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Review

Microplastic Pollution and Monitoring in Seawater and Harbor Environments: A Meta-Analysis and Review

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Abstract: Due to its widespread occurrence in practically all environmental sectors, including the terrestrial, marine, and atmospheric, microplastics (MP) have transitioned from an emerging pollutant to a chronic contaminant. Studies on the prevalence and hazardous effects on marine creatures have been conducted all over the world, but only in coastal environments. Microplastic pollution has emerged as a global concern in marine environments and a danger to animals, predators, and humans because it has been discovered in the marine environment all over the world. This review examines the quantity of MP samples around the world and their colonization by marine microorganisms, as well as the detection, features, origins, and ecological implications of paint fragments and resins in our oceans and ports. These polymers are derived from paints and the fiber reinforced plastic (FRP) matrix used in shipbuilding. Microplastics should be regarded as coming from synthetic polymers found in ship coatings. For assessing microplastic pollution, choosing an appropriate sample technique is essential. Additionally, this review offers an overview of MP investigation methods, concentrating on sampling techniques, laboratory procedures, and the identification of MPs found in seawater, as well as assessing how well they apply to the seaport environment. Because of the widespread discovery of MP pollution, particularly in Africa, Asia, India, South Africa, North America, and Europe, it is clear that monitoring is crucial for determining the efficacy of mitigation efforts to limit the quantity of waste plastic entering the environment, especially through sensors and real-time information transfer systems (e.g., smart digital seawater monitoring).

Keywords: microplastics; marine debris; marine pollution; port environment; monitoring; meta-analysis

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1. Introduction

Microplastics and other inert anthropogenic stressors in aquatic media are contributing to an ever-growing amount of environmental contamination. More and more plastic particles are entering the water as primary microplastics as a result of the widespread usage of plastic products in daily life. The issue of microplastic contamination is one that the public is becoming more concerned about because it has become a severe threat to both human and ecological health on a worldwide scale [1,2]. In general, fragments of any type of plastic smaller than 5.0 mm can be classified in the category of Microplastics, according to the U.S. National Oceanic and Atmospheric Administration (NOAA) [3,4]. Although the bottom limit (size) of the microplastics is not specified, it is customary to utilize the neuston nets' mesh size (333 µm or 0.33 mm), which was employed to gather the samples [5]. Primary and secondary microplastics are the two main ways that microplastics are created and released into a body of water [3,5]. There are many sources of microplastics, as well as many different characteristics:

Microplastic waste in freshwater and marine ecosystems has grown in importance during the past ten years [6]. Given how poorly understood the effects of microplastics on aquatic species are, there is a growing interest in learning more about them. Spherules in plankton tows off the coast of New England were the first signs of microplastics in North America in the 1970s, for example [7,8]. Microplastics were since discovered in the majority of significant bodies of water (oceans, seas, lakes, and rivers) [5].

The weathering process is thought to be the primary cause of plastic fragmentation, much like photodegradation caused by sunshine. Sunlight's ultraviolet rays cause the polymer matrix to oxidize, which causes chemical bonds to be broken. In comparison to beach or land environments, the lower temperature of the marine environment reduces the pace of plastic decomposition [9–11].

Furthermore, abrasion, wave action, and turbulence are some of the mechanical factors that can cause plastic debris to fragment. Because certain biodegradable plastics contain conventional synthetic polymers, which are not biodegradable, the inappropriate disposal of biodegradable plastics may result in secondary microplastic accumulation in the marine environment. Moreover, seawater lacks the anaerobic conditions necessary for biodegradable polymers to break down [12,13].

The polymers created to be microscopic are referred to as primary microplastics [14]. The majority of the principal microplastics found in the marine environment are produced by commercial and home cleaning products. Exfoliants are the principal microplastic kinds that are reported the most frequently [15]. For instance, a lot of microplastics can be found in personal care items such as toothpaste and hand or facial cleaners [16]. Microplastics used in cosmetics and personal care products (PCP) and small plastic fragments produced by the breakdown of macroplastics are causing growing environmental concern [17]. There are many potential contaminants that can be identified in wastewater treatment plants (WWTPs), but there are also newly emerging pollutants such as personal care products (PCPs) [18]. A scientific interest in microplastics has revealed that these contaminants are pervasive and ubiquitous in the marine environment and have the potential to harm biota [10,19]. The discovery of microscopic plastic particles in the open ocean occurred in the 1970s [20]. Microplastics are thought to be accessible to organisms at all levels of the food chain due to their microscopic size. Due to their relatively wide surface area, they are vulnerable to hazardous plasticizers leaking and attaching waterborne organic contaminants. Therefore, ingesting microplastics may be delivering toxins to the base of the food chain where there is a chance that they will bioaccumulate [14,21].

Moreover, microplastic particles are produced by industrial processes, particularly in the oil and gas sector where they are used as drilling fluids and abrasives. In order to clean engines and remove paint from metal surfaces, microplastics are utilized as air-blasting media [22]. Khasawneh et al. claimed that due to their potential or established negative effects on human health and the aquatic environment, pharmaceutical chemicals, such as antibiotics, nonsteroidal anti-inflammatory medications, etc., that could be regarded as sources of microplastics have arisen as new groups of water pollutants. The concentrations of medications vary significantly between different geographical areas. Twelve of the monitored medications were found to offer a significant potential risk to aquatic ecosystems, according to an environmental risk assessment based on the risk quotient (RQ) [23]. Additional industrial processes that produce primary microplastics include the manufacture of plastic products, which uses plastic resin pellets or flakes as well as plastic powder or fluff [24]. Microplastics are utilized as carriers to transport active medication agents in medical applications, such as dental cleaning [22]. Another significant source of microplastic might come from washing household textiles. Moreover, the degradation of cigarette butts and fragmentation of maritime equipment may be linked to the presence of fiber in the marine environment and ports (e.g., ropes and nets) [13,14]. During production or transit, these microplastics were unintentionally released into the ocean [13,16]. Primary microplastics are created raw plastic materials that enter the ocean through runoff from land, such as virgin plastic pellets, scrubbers, and microbeads [3].

When bigger plastic items (meso- and macroplastics) reach a beach or ocean and degrade mechanically, chemically, or biologically, secondary microplastic introductions take place [6–8]. The larger bits are reduced by this degradation into progressively smaller plastic fragments that are eventually invisible to the human eye [5,6,10]. Hence, it is possible to link the massive plastic waste from both terrestrial and aquatic sources to secondary marine microplastics. According to estimates, the proportion of plastic in the marine environment that comes from land-based and ocean-based sources, respectively, is 75–90% and 10–25% [8,25]. Many plastics can stay in the environment for months to millennia, but the lifetime of many of them is still debatable. Large plastic waste can break up into smaller pieces after entering the marine environment due to physical, biological, or chemical weathering processes, which reduce the structural integrity [9,13,26].

Many studies have shown that marine creatures are capable of ingesting microplastics, frequently with serious repercussions since they can collect in tissues, act as carriers of infections, and absorb and deposit hazardous chemicals. Microplastics can have a wide range of negative effects, including cancer, poor immunological function, malformation, and impaired reproductive function in both people and animals. Microplastic pollution of the marine environment poses a risk to both human health and the economy. Due to these particles' small size and difficulty in visualization, hand removal of these particles is exceedingly difficult, if not impossible, which poses a problem for prevention and control methods. Microplastics will become more persistent with time. According to reports, there will be more microplastic in our oceans than fish by the year 2050 (World Economic Forum, 2016) [27].

Microplastic pollution of the marine environment is believed to represent a severe hazard to the survival of marine life. Numerous studies have shown that many species have issues with plastic ingestion or entanglement. Due to its light weight, high strength-to-weight ratio, thermal and biodegradation resistance, among other characteristics, plastic is utilized in a number of applications, including packaging, personal and household cleaning products, and industrial construction materials, as mentioned above [13].

Assigning a name and address to a source of pollution can be challenging because microplastics that end up in the water typically come from a variety of distinct sources, originate in various regions, and are released at various periods. In order to suggest potential solutions to reduce the entry of microplastics into the aquatic environment, it will be helpful to identify the original sources and classifications of both plastics and microplastics [27]. Microparticles can be both zooplankton and phytoplankton in size, the former of which is the primary source of food for the latter. Hence, filter-feeders or more powerful predators are likely to consume microplastic, which will have detrimental effects at the base of the marine food chain. Due to the consequences of floating debris in the marine environment at oceanographic convergences, where floating particles aggregate naturally and high rates of contact between live animals and micro-debris are anticipated, worry is on the rise [8,28].

As was mentioned before, worry is growing because of the effects floating debris has on the marine ecosystem at oceanographic convergences, where floating particles naturally collect and high rates of contact between live species and micro-debris are anticipated [29]. Because of the fact that harbor sediments have long served as sinks for pollutants from nearby industry and urbanization, the historical contamination of ports and harbors continues to be a severe danger. The restoration of productive uses for waterways and protection of human health and the environment depend on prompt and efficient treatment of contaminated sediments. Ports all over the world use maintenance dredging to keep berths and waterways at a safe operational depth. Several rules and procedures exist to test the dredged silt for recognized pollutants due to the high pollutant levels in an industrial port environment [30]. Hence, a deeper comprehension of microplastic abundance, distribution, and accumulation is necessary to reduce future dangers.

