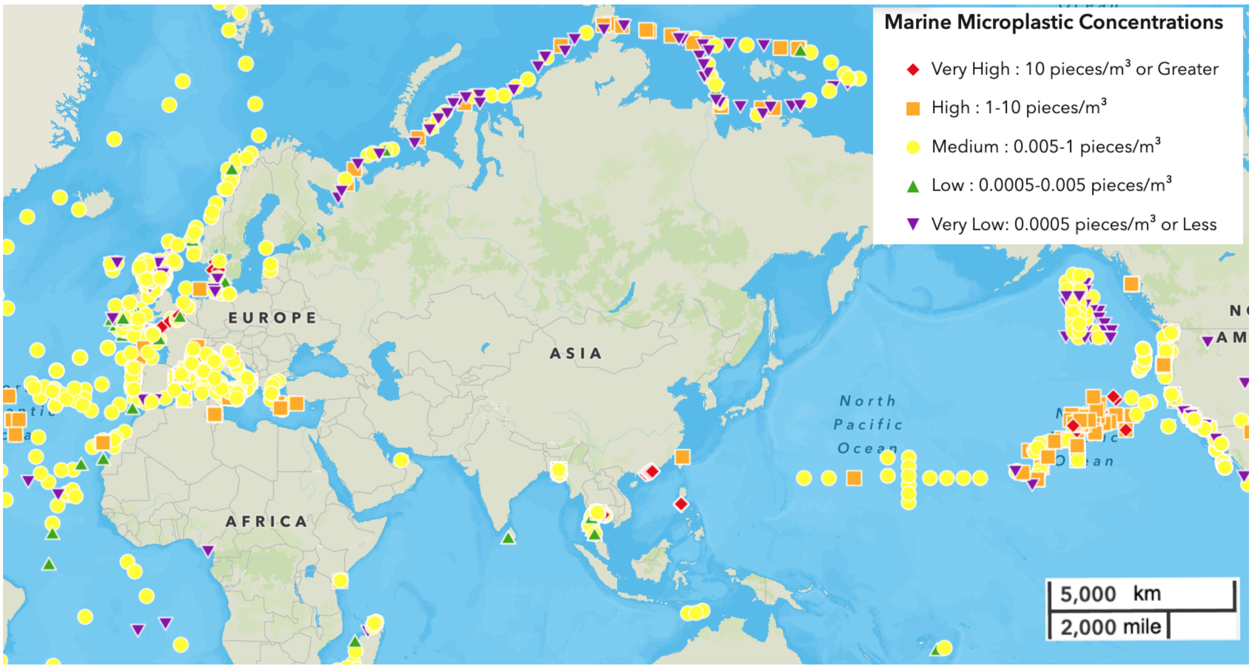

Figure 6. Concentration map of marine microplastics in Asia (Results were analyzed from NOAA/NCEI Microplastics Database (https://experience.arcgis.com/experience/b296879cc1984fda833a8acc93e31476, accessed on 18 June 2023) [39]).