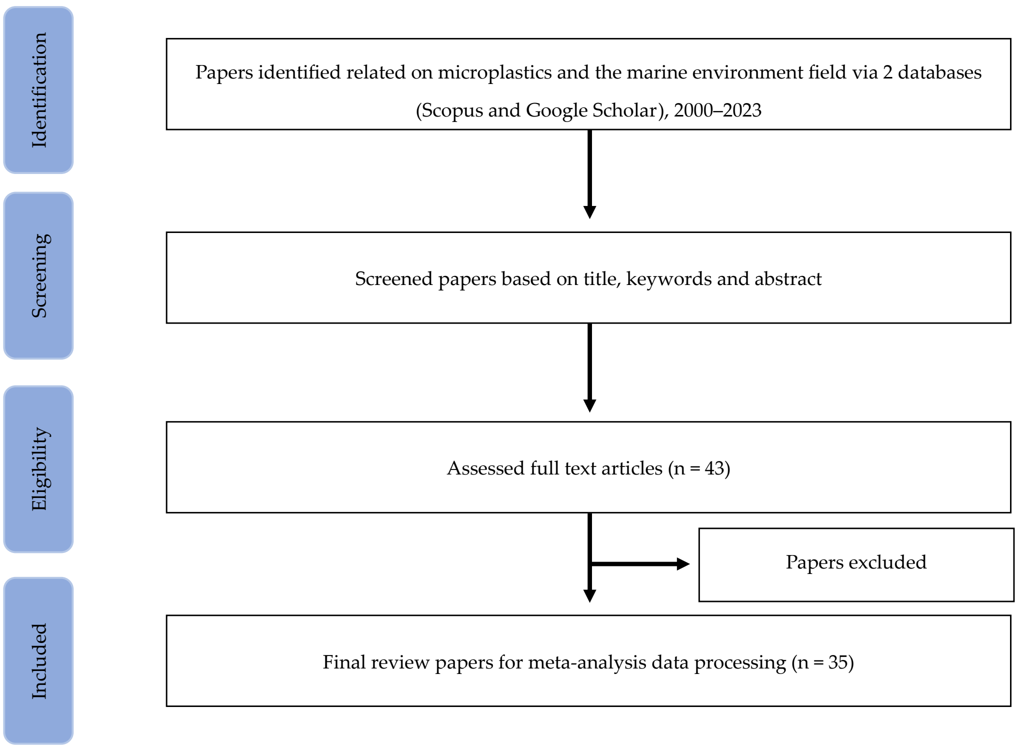
However, this presents difficulties for timely monitoring of the dissemination of trends across time and place of microplastic pollution at global, regional, and national levels due to the limitations in the detection technology [31]. The fact is, numerous different techniques are employed to check for microplastics in maritime sediment, and as a result, the results are sometimes incomparable, which is a general issue in microplastics research. As a result, accurate information regarding MP's existence, distribution, and ecotoxicological effects in the (marine) environment is currently scarce [32].

The objectives of this study were (1) to briefly analyze the selected review papers (meta-analysis) published since 2000 based on general interest data (e.g., years, journal of publication, etc.) and provide a detailed analysis based on different categories of environmental issues; (2) to review the types, properties, and distribution of microplastics in marine, harbor, and coastal environments; (3) to summarize the different kinds of microplastics by mapping the globe marine/harbor and coastal environments based on the results from a literature review; (4) to discuss the necessity of monitoring the microplastics in marine sediments, as this paper proposes the monitoring of potential input sites and accumulation zones within harbors; and (5) to briefly discuss the gaps in the literature, as well as potential future actions or goals. The importance of monitoring and the meta-analysis of the published review papers are also the innovation of this paper.

2. Research Methodology

Interventionary studies involving animals or humans, and other studies that require ethical approval, must list the authority that provided approval and the corresponding ethical approval code.

The ideal reference criteria for systematic reviews and meta-analyses set by Moher et al. were used in this review paper's research approach. Systematic reviews make up the first section. They offer unbiased summaries of what has been written and discovered about the study subjects with the aim of giving a complete overview of all research conducted in a certain field to date [33]. The second step is the meta-analysis, which involves integrating the results statistically using a variety of statistical techniques and aggregate data. The main goal of the PRISMA approach is to assist researchers and practitioners in producing a well-organized literature review report [34]. Several of the earlier review studies have reportedly employed the PRISMA approach, according to the study for this paper. As a result, the three primary PRISMA steps—literature review, selection of published papers that qualify, data export, and finalization—were used. Scheme 1 depicts the comprehensive workflow of the research project.



Scheme 1. Comprehensive workflow of the research project.

3. Data Collection/Bibliometric Analysis for the Meta-Analysis

The Scopus and Google Scholar databases were chosen as a starting point for the initial phase of the search for pertinent material. The purpose of this selection was to look for publications in a very broad context, and the literature search was conducted by looking for papers with literature reviews based on keywords such as "microplastics" or "marine environment" or "marine" or "marine debris" or "marine litter" or "coastal environment" or "pollution" or "plastics", as well as combining keywords related to marine and microplastics factors. Considering the time periods, the search was limited to articles from 2000 to 2023. After conducting the proper searches in the relevant databases, all of the results in Scopus and Google Scholar were exhausted, and we stopped when there were many pages of results with no pertinent publications. Case studies, book chapters, conference papers, postgraduate and doctoral theses, and papers written in a language other than English were all eliminated from the search because it was specifically looking for publications containing literature reviews. Review papers were, therefore, screened by title, keywords, and abstract while keeping in mind the aforementioned criteria, and the pertinent publications were listed in our list. We looked over each paper's main body, paying close attention to the abstract and conclusion sections in particular.

The acquired papers were then subjected to a bibliometric analysis, with the analysis findings displayed in Figures 1 and 2. It can be seen that the number of relevant papers is on the rise annually (As shown in Figure 1). Since 2016, there have been a lot more papers that are connected, which shows that this issue is receiving more and more attention.

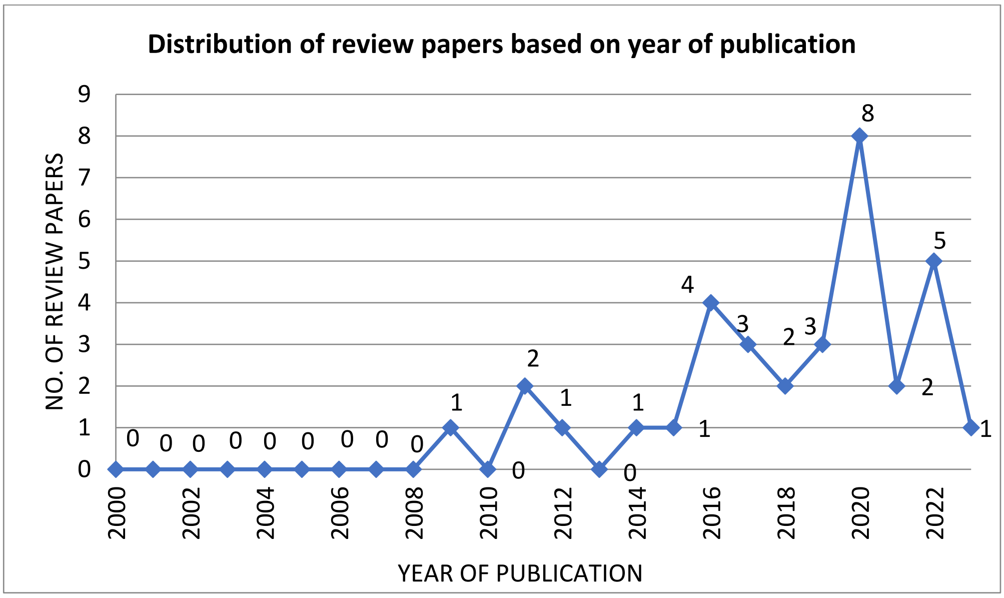


Figure 1. Number of relevant review papers annually.

These papers frequently used the terms "microplastics", "marine environment", "marine", "marine debris", and "coastal environment" as keywords (As shown in Figure 2). This showed that throughout the previous ten years, research on microplastic pollution in the maritime environment was very active. Furthermore, the significant buildup of microplastics in marine sediments caused researchers to become generally concerned.

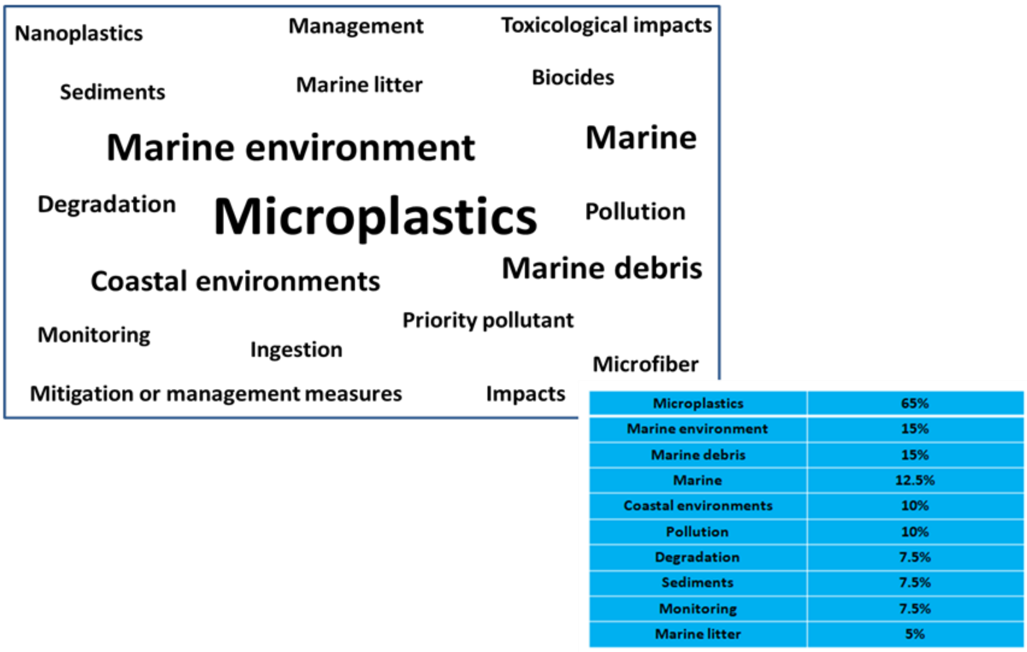


Figure 2. Most frequently (and top 10) used keywords.