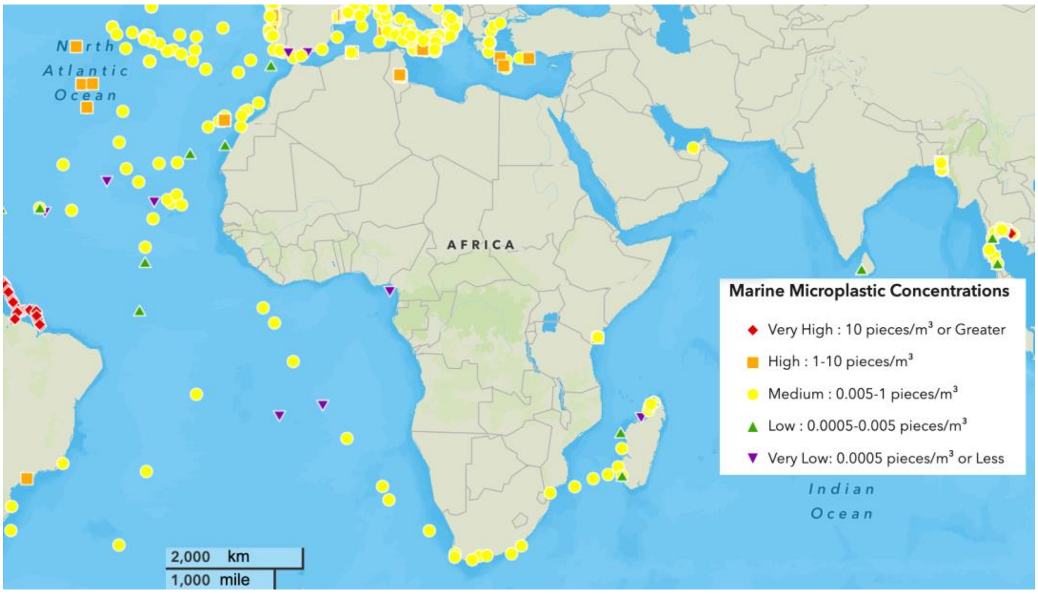

Figure 7. Concentration map of marine microplastics in Africa. (Results were analyzed from NOAA/NCEI Microplastics Database (https://experience.arcgis.com/experience/b296879cc1984fda833a8acc93e31476, accessed on 18 June 2023) [39]).

Figure 10 displays the concentration map of marine microplastics in Europe. Most areas are below the medium concentration, high concentrations in some North Atlantic and Mediterranean regions, and very high concentrations appear in the English Channel and the Skagerrak Sea.

Figure 8. Concentration map of marine microplastics in South America. (Results were analyzed from NOAA/NCEI Microplastics Database (https://experience.arcgis.com/experience/b296879cc1984fda833a8acc93e31476, accessed on 18 June 2023) [39]).

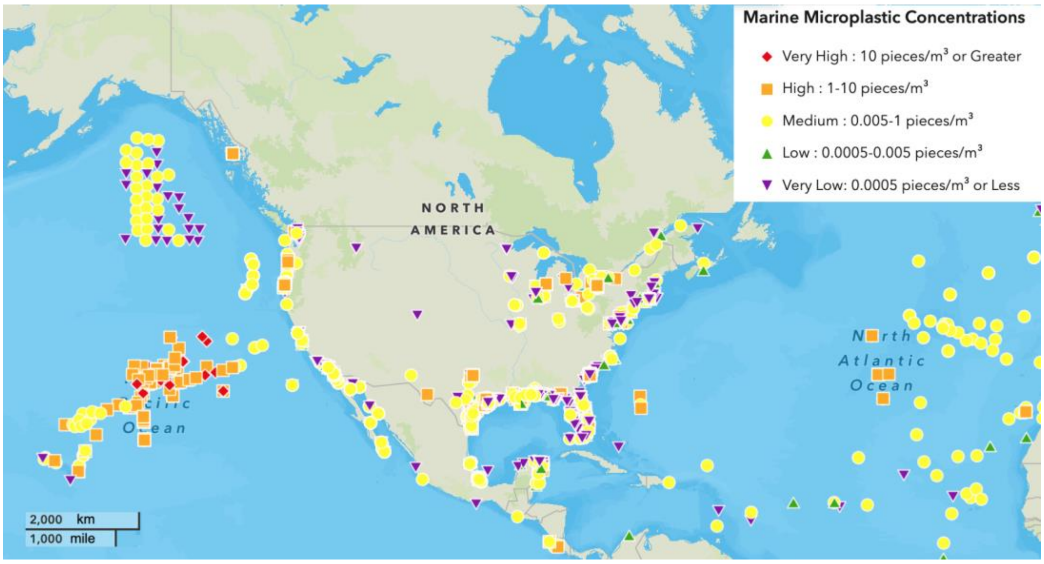

Figure 9. Concentration map of marine microplastics in North America. (Results were analyzed from NOAA/NCEI Microplastics Database (https://experience.arcgis.com/experience/b296879cc1984fda833a8acc93e31476, accessed on 18 June 2023) [39]).

3.5. Impact of Microplastics on Marine Ecosystems

Table 1 comprehensively lists the impacts of microplastics on various marine ecosystems, including a wide range of organisms such as zooplankton, fish, invertebrates, seabirds, marine mammals, and humans. The impacts of microplastics include impediments to nutrient intake, physical damage, lifespan reduction, decreased fertility, and even threats to human food safety. This table underscores the broad and profound effects of microplastic pollution on marine ecosystems.