For the past years, scientists from all over the world have contributed to the advancement of knowledge in the field of study on microplastics in the marine environment. In addition to several other smaller groups in other regions of the world, the major spatial clusters of institutions/universities working in this topic are dispersed throughout 21 nations, including the United States, Europe, and Asia. China has provided the most review researchers overall, by far. The nations with the most review publications published on microplastic pollution in marine environments over the previous years, according to Table 1, were China, Germany, the UK, Brazil, and Nigeria. These studies were conducted both in economically and non-economically developed countries, as well as in heavily populated locations, demonstrating that these regions place a high value on addressing the environmental issues brought on by microplastic contamination in seawaters.

Table 1. The nations with the most review publications published on microplastics.

Country	%
China	41
Germany	27.3
UK	22.7
Brazil	18.8
Nigeria, USA	13.6

Many of the journals that have published studies on microplastics in the marine environment are regarded as high-impact journals. Many papers over the previous ten years were discovered in ten major journals. Figure 3 revealed that “Marine Pollution Bulletin”, a journal that specializes on marine pollution first, and second, the “Science of the Total Environment”, have the most articles published on microplastics in harbors and coasts over the previous years. The journals that follow are “Environmental Science and Pollution Research” and “Environmental Pollution”, together with “African Journal of Marine Science”.

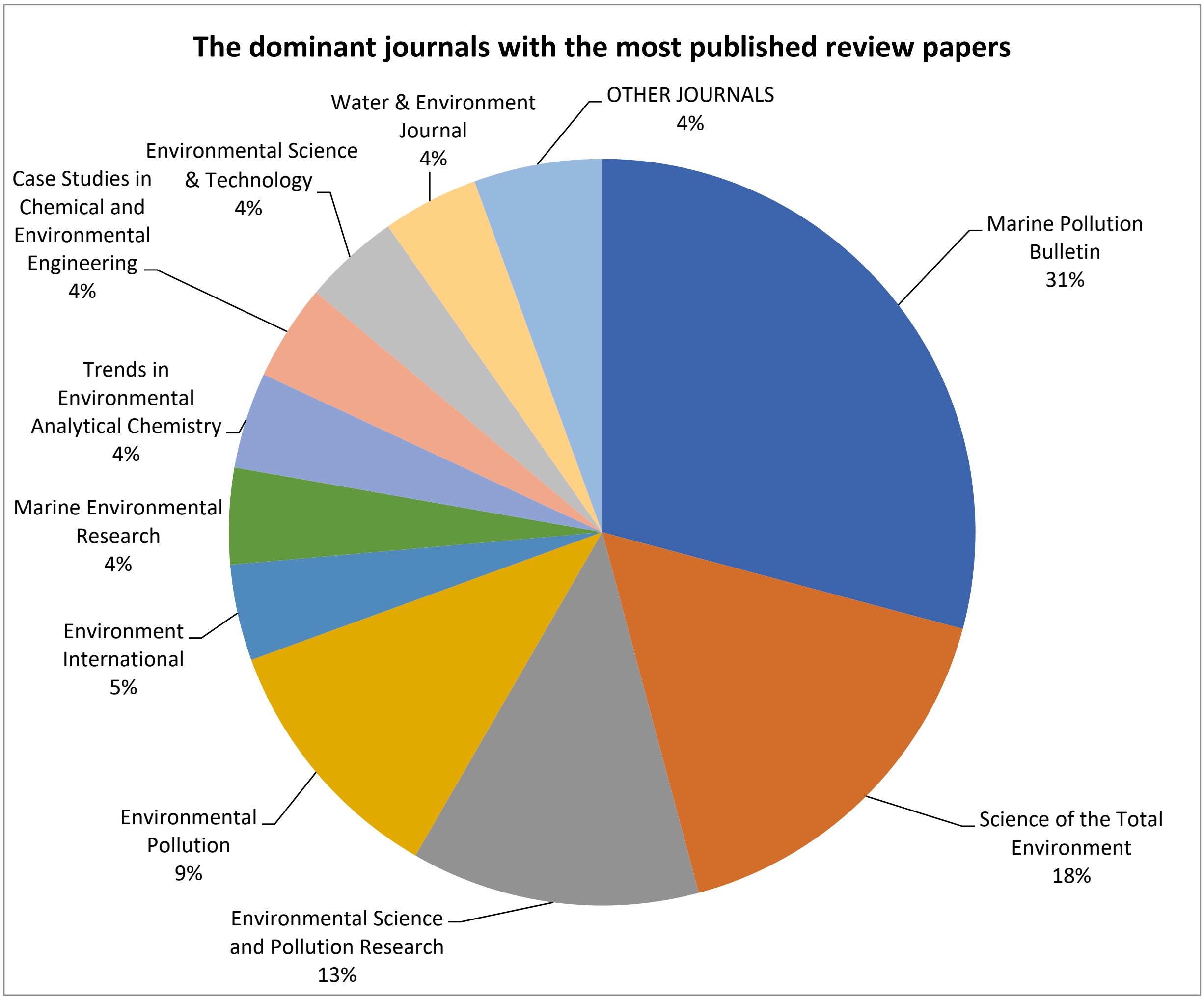


Figure 3. Journals with the most review articles published on microplastics in marine environments over the previous years.

4. Analysis of Review Papers

In this section, only review papers published on microplastics in marine environments are analyzed.

Cole et al., in 2011, published a review to summarize the characteristics, nomenclature, and the sources of microplastics, as well as to talk about the ways in which they enter the marine environment, to assess the techniques used to find them there, to determine the spatial and temporal trends of their abundance, and finally, to talk about their effects on the environment. The marine environment is full of microplastics, which are both numerous and pervasive. They are most prevalent around coastlines and in mid-ocean gyres. He highlights that many marine creatures are shown to ingest microplastics, which may make it easier to transfer hydrophobic waterborne pollutants or chemical additives to biota, and outlines the importance of the future study areas for academics and decision-makers [14].

On the basis of the laboratory findings that were described in the literature and data from environmental monitoring, Guo and Wang summarized the interactions of organic contaminants and metals with microplastics and made a brief assessment of the effects of microplastics on marine creatures. First, they examined the types, characteristics, and how the distribution of microplastics in the environment occurred. Second, they discussed how microplastics' properties changed once they degraded. Finally, they presented the pollutant concentrations on microplastics in various global habitats, and the impact of several variables (such as microplastic kinds and characteristics, different types of pollutants, and environmental conditions) on the sorption behaviors of microplastics was then thoroughly explored [35].

More research from Kavya et al. shows that microplastics pose a greater danger than previously believed; they are an environmental hazard that has recently gained relevance. In their study, scientists from all over the world have employed a wide range of methodologies and have made adjustments in response to the unique characteristics of the studies they have conducted. The historical evolution of the microplastic threat, the creation of research tools and methodologies, as well as the difficulties that must be overcome for continuing progress, are all covered in this article. The article covers microplastic characterization, isolation, extraction, and sources as well [36]. The detection, features, sources, and ecological implications of paint fragments in our oceans is another topic covered in a paper from Gaylarde et al., who also examines the prevalence of paint fragments in microplastic samples from around the globe and how this differs from the colonization of non-paint microplastics by marine microbes. Road markings, outside building surfaces, and watercraft and shipping operations all produce paint pollutants. Antifouling paints used on commercial ships and recreational boats produce a lot of paint fragments, which can be considered a special kind of pollutant because they not only contain heavy metals and biocides but also leach them [37].

An extensive literature review conducted by Yin focused on the research of microplastic pollution in sediments between 2013 and 2022. The findings indicated that microplastic pollution in sediments posed a possible hazard to marine ecology and the world's food supply. Furthermore, in the current ecological risk assessment of microplastics in sediments, the pollutant load index, polymer risk index, and potential ecological risk index of microplastics were widely used. These ecological risk assessment indicators can be improved with a lot of monitoring and simulation data, and thus, it is proven that it is possible to further enhance the current microplastic pollution source analysis system, as well as to manage the discharge of microplastics in the pollution source by developing more precise detection and analysis technologies [38].

In addition, Auta et al. examined the origins, global dispersion, fate, and effects of microplastics on marine biota, particularly the food chain. According to them, microplastics have a significant negative influence on many marine animals because they are known to infiltrate the marine environment through land-based and terrestrial activities, particularly through runoffs. National and international environmental groups have also explored and outlined a variety of control strategies to address the effects of microplastics, and at the same time, in order to improve comprehension of the effects on the marine environment, the corresponding behavioral mechanisms were also mentioned [27].

Prior to discussing specifics about textile fibers as microplastics, broad information about marine debris and plastics was presented by Cesa et al. Following that, fiber sources for microplastic pollution were reviewed, with a particular emphasis on household washings that are processed at WWTPs. Domestic washing was identified as a source of microplastics, and there is a severe lack of methodological uniformity and the inclusion of textile considerations in experimental design. The properties of textile products (such as yarn type and fabric structure) and laundry parameters (such as water temperature and chemical use) that are controlled by consumer preference are examples of areas where knowledge gaps exist. Another obstacle to a comprehensive understanding of such sources is the lack of information on the effectiveness and coverage of sewage treatment facilities for removing textile fibers [39].

Wang et al. made a similar review that examined studies on seawater, sediment, and biota, as well as the information that is currently available on microplastics in the China Sea. The status and restrictions of sample techniques, including their sampling instruments, volume, and depth, were outlined. There was a description of the analytical techniques used by microplastics, including sieving, density separation, purification, filtration, and visual sorting. Finally an extensive analysis was performed on microplastic properties such as abundances, sizes, forms, types of polymers, origins, and fates [40]. Despite the pollution caused by microplastics being acknowledged on a global scale, the knowledge of how they behave in the marine environment is still limited. The maritime environment is awash with microplastics, which have the potential to disrupt the marine ecology. Because of the above, Wang et al. categorized the behaviors of microplastics as physical (i.e., migration, sedimentation, and accumulation), chemical (i.e., degradation and adsorption), and biological (i.e., ingestion, translocation, and biodegradation), and a more detailed analysis on their behavioral mechanisms was presented from them to better understand their impacts for the marine environment [41].

Ivar do Sul and Costa were directed towards the first comprehensive examination of how microplastics affect the marine environment and biota. In reaction to the current and anticipated plastic usage and waste trends, there will be a rise in the quantity of scholarly publications. As a result, they suggest fresh ideas and crucial strategies for future research from their study as well [42]. Another review was conducted by Cutroneo et al., which provided an overview of MP investigation approaches, concentrating on sample methodology, MP identification in seawater, and evaluating their suitability for the maritime port environment [43].

Due to the fact that coastal lagoons provide important ecosystem services that are crucial for society and the economy worldwide, microplastic contamination is one of the many anthropogenic pressures on these delicate ecosystems. Hence, another review had the objective to discover and compile recent developments in the study of MP contamination in coastal lagoons around the globe [44]. The rise in marine plastic pollution was also reviewed by Alimba et al., with an emphasis on the most recent toxicological repercussions. Additionally, this is because polymers seldom biodegrade but instead fragment into microplastics and nanoplastics, which are identified as pervasive contaminants in all marine habitats throughout the world, through various mechanisms [45]. Another relevant study made by Torre et al. concentrated on the state of a better understanding of antifouling paint particle quantity, distribution, and ecotoxicological effects in the marine environment. Paint particles with harmful biocidal chemicals are known as antifouling paint particles. Their presence in boatyards and port locations is mostly related to boat repair. Recent ecotoxicological investigations have also shown that paint particle concentrations in the environment cause the death of macroinvertebrates and sediment dwellers [46].

One of the current reviews on this topic was developed by Llorca et al. The Mediterranean Sea is the subject of this assessment because it is a semi-enclosed sea with a high number of plastic-marine-litter-generating activities, making it one of the world's hotspots for microplastic pollution. They summarized the main issues and shortcomings related to microplastic analyses, such as their identification and quantification or the requirement of standardized protocols. They also shed light on various European legislation initiatives that were launched in recent years in order to prevent contamination and to deal with the derived problems [47]. Moreover, other researchers such as Chatziparaskva et al. examine microplastic accumulation, marine contamination, and abundance in Eastern and Western Mediterranean nations. The projected microplastic inputs into the Mediterranean Coastal Belt, repercussions on the economic and environmental sectors, and effects of marine pollution on human health and marine life are all provided. It is also discussed if current monitoring technologies are effective and why developing a strategy to stop marine plastic pollution is essential [48].

To evaluate the claim that particle density is a crucial element in explaining the sinking behavior and vertical distribution of microplastics and to take into account the uptake and trophic transfer of microplastics, a thorough literature analysis was conducted by Coyle et al. [49]. Ryan et al. were interested in providing a summary of the baseline information currently available that can be used to track changes in marine plastics in South Africa and recommend preferred methods for tracking changes in marine debris in the area in relation to some of the most urgent concerns about marine macro- and microplastics [17,50]. At the same time, Syakti emphasizes the need for future spatiotemporal comparisons of the presence of microplastics across the marine ecosystem, through standard procedures for sampling and analyzing microplastics in the seawater, beach and seabed sand, and marine organisms [51].

Regarding the approaches utilized for the identification and quantification of microplastics from the marine environment, a review by Hidalgo-Ruz et al. describes all the details. The major goal of the current research was to evaluate the various approaches used for the detection and measurement of microplastics in marine settings. In light of the findings, they suggest fundamental standards and methods to guarantee that future quantitative estimates are similar and provide consistent data on the presence of microplastics in the marine environment [52]. Kane et al., via their review study, seek to combine existing knowledge on the distribution of seabed microplastics with a process-based comprehension of how particles are transported, as well as with the established sedimentology of deep-marine systems. We do this in order to share fresh perspectives from the current research and to pinpoint problems for the future studies [53].

In order to determine what steps should be taken to best preserve world health, Hale et al. wished to strike a balance between the benefits and drawbacks of plastics. Given that the majority of researchers studying microplastics in the environment have mostly worked within their own fields of expertise, such as polymer chemistry, waste management, atmospheric, terrestrial, freshwater, and marine science, they completed their review by identifying the main obstacles that must be overcome in order to accomplish these goals, which is meant to ease that shift [54]. Solomon et al. focused on extracting and measuring microplastics from marine matrices using both traditional and cutting-edge methods. Although addressing the issues of microplastics in the water is a complex and enormous endeavor, some of the methods to minimize them are highlighted. They summarized the biological and ecological effects of microplastics on marine life and the environment, reviewed the solutions to reduce the disposal and occurrence of microplastics and stop the threat of microplastics in the ocean, and reviewed various microplastic assessment methodologies for various marine matrices [55]. The main goal of another study from the same author was to review some of the current, advanced strategies in reducing the occurrence and menace of microplastics in the environment [56].

Diaz-Mendoza et al. gathered the various categories of plastics that can be found in coastal marine debris, including information on the classification of microplastics according to various studies. The various methodologies used to estimate the quantity and abundance of microplastics that may have an impact on human health and coastal marine ecosystems are also described [57]. Yang et al. investigated the origins and fates of MPs in the marine environment, the effects of microplastics on marine animals, and the microorganisms for microplastic degradation in the marine environment. They also address the issues with microplastics' impact on the environment and highlight the necessity of future studies and management plans for marine microplastics [58]. Similarly, See et al. reviewed the sources, motions, and concentration of microplastics in the marine environment in addition to the findings of this investigation and sought to comprehend the strategies for sampling and laboratory testing for the presence of microplastics, as well as their shortcomings [59].

Over the previous years of research, the interest in tackling various topics was sparked by the publications published in these journals. In a nutshell, the research focused on the effects of microplastics on the marine environment, their capacity to interact (sorption/desorption) with other environmental contaminants, the transport routes of microplastic debris and potential sites for their deposition, the consumption of microplastics by marine organisms, and the quantification and characterization of these plastic microparticles in marine and coastal environments.

As it appears in Figure 4, the dominant analyzed topic from the reviews is related to the type, properties, and distribution of microplastics, comprising 14 review papers, occupying almost 70% of all review papers. The next category is the sources of microplastics, with 13 review papers and a 65%, followed by the environmental impact of microplastics, with 12 review papers. Some other popular topics were the trends in microplastics abundance, the detection methods, the degradation, the strategies, etc. However, very few studies focused on the legislation regarding the microplastics, the ecological risk, the mechanisms, the advances, etc. In general, it could be argued that there are a variety of topics that concern microplastics, but at the same time, there are gaps and lack of information for some other relevant topics.