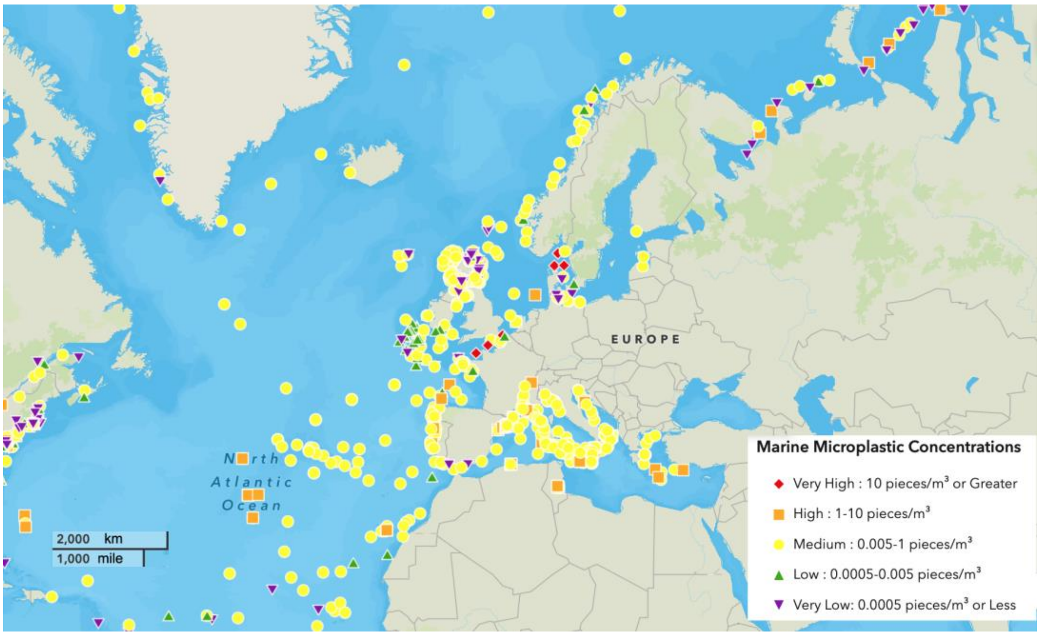

Figure 10. Concentration map of marine microplastics in Europe. (Results were analyzed from NOAA/NCEI Microplastics Database (https://experience.arcgis.com/experience/b296879cc1984fda833a8acc93e31476, accessed on 18 June 2023) [39]).

Table 1. Impact of microplastics on marine ecosystems.

Type of Impact	Species	References
Decreased viability and vitality	Zooplankton, fish, seabirds, turtles, marine mammals	[40–44]
Growth and development are affected	Corals, mussels, oysters, clams, worms, crustaceans	[41,45–52]
Decreased feeding behavior and food consumption	Fish, crabs, lobsters, sea stars, sea cucumbers	[41,45,53–56]
Toxicology and health effects	Fish, mollusks, echinoderms, cnidarians, sponges	[26,41,45,52,53,57–62]
Microplastic accumulation in higher food chains	Fish, seabirds, marine mammals, humans	[25,27,41,45,53,54,57,60,63]
Ecological knock-on effect	Phytoplankton, zooplankton, benthic communities, microbial communities	[57,64–69]
Impaired ecosystem function	Coral reefs, seagrass beds, mangroves, salt marshes	[46,60–62,64,65,68,70,71]
Species diversity decline	Marine flora and fauna	[44,61,62,67,72–75]
Human health risk	Humans	[9,25–27,41,45,53,56,57,63]

4. Discussion

4.1. Exploring the Variations in Global Marine Plastic Pollution

The global problem of plastic pollution has attracted widespread attention, yet the distribution and impact of plastic pollution vary significantly across the globe [76]. These variations could be due to factors like geographical location, level of economic development, waste management systems, and local consumption habits.

The nature of oceanic currents allows for plastic waste to move from one place to another, causing certain areas, such as regions with weaker marine currents or frequent human activities, to become "hotspots" of plastic waste [77,78]. The level of plastic pollution in these areas typically far exceeds that of other regions.