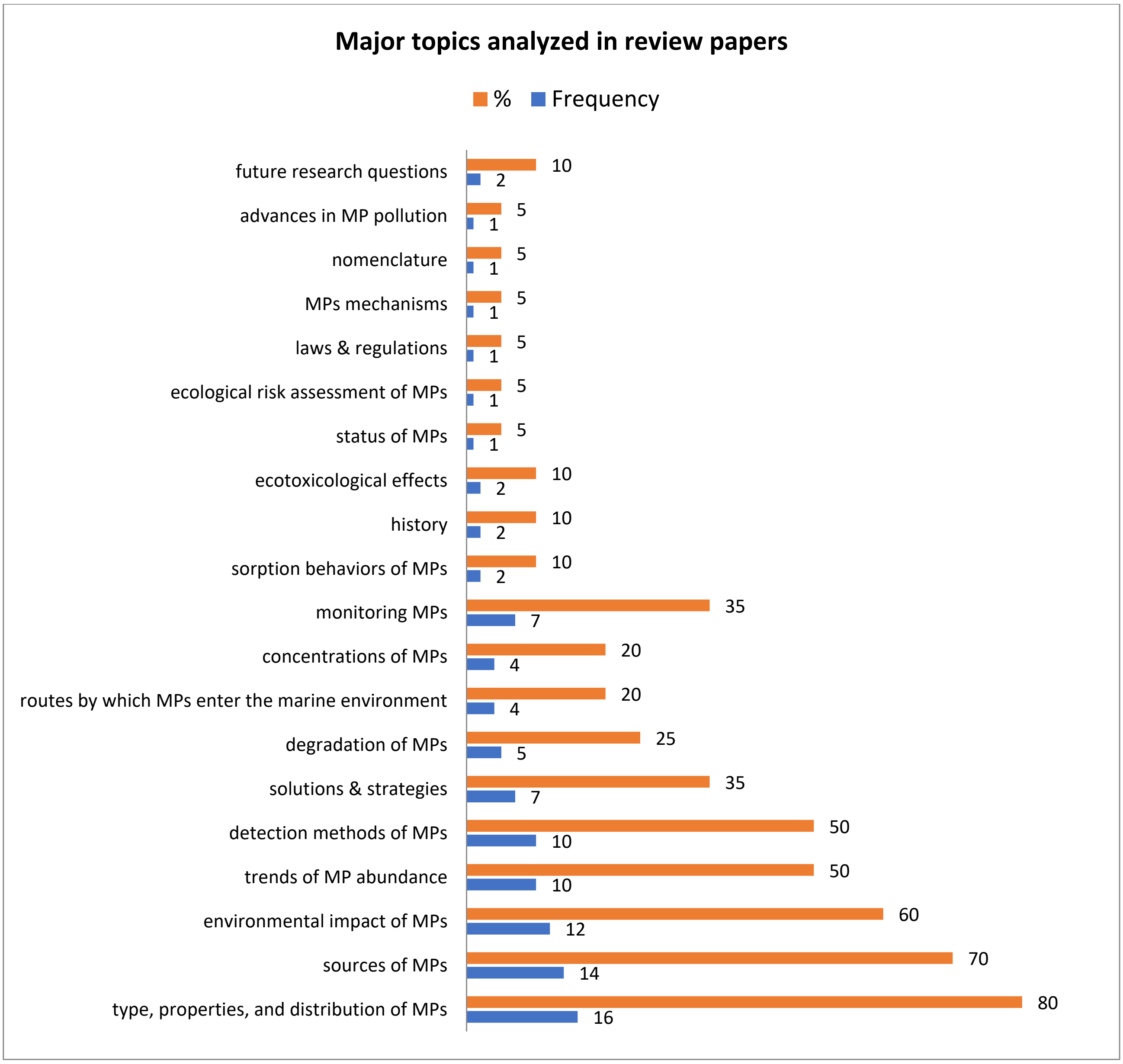


Figure 4. Distribution of the review papers according to the major topics they analyzed.

Studies on microplastics in ports and coasts have become more prevalent over the past 20 years, according to the annual production of publications on microplastics in the maritime environment. This tendency became more apparent starting in 2010, when the publications' yearly growth rate began to rise. These studies sought to determine the relationship between marine pollution and human activity in ports and harbors.

5. Bibliometric Analysis of All Articles for Microplastics in Ports and Coasts

In this section, an analysis is carried out regarding all articles published on microplastics in ports and coasts, not only reviews, as was the subject of Section 4. Regarding the review that aims to summarize the data and the results gathering information from different ports and coasts and to map the situation around the world, the method that we used was the same method by Moher et al. as in the first part of this paper [34]. The initial step of the search for applicable content was launched from the Scopus and Google Scholar databases. This selection was made with a fairly broad context in mind, and the literature search was conducted by looking for papers that contained studies on microplastics, mostly in ports and then secondarily in beaches. The study used keywords such as "microplastics", "marine environment", "marine", "marine debris", "marine litter", "coasts", "harbors", and "ports", as well as a combination of marine- and microplastics-related phrases. The search was restricted to items from 2010 to 2023 due to the time frames. After doing the appropriate searches in the pertinent databases, we exhausted all of the Scopus and Google Scholar results, and we stopped when there were several pages of results with no relevant publications, as we did with the meta-analysis. The following were excluded from the search: book chapters, conference papers, master's and doctoral theses, and anything written in a language other than English. In light of the aforementioned criteria, the papers were subsequently checked by title, keywords, and abstract and the relevant publications were noted in our list. We read the main body of each document, paying particular attention to the abstract and conclusions sections.

The obtained papers were then put through a bibliometric analysis, and Figures 5 and 6 show the results of the analysis. The quantity of pertinent papers is increasing yearly, as may be shown (as shown in Figure 5). Among the 78 documents acquired, 57 were examined and further categorized because they dealt with incidents that occurred in ports and along the coast, while the remaining 21 examined the significance of keeping an eye on the waters. There were a significant number of studies since 2014 that discussed microplastics in harbors and on the shore, indicating that this problem is gaining more and more attention. These papers frequently used the terms "microplastics", "(coastal) (harbour) (surface) sediment", " Water, marine, coastal, ocean pollution", " (marine) (plastic) (Floating) debris", and "monitoring" as keywords (as shown in Figure 6). This showed that throughout the previous ten years, research on microplastic pollution in the ports was very active.

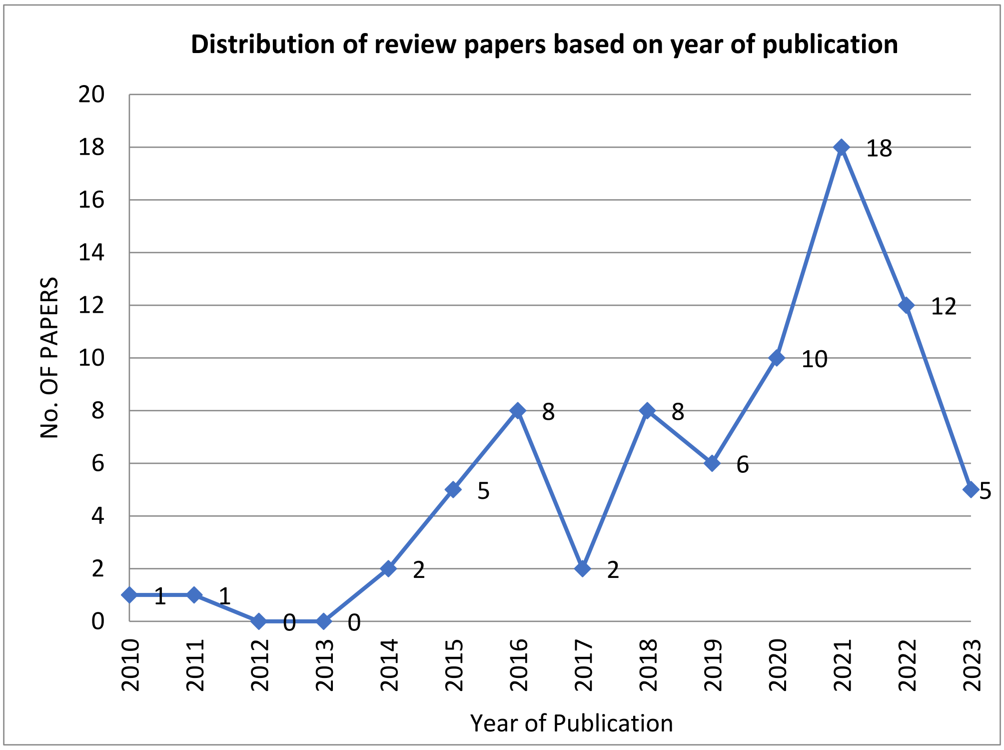


Figure 5. Annual number of relevant papers.

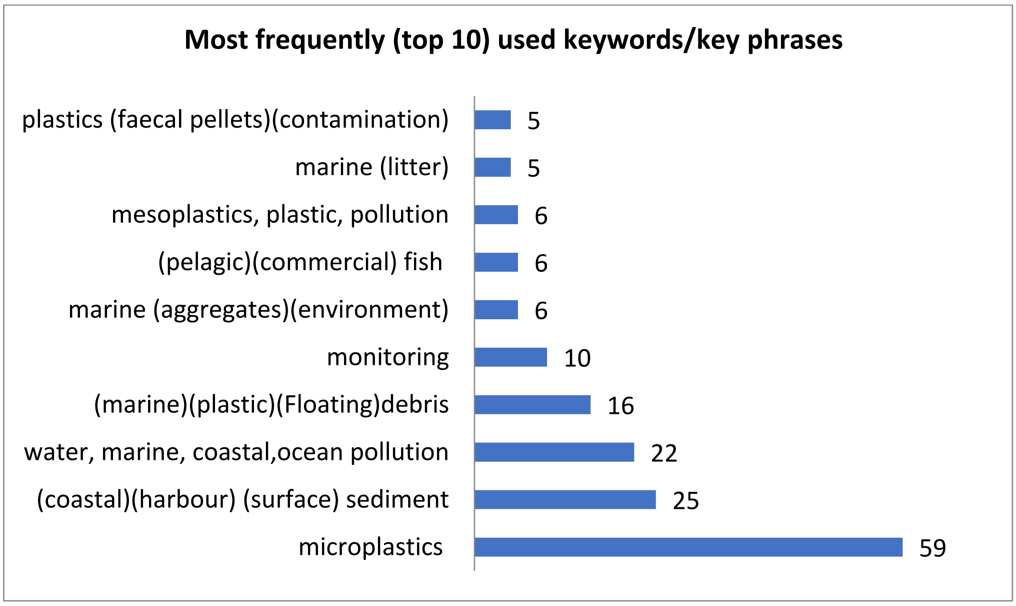


Figure 6. (Top ten) Most commonly used keywords (the numbers denote No. of papers).