In developing countries, where waste management systems are often less developed, much plastic waste is disposed of indiscriminately and ultimately ends up in the ocean [79,80]. In contrast, developed countries with more comprehensive waste management and recycling systems tend to experience less severe plastic pollution problems.

Differences in consumption patterns and lifestyle habits between countries also contribute to the variations in plastic pollution. Developed countries, despite having effective waste management systems, often have high per capita plastic consumption, and their exported waste can exacerbate plastic pollution in developing countries [81,82].

Understanding the role of microplastics, the invisible fraction of plastic pollution, is another important aspect of exploring global variations. Microplastics can originate from a variety of sources, and their distribution and impacts can differ significantly from macroplastics. The pervasive presence of microplastics, even in remote and seemingly pristine environments, underscores the global reach and insidious nature of plastic pollution [83].

It's important to note that even within the same country, the severity of plastic pollution can vary greatly. For instance, the conditions of plastic pollution may vastly differ between urban and rural areas or between coastal and inland regions [80].

To effectively combat the global problem of plastic pollution, it's imperative to understand these variations and devise strategies and methods tailored to different situations [76]. Conclusively, the conditions of plastic pollution worldwide are intricately linked to complex social, economic, and environmental contexts. Only through a deep understanding of these differences can we effectively address this global issue [35].

4.2. Comparing the Effects of Different Pollution Sources on Marine Ecosystems

Marine ecosystems worldwide are under threat from a wide array of pollution sources. Two primary sources, plastic pollution and chemical pollutants (such as heavy metals and pesticides), have garnered significant attention due to their global prevalence and potential for harm [84,85].

Plastic pollution, primarily in the form of microplastics, poses a significant threat to marine wildlife. Microplastics can be ingested by a wide range of marine organisms, from plankton to larger predatory species, causing physical harm and often transferring along the food chain [84,86,87].

Furthermore, plastics are not inert; they can absorb other pollutants, such as Persistent Organic Pollutants (POPs), and transport them to areas where they would not naturally occur. This can have far-reaching consequences for the health of marine organisms and the wider ecosystem [9,87].

Chemical pollutants, on the other hand, tend to be more insidious. They can bioaccumulate in organisms and biomagnify up the food chain, leading to toxic effects in top predators and potentially impacting the stability of entire ecosystems [88–90].

These chemical pollutants can also cause subtle changes in the reproduction and behavior of marine organisms. Such alterations can disrupt the balance of marine ecosystems and result in declines in biodiversity [61,72,91]. While both plastic and chemical pollutants are harmful, their effects on marine ecosystems are distinct. Plastic pollution's impact is often more immediate and visible, such as entanglement or ingestion causing physical harm to marine animals [84,92]. Conversely, the effects of chemical pollutants are usually less immediately visible but can lead to long-term changes in species health and ecosystem dynamics [93].

Additionally, the sources of these pollutants differ greatly. Plastic pollution primarily results from poor waste management and the ubiquity of single-use plastic items. Chemical pollution, however, is often a byproduct of industrial processes, agriculture, or the result of historical pollution [35,94,95].

After all, while both plastic and chemical pollution pose significant threats to marine ecosystems, the sources, modes of action, and long-term effects of these pollutants are distinctly different. Comprehensive strategies are needed to mitigate the effects of these diverse pollution sources.

4.3. The Connection between Microplastic Pollution and the Great Pacific Garbage Patch

The GPGP represents one of the highest concentrations of marine debris in the world's oceans [38]. It's a clear testament to the pervasiveness of human-generated waste, notably plastic waste, which constitutes a significant portion of the GPGP. Microplastics, tiny fragments of plastic less than 5mm in size, make up a substantial part of the GPGP [96]. These microplastics originate from larger plastic debris that gets broken down by environmental forces such as sunlight and wave action, or they enter the ocean already in their microscopic form from various sources like personal care products and synthetic clothing.

The GPGP's significance in the context of microplastic pollution cannot be overstated. As the oceanic currents, specifically the North Pacific Gyre, draw in debris, microplastics in the GPGP continue to accumulate. Consequently, the GPGP serves as a significant reservoir and source of microplastic pollution [35,97].

Microplastics in the GPGP present numerous ecological threats. The ingestion of microplastics by marine animals can cause physical harm and introduce toxic substances, posing a serious threat to the marine food web [27,98,99]. Moreover, the transport and degradation processes of microplastics within the GPGP are still not fully understood. Some studies suggest that microplastics can sink to the ocean floor due to biofouling or can be transported vertically by marine organisms [87,100,101].

Furthermore, research on the microbial communities that colonize these microplastics in the GPGP may provide insight into the ecological roles of microplastics, which may potentially act as vectors for harmful microbial species [102,103]. Despite its seemingly remote location, the GPGP and the associated microplastic pollution have implications for the entire global marine ecosystem due to the potential long-range transport of microplastics by ocean currents, affecting areas far beyond the GPGP itself [38,101,104].

Lastly, understanding the relationship between the GPGP and microplastic pollution is essential for grasping the full extent of this global environmental issue and for planning effective mitigation strategies [105–107].

4.4. Marine Organisms' Reactions and Adaptations to Microplastic Pollution

Marine organisms interact with microplastics in a variety of ways, ranging from unintentional ingestion and entanglement to colonization by smaller organisms [43,108]. The impacts of these interactions are diverse and often harmful, potentially affecting individual organisms, populations, and entire ecosystems. Many marine species, from plankton to large predators, inadvertently ingest microplastics. This ingestion can lead to physical damage, nutrient dilution, and toxicological effects, affecting the health, reproductive success, and even survival of these organisms [10,41,65].

Some marine organisms, particularly filter feeders like mussels and oysters, are at a heightened risk of microplastic ingestion due to their feeding mechanisms [47,48,60]. The effects of microplastics on these organisms can ripple up the food chain, affecting predators and the overall ecosystem stability.

Beyond ingestion, entanglement in larger plastic items and microplastic aggregates is another significant concern. Entanglement can result in physical injury, impaired movement, and reduced foraging success in affected organisms, with particularly notable impacts on larger animals such as marine mammals and sea turtles [25,73,109,110]. The specific impacts of microplastic pollution on seabird populations was elucidated by various studies, with [74] uncovering the threats of fishing and plastic pollution to all 359 species of seabirds; Ref. [111] revealing the need for further study of the Odra Estuary as a key wintering site for Greater Scaup; Ref. [75] providing annual bycatch mortality data; Ref. [112] emphasizing bycatch as one of the main threats to seabirds globally; and Ref. [44] identifying the risk of plastic ingestion in Long-tailed Ducks. Together, these studies illustrate the multifaceted impact of microplastics on marine ecosystems, including direct threats to seabird health and indirect effects on the food chain.

In terms of adaptation, certain organisms, like bacteria and small invertebrates, were found to colonize microplastics. These "plastispheres" can offer new habitats but can also transport invasive species and pathogens across large distances [113–115].

Interestingly, some species show behavioral adaptations to plastic presence. For example, some seabird species were observed using plastics in nest-building, while others appear to be selectively feeding on certain types of plastic, likely mistaking them for prey. However, the long-term impacts and potential evolutionary consequences of such behaviors are still largely unknown [116–118].

On a larger scale, some evidence suggests that marine ecosystems might be adapting to the prevalence of microplastics, although the overall effects and long-term implications of these adaptations are not yet fully understood [119,120].

Mitigating the effects of microplastics on marine organisms will require reducing plastic waste, improving waste management, and possibly developing plastic alternatives. However, it's also crucial to continue studying how marine organisms respond and adapt to microplastics, as this knowledge could help inform future mitigation strategies [107,121,122]. In the face of the microplastic pollution problem, it is also imperative to foster interdisciplinary collaborations involving ecologists, toxicologists, material scientists, and policymakers. Such collaborations can help in developing innovative solutions and policies to reduce microplastic pollution and its impacts on marine organisms and ecosystems [8,123,124].

In the end, while marine organisms have exhibited various reactions and adaptations to microplastics, the overall impacts of microplastic pollution on marine life and ecosystems are primarily negative, necessitating urgent and comprehensive action.