Over the past few years, researchers studying microplastics in the marine environment from all over the world have advanced our knowledge in this area. The largest spatial clusters of institutions/universities researching on this topic are scattered throughout 26 countries, including the United States, Europe, and Asia, in addition to numerous additional smaller groupings in other parts of the world. China has, by far, contributed the most reviewers overall. According to Table 2, China, Germany, the UK, Brazil, and Italy had the most review articles published on microplastic pollution in harbors in the previous years. For one more time, as with the results of the meta-analysis before, these studies show that these areas place a high emphasis on addressing the environmental challenges caused by microplastic contamination in seawaters because they were carried out in both economically and less economically developed nations, as well as in densely populated areas.

Table 2. The nations with the most publications on microplastics in ports and coasts.

Country	Publications on Microplastics in Ports and Coasts (%)
China	17.2
Brazil	15.5
Italy	13.8
UK	12.0
Germany	10.3
Japan, India, Norway, Australia	8.6
New Zealand, South Korea	7.0
South Africa, USA, Netherlands	6.9
Indonesia, Spain, France, Iran	5.2
Russia, Kenya, Croatia, Peru, Malaysia, Portugal, Egypt	3.5

Studies on microplastics in the marine environment are published in numerous publications, many of which are recognized as having high impact factors. In eleven leading journals, many papers from the past ten years were found. According to Figure 7, the journals "Marine Pollution Bulletin", which focuses on marine pollution, and "Science of the Total Environment" have published the most studies on microplastics in marine environments during the past few years. The following periodicals are Environmental Pollution, Marine Environmental Research, and Case Studies in Chemical and Environmental

Engineering. This supported the claim that pollution in the maritime environment was one of the study's expanding focal areas.

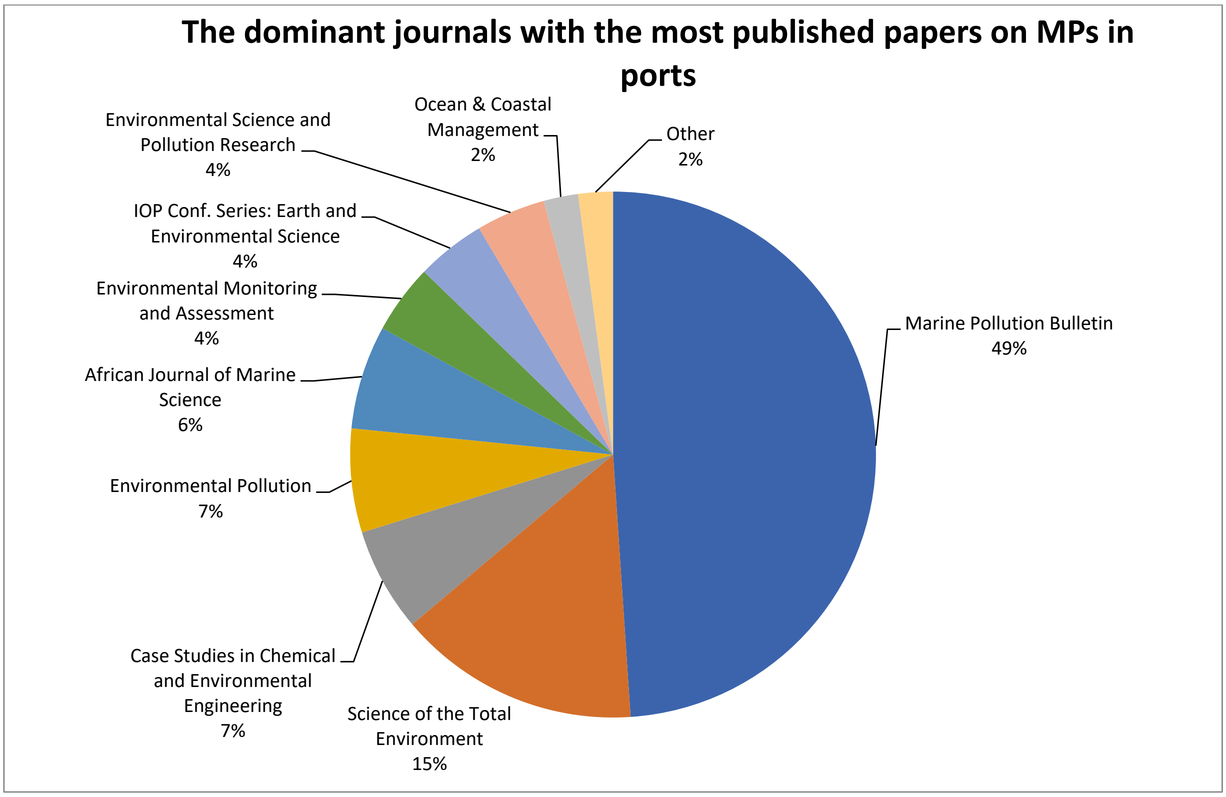


Figure 7. Journals with the most articles published on microplastics in ports and coasts.

In Table 3, all the results are gathered and the data for the microplastics are classified according to special criteria such as polymer type, shape, size of materials, pollution source, method of detection, and the studied location.

Table 3. Classification of microplastic (MP) samples in recent studies (abbreviations: PA: polyamide, PE: polyethylene, PET: poly(ethylene terephthalate), PMMA: poly(methyl methacrylate), PP: polypropylene, PS: polystyrene, PU: polyurethane, PVC: poly(vinyl chloride), LDPE: low-density polyethylene).

Polymer Types	Shape	Size	Color/Texture	Pollution Source	Method of Detection	Location/Area	Ref.
polyesters, PS, PA, PVC, PP, and PE	Fragments and filaments	5 mm	black or grey color	anthropogenic activities	ATR-FTIR analysis	Kuala Nerus coast and Kuantan port (Malaysia)	[60]
nylon, PU, PE, and PET	Filaments, fragments, and films	1–5 mm	range of colors	multiple sources	FTIR	port of Piombino, port of Portoferraio (Italy)	[61]
Polyester, PE, alkyd resins, and PS	Fibers, hard plastic, and paint particles	(<2 mm)	-	industrial facilities	FTIR	Southeastern coast Sea (Korea)	[28]
PP, LDPE, PE, PS, PA, PMMA, cellophane, and acrylonitrile	Granular shape and fibrous	125 µm–1.82 mm	-	anthropogenic activities, oil-rig installations, and shipping operations	ATR-FTIR	Qatar's Exclusive Economic Zone coast	[62]
resins	Fragments and foams	4–5 mm	-	industrial, commercial, and fishing activities	stereomicroscopy	Portuguese coast, fishing ports	[63]
rayon, PE, PP, PA, PET, PS, PMMA, and PU	Fibers, films, fragments, and pellet	<500 µm	-	river and sewage discharge and maritime activities, shipping	µ-FTIR	Sishili Bay, North Yellow Sea coast, China	[64]
PE, PP, and PET	Particles, pigments	200–34,900 µm	-	-	Raman spectroscopy, energy-dispersive X-ray spectroscopy (EDX)	Malaysian coasts	[65]
PP, PE, PS, and nylon	Filaments and fragments		blue, white, and red	anthropogenic activities	Raman spectroscopy	Kuwait coastal areas	[66]
Nylon, acrylic, and ionomer surlyn	Fibers, fragments, and pellets	>251 µm	-	anthropogenic activities, maritime activities	ATR-FTIR	Port Blair Bay, Andaman Islands, India	[67]
PE	Microcapsules and fragments	2–3 mm	various colors	fertilizers	FTIR and SEM	Japanese coast	[68]
PE, PP, alkyd resin polyester, polyolefins, polyester, PS, and PA	Fibers and fragments	5000 µm	-	-	FTIR	Vietnam coast	[69]

Table 3. *Cont.*

Polymer Types	Shape	Size	Color/Texture	Pollution Source	Method of Detection	Location/Area	Ref.
PE, PP, PS, and PET	Particles	5 mm	-	maritime activities	ATR-FTIR particle size analysis PSA	Port of Durban, South Africa	[30]
PE, HDPE, and PP	Microfibers and particles (mostly fragments and films)	-	transparent and blue	swimming, walking, playing with sand, seaside camping, and fishing	binocular microscope	Busher port coastline. Persian Gulf, Iran	[70]
PP, PE, and polyester	Fibers, fragments, spheres, films, and foams	0.25–5.0 mm	transparent, blue, yellow, black, and green	port activities and tourism economic activities	Raman	tropical bays (Manzanillo, Santiago, Navidad and Cuastecomates) of the central Mexican Pacific	[71]
Rayon and PET	Fibers, fragments, and films	5 mm, 1 mm, 300 µm, and 45 µm.	white, green, black, yellow, and red	human activities, fish and port activities	FTIR-ALPHBROKER-Platinum-ATR spectrometer	Damietta and Port Said, Red and Mediterranean seas, Egypt	[72]
alkyds, epoxy resins, poly(acrylate-styrene), and PU	Foams, hard plastic fragments, paint fragments, and pellets	1–5 mm	yellow, gray, and pink	urban and port activities, boat and ship coatings	optical stereomicroscope	Paranagua Estuarine port and coast, South Brazil	[73]
PE, PP, PET, polyester, nylon, PU, and resins	Filaments, fragments, granules, and spheres	63–1000 µm	white, black, blue, grey, and brown	fish and port activities	X-ray diffraction (XRD), µ-Raman spectroscopy	Genoa port and a fishpond, Italy	[74]
HDPE, PS, PP, and PET.	Lines, fragments, pellets, foams, and fibers	<5 mm	-	tourism, anthropogenic, and maritime activities	FTIR	Port Blair, coast of the Andaman and Nicobar Islands, India	[75]
PET, PP, and PE	Films	<300 µm	white	human activities	Stereomicroscope, FTIR	Vava'u archipelago coast, Tonga	[76]
Polyether PU, PE, PP, and PS	Foams, pellets, fragments, flakes, fibers, films, and sponges	<1 mm	transparent, white, and yellow	high-intensity human activities, mariculture, tourism, and port construction	ATR-FTIR, SEM	coastline in Shandong province, east China	[77]
PP, PE, and PET	Fibers and fragments	25–150 µm	black, red, and blue	port activities	Stereomicroscope, laser infrared imaging spectrometer	fishery port city in southern China	[78]