4.5. Long-Term Impacts and Risks of Microplastic Pollution

Microplastic pollution poses significant long-term threats to the world's oceans. The persistence of plastic in the marine environment, which can extend for hundreds to thousands of years, allows for the continuous accumulation of microplastics, exacerbating their impacts over time [125–128].

One long-term effect is the physical harm and potential mortality in marine organisms due to microplastic ingestion and entanglement. These impacts can lead to changes in population dynamics and disrupt marine food webs [129–131].

Additionally, due to their extensive surface area-to-volume ratio and chemical properties, microplastics can absorb and release anthropogenic greenhouse gases, such as methane and ethylene, contributing to global warming [132–135]. The long-term implications of this role played by microplastics in the climate system are yet to be fully understood and quantified.

In addition, microplastics can serve as vectors for other pollutants, such as heavy metals and organic pollutants, enhancing their bioavailability and potential for bioaccumulation and biomagnification [21,136,137]. This interaction could have far-reaching implications for the health and survival of marine organisms. Furthermore, the potential effects of microplastics on the genetic and physiological levels of marine organisms are a significant concern. Recent studies suggest that microplastic exposure may cause genetic alterations and affect the reproductive success of marine species [138–140].

Moreover, long-term microplastic pollution might cause changes in community composition and diversity in marine ecosystems. Some research suggests that organisms, which are more resilient to plastic pollution, may outcompete sensitive species, potentially leading to decreased biodiversity [67,141]. At the ecosystem level, the long-term presence of microplastics could potentially alter habitat structures and influence biogeochemical processes [142,143]. While the exact nature and extent of these impacts are still under investigation, the risks associated with these potential changes underscore the urgency of addressing microplastic pollution.

The persistence and ubiquity of microplastics also raises concerns about their potential impacts on human health. Microplastics can accumulate in seafood and other marine products consumed by humans, potentially leading to exposure to plastic-associated chemical additives and contaminants [144,145]. Researching the direct and indirect impacts of microplastics on human health through the food chain, including potential toxicological effects, such as endocrine disruption and oxidative stress, is of critical concern [26,146,147]. Specifically, microplastics were found in human placenta and meconium samples, suggesting that pregnant women and infants are widely exposed to these pollutants. This alarming evidence was presented in the study titled "The Association Between Microplastics and Microbiota in Placentas and Meconium: The First Evidence in Humans" by Liu et al. (2022) [148].

In conclusion, the long-term impacts and risks of microplastic pollution pose significant threats to marine organisms and ecosystems, and potentially human health, highlighting the need for concerted global efforts to mitigate this pervasive form of pollution [149,150].

4.6. Solutions and Recommendations for Microplastic Pollution

Before we delve into the proposed solutions and recommendations for mitigating microplastic pollution, it's crucial to fully grasp the scope of threats imposed by this issue. Figure 11 provides us with a holistic view of these threats, illustrating the impact on marine life due to ingestion, bioaccumulation in the food chain, disruption to the ecosystem, public health concerns related to the release of toxic chemicals from plastics, and economic impact on industries such as fishing and tourism. Understanding the extent of these threats is vital to propose effective and comprehensive strategies to combat the issues raised by microplastic pollution. With these threats in mind, we can now explore potential solutions and recommendations.