Table 3. *Cont.*

Polymer Types	Shape	Size	Color/Texture	Pollution Source	Method of Detection	Location/Area	Ref.
PP, PE paint, and epoxies	Fibers and fragments	100 µm–5 cm	yellow and blue	Marine coating (boat paint and epoxy)	stereo zoom microscope	coast of South Andaman Island, India	[79]
PET and nylon	Fibers and spherules	0.1–1 mm	white and black	fishing and fish processing activities along with intensive anthropogenic and industrial activities	FTIR	seaports (Port Jackson, Botany, Kembla, Newcastle, Yamba, and Eden) of New South Wales, Australia	[80]
PS and cellulose	Fibers, fragments, and films	~1 mm	black/grey and blue	anthropogenic influence, fisheries, industrial, and port activities	Raman spectroscopy	Ushuaia Bay, Argentina	[81]
PA, PE, PET, PP, and cellulose	Fibers and fragments	~1 mm	blue and transparent	industry—tourism, fishing, and shipping ports	FTIR	South Australian coastline	[82]
Nylon	Fibers	>1000 µm	black	landfill leachate	micro-Raman analysis	Bushehr port, Iran	[83]
PVC, PP, PE, PS, and PA	Fibers and fragments	100–500 µm	-	human activities	µ-FTIR	port of Rimini Adriatic Sea, Italy	[84]
PET, PP, PP-co-PE, alkyd, cellophane, PU, PA, and rayon	Lines and fragments	<1 mm	black and white	harbor, industrial, activity and populated, tourist, residential, and aquaculture area	FTIR	Tanmen Port, China	[85]
PP, PS, PET, PVC, and PE	Fibers, fragments, films, and beads	195–4780 µm	red, blue, black/brown, and transparent/white	Packaging, human activities, port and industrial, activity	ATR-FTIR and Micro-Raman spectroscopy	7 port Cities in China, Japan, South Korea, Sri Lanka, Taiwan, Thailand, and Vietnam	[86]
Polyester, PP, PE, PET, PS, PVC, nylon, and PU	Fibers, fragments, films, foams, and pellets	0.3–5 mm	white, transparent, and yellow	Fishing, human activities, construction of ships, insulating materials, fabrics. packaging	FTIR	Goa coast, India	[87]

Table 3. *Cont.*

Polymer Types	Shape	Size	Color/Texture	Pollution Source	Method of Detection	Location/Area	Ref.
PP, PS, PET, and PE	-	63–500 µm	-	tourism, anthropogenic, and maritime activities	-	New Zealand coasts	[88]
LDPE	Pellets and fragments	≤1 mm	white and transparent	Harbor activities	ATR-FTIR	Deep Bay, coast, Tolo Harbour, Tsing Yi coast and Victoria Harbour, Hong Kong, Japan	[89]
PE and PP	Fragments, fibers, foams, and micro-beads	~250 µm	transparent, opaque, white, black, blue, green, red, yellow, or multi-colored	Harbor activities	(FTIR)	Kingston Harbour, Jamaica	[90]
PE, PP, PS, PET, PA, and PVC	Fibers, fragments, spherules, and granules	0.1–0.5 mm	black, transparent, yellow, red, and blue	Harbor activities	Scanning electron microscopy/energy dispersive spectroscopy	Sanggou Bay, China	[91]
-	-	1–5 mm	-	tourism, anthropogenic, and maritime activities	-	Sile Port, Black Sea Coast, Istanbul, Turkey	[92]
-	Fibers, fragments, and micro-beads	-	brown, grey, semitransparent, and green	anthropogenic pollution	optical microscopy	Fishing port, coast of Peru and Chile	[93]
-	Pellets	-	white, yellowish, orange, brown, and pigmented	Loading in harbor areas and transport by ships	Visual classification	Port of Santos, Brazil	[94]
-	Fibers, fragments, and films	-	-	human activities	FTIR	Fishing Ports in Java Island, Indonesia	[95]
PE, PVC, PET, PS, and PP	-	<200 µm, 200–500 µm, and >500 µm	-	anthropogenic pollution	laser direct infrared (LDIR) technique	Mediterranean marine samples	[96]
Rayon, PET, PS, PE, and PP	Fibers, fragments, granules, and films	<1 mm	transparent, purple, brown, white, black, blue, and red	human activities	m-ATR-FTIR and SEM-EDS	Qingdao and Dongying, China	[97]

Table 3. *Cont.*

Polymer Types	Shape	Size	Color/Texture	Pollution Source	Method of Detection	Location/Area	Ref.
-	Fragments, foams, fibers, films, pellets, and filaments	1.6 ± 1.4 mm	-	human activities: packaging materials, and resins	-	Baseco Port Manila Bay, Philippines	[98]
Polychlorobiphenyls and PU	Fibers, fragments, Styrofoam, and pellets	<5 mm	yellow-brown, black, blue, red, and green	fishing and harbor activities	visual identification under a stereomicroscope	Guanabara Bay, Southeast Brazil	[99]
PP, PE, PS, PVC, PET, and PMMA	Fibers	~125 µm	-	Offshore, industries, and ports activities	pyrolysis–gas chromatography–mass spectrometry/thermochemolysis (Py-GC/MS)	German Bight North Sea, Germany	[100]
Nylon, PET, and PP	Fibers, filaments, and fragments	<5 mm	-	port, industries, and residents activities	light microscope	Dumai Port, Indonesia	[101]
-	Foam and Styrofoam pieces, rope pieces, and fibers	2 mm to 40 cm	-	Fishing, shipping, and touristic activities	visual sorting	Port of Cristo and Port of Colonia de Sant Jordi of the Island of Mallorca, Spain	[102]
-	Fibers, fragments, and films	500–5000 µm	black, green, red, purple, blue, transparent, and brown	Anthropogenic activities: shipping, plastic production, port activities, and sewage treatment	-	Tudor, Port Reitz, and Mida creeks, Kenya	[103]
-	Fibers, fragments, and films	-	-	Tourism and industry activities	Stereo Microscope	Kendari Archipelago Harbor, Indonesia	[104]
PVC and PET	Fibers, fragments, and nurdles	63–5000 µm	black and grey	Human activity and port activity	Bestscope dissecting microscope	Richard's Bay Harbour, Durban Harbour, South Africa	[105]
-	Fibers	<5 mm	red, yellow, black, pink, orange, purple, green, blue, and transparent	Human activities	dissecting microscope	Tudor, Port Reitz, and Mida creeks, Kenya	[106]
PP, PE, phenoxy resin, PS, polyester, and synthetic rubber	Fragments, spherules, and fibers	<1 mm	white, blue, green, and red	Harbor activities and ship paint resin	FTIR	Jinhae Bay, o southern coast of Korea	[107]

Table 3. *Cont.*

Polymer Types	Shape	Size	Color/Texture	Pollution Source	Method of Detection	Location/Area	Ref.
-	Fragments and pellets	<1 mm	white, blue, brown, and green	Port facilities	stereomicroscope	Northeast coast of Brazil	[108]
PCBs	Filaments	<5 mm	-	Port activities	stereomicroscope	Grand Harbour Valletta, Malta	[109]
PVC, rayon, PE, polyester, PS, and cellulose	Fibers, pellets, and plastic fragments	-	black, blue, or white	fishers and maritime ports activities	FTIR	coast of Asturias, Spain	[110]
alkyds and poly(acrylate-styrene)	Fragments, spherules, and fibers	<1 mm	green, blue, and white	Harbor activities, ship paint resin, and ship coatings	FTIR	southern coast of Korea	[111]
PS, PE, and PP	Microbeads and pellets	<1 mm; 1–2 mm; or 2–5 mm	white, transparent, red, blue, and green	estuarine and harbor environments	optical/fluorescence imaging and micro-Raman spectroscopy	coastlines in the Canterbury region of New Zealand	[112]
PE and PP	Fragments and pellets	1–5 mm	-	human activities	FTIR	Bristol Channel, UK	[113]
PP-co-PE, PA, PE, PET, PP, and PVC	Fibers, thin films, and fragments	<0.5 mm	blue, black, red, yellow, green, and white	marine fishery and port transportation	FTIR	Tianjin coastal waters, China	[114]

6. Results and Discussion

6.1. Sources, Fate, and Route, Transfer

Marine litter is the outcome of careless garbage dumping that is carried either directly or indirectly to our seas and oceans. We examine many sources of plastic waste and talk about both direct and indirect ways that plastic might reach the marine environment in this part. Although the focus of this review is on microplastics, in this section, we also take into account the careless disposal of macroplastics because, over time, they may break down into secondary microplastics [17,115]. Similar to this, synthetic garment fibers cause shedding in microplastics, which are washed into wastewater or water treatment facilities as effluents [27].