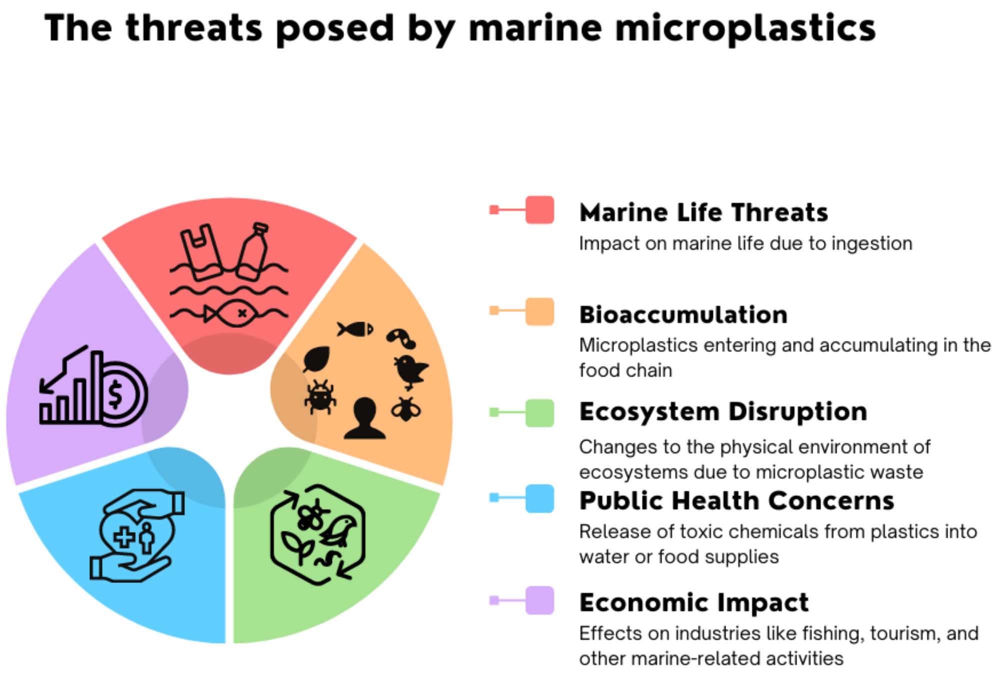

Figure 11. The threats posed by marine microplastics.

Addressing the global issue of microplastic pollution requires a comprehensive, multifaceted approach that spans prevention, mitigation, and remediation strategies. Prevention is the first and, arguably, the most critical step. This includes reducing overall plastic production and consumption, particularly single-use plastics, and promoting alternatives to plastic where possible [82,151].

Advancements in material science can also contribute to prevention strategies. This includes the development of biodegradable plastics or materials that mimic the convenience and versatility of plastics but minimize environmental harm [152–154]. Improvements in waste management systems, especially in countries with high levels of plastic waste leakage into the oceans are also crucial. These can involve better waste collection infrastructure, recycling programs, and disposal methods to prevent plastics from entering the marine environment [150,155].

Cleanup efforts are another important component, although they should not be relied upon as the sole solution due to the vastness of the oceans and the difficulties in collecting microplastics [156]. Nonetheless, ongoing initiatives to remove larger plastic debris, which can break down into microplastics, from the environment are important. Public education and awareness campaigns can play a pivotal role in driving behavioral changes necessary for reducing plastic waste [157,158]. These efforts can help foster a culture of responsible consumption and waste disposal.

Engaging stakeholders at all levels—from individual consumers to large corporations and governments—is crucial. Collaborative efforts and shared responsibility are key to achieving substantial reductions in microplastic pollution [159,160]. At the regulatory level, policies and legislation can play a critical role in managing plastic waste and reducing microplastic pollution. This can include bans on microplastics in personal care products, restrictions on single-use plastics, and incentives for plastic reduction and recycling [107,161]. Exploring policy interventions, regulations, and management strategies to mitigate microplastic pollution and protect marine ecosystems is an essential approach to addressing this environmental concern [161–163].

Overall, solving the microplastic pollution issue is a significant and complex task that demands concerted global efforts, involving prevention, mitigation, remediation, education, and policy initiatives. Continued research is also vital for understanding the full extent of this problem and evaluating the effectiveness of various solutions [150,164].

5. Conclusions

The results of this study indicate that global marine microplastic pollution is a serious issue, posing significant threats to marine ecosystems and human health. We have examined the pathways through which plastic enters the oceans and the accumulation of plastic, particularly the formation and impact of the GPGP. Through a comprehensive examination of marine microplastic concentrations across five continents, we have revealed the global distribution of microplastic pollution. Additionally, we have explored the impacts of microplastics on marine ecosystems and their potential entry into the human food chain, posing risks to public health. These findings underscore the urgent need for more scientific research and policy measures to address the severe threats of microplastic pollution to global marine ecosystems and human health. We call for stricter control measures to reduce plastic consumption, promote sustainable production and consumption practices, develop alternatives, and enhance public awareness of environmental protection. Only through global cooperation and collective efforts can we protect and restore our valuable marine ecosystems, ensuring the sustainable development of humanity and the planet.

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