Some notable amount of the plastics in marine litter comes from terrestrial sources. These plastics include the major microplastics used in cosmetics and air-blasting, as well as "user" plastics that were incorrectly disposed of and plastic leachates from landfills. Certain types of plastic have a significant potential to infiltrate the marine environment through rivers and wastewater systems or by being blown off-shore because over half of the world's population lives within fifty miles of the coast [14,16,116].

In oxidation ponds or sewage sludge, waste-water treatment facilities will catch macroplastics and some small plastic debris; however, a considerable amount of microplastics will slip through these filtration systems. This transport of terrestrial waste from land to water can be made worse by extreme weather events such as hurricanes or flash flooding [7]. After the original debris that entered the ocean lost its structural integrity, physical forces such as surface waves, turbulence of the water currents, etc., are also thought to be important drivers of fragmentation [7,9]. Road marking paints degrade and release chemicals depending on their composition, where they are placed (in the middle of the road or on the edge), how much traffic they receive, and finally, the climatology of the area [22].

Coastal tourism, commercial and recreational fishing, marine boats, and marine industries are all sources of plastic that can enter the marine environment directly and end up as secondary microplastics after long-term degradation, endangering the biota. While it is important to note that marine debris visible on beaches also results from the beaching of materials carried on in-shore- and ocean currents, tourism and recreational activities are responsible for a variety of plastics being thrown along beaches and coastal resorts [19,116].

The production of plastic goods using granules and tiny resin pellets, or "nibs", as its basic material is another noteworthy source of plastic waste. These raw materials have the potential to enter aquatic environments through unintentional spillage during transport—on land as well as at sea—inappropriate usage as packing material, and direct outflow from processing facilities [14,42]. Boats and ships are typically regarded as the main contributors of paint shards in the waters; however, stationary buildings such as piers and oil rigs also contribute. Synthetic polymers, such as alkyds, epoxy resins, poly(acrylate/styrene), and polyurethane, are frequently found in protective coatings used on ship hulls and superstructures because they are relatively durable and long-lasting. They eventually raise the microplastic content of the water when they are abrasively removed [37]. Microplastics may also be created during painting spills or during dry dock painting [111].

Microplastics are found in a wide variety of marine creatures, including seabirds, fish, bivalves, mammals, and crabs, as well as on beaches, in seabed sediments, and in surface waters. Microplastics may enter the oceans through zooplankton excrement as a different entry point [117]. A study from Cole et al. proved that fecal pellets are a source of microplastics in the marine environment by showing that they can be indirectly swallowed through the eating of fecal pellets [14,118].

Moreover, sea-based sources include the deliberate or unintentional loss of plastic products into the ecosystem, as in the instance of discarded fishing gear [8]. Microplastics are a byproduct of packaging and single-use plastic bags, which are often used in daily life [27]. Particularly as a result of the COVID-19 outbreak, an excessive amount of plastic waste—including bottles for hand sanitizer, surgical gloves, and face masks—is being produced quickly [119]. In Figure 8, the most dominant sources of microplastics are presented.

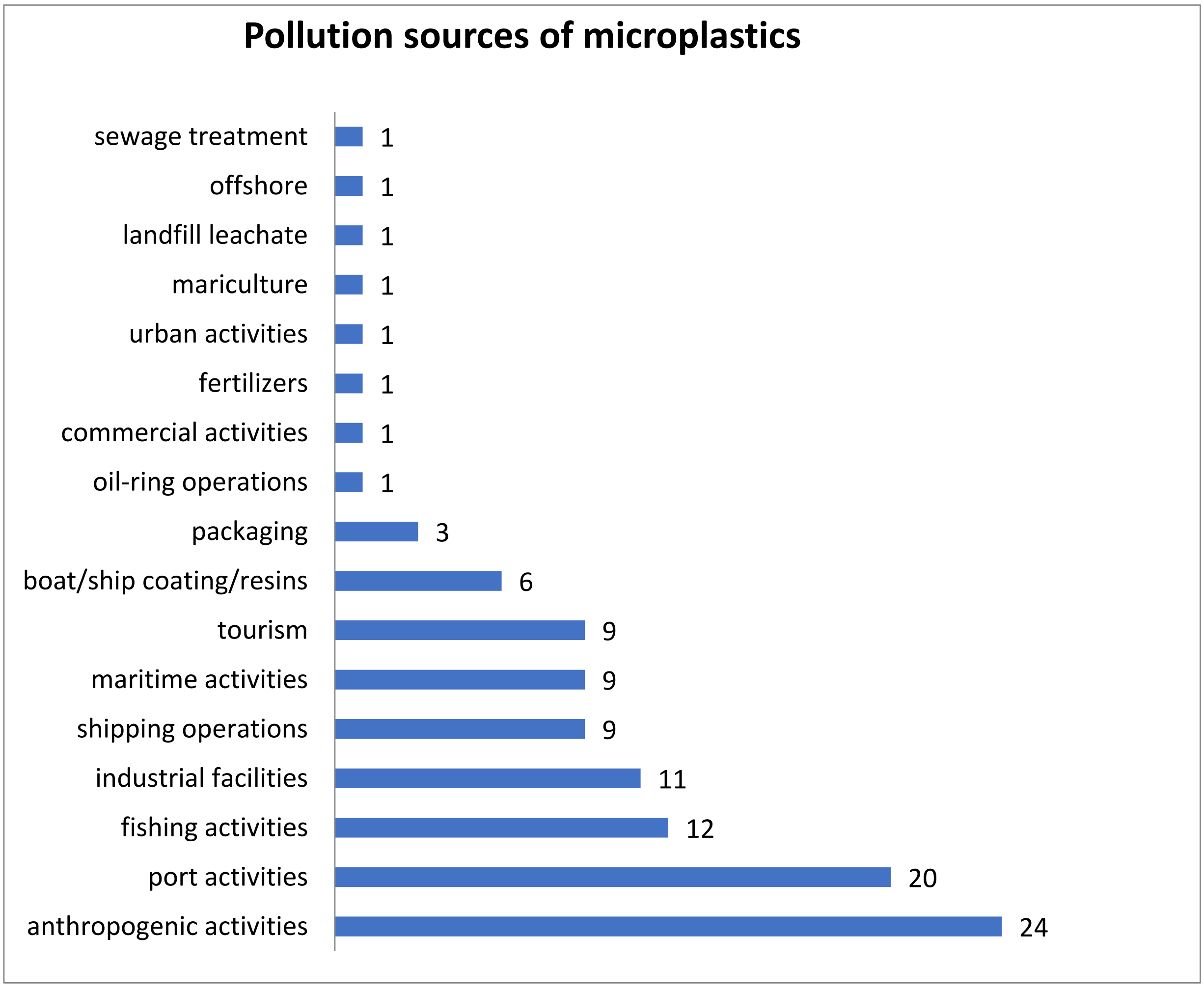


Figure 8. Most dominant sources of microplastics.

Last but not least, the disintegration of plastics is aided by the oxidative deterioration brought on by UV radiation and high temperatures. However, it will take hundreds or thousands of years for the plastic particles in the environment to entirely mineralize, not within a short period of time [120]. In general, hydrological features, such as seasonal fluctuations in water velocity, depth, and flow, have an impact on the transportation of microplastics in the aquatic environment [121,122]. UV light's radiation strength can fluctuate in addition to its spectrum of wavelengths. Location, season, time of day, and weather on the Earth's surface all affect how intense the radiation is. The closer a site is to the equator, the higher the average UV radiation intensity [123,124].

In most cases, trash in any body of water will eventually reach the ocean. Microplastics are slowly migrated and diffused across the ocean by the strength of water and wind, eventually becoming as common as they are now, ranging from the vast ocean gyres. The ecosystems most severely impacted by microplastic pollution include marine circulation, estuaries, and other coastal areas where humans are involved [58,125,126].

6.2. Methods of Detection/Identification/Characterization

An appropriate analytical method is crucial for MP investigations, according to Song et al., who pointed out that compared to Fourier transform infrared spectroscopy (FTIR) identification, conventional stereomicroscope identification might both underestimate and overestimate the number of MPs in a combination. Although there are alternative techniques such as pyrolysis GC-MS, microFTIR and microRaman spectroscopy are the most frequently utilized. Evidently, in some studies, researchers employed the best approach, which entails using a range of strategies to overcome the limitations of individual methodologies [36,127].

Direct light microscopy is traditionally used to examine microplastics that are taken from the environment, choosing and categorizing particles by their form, size, and color [42,107]. In some investigations, researchers used the most effective strategy, which calls for utilizing a variety of tactics to surpass the constraints of unique approaches [37].

A frequently employed method for investigating the bigger particle masses is optical microscopy. This technique enables the separation of microplastics from the contaminating ambiguous mass and permits the analysis of surface roughness [126]. With all these shortcomings of conventional optical microscopy, scanning electron microscopy (SEM) can offer a considerably sharper image. We can easily distinguish between organic and plastic particles due to the high resolution of electron microscopy [6,36].

The use of Fourier transform infrared (FTIR) spectroscopy as a tool for microplastic characterization has also proven to be quite beneficial and was used in the majority of the reviewed studies. Each polymer creates a distinct set of spectroscopic band signatures that enable discrimination between plastics, as well as between plastics and organic material. The identification of polymers is made simple by a properly constructed and comprehensive database of available standard spectroscopic data for the various plastic polymers. The option of microFTIR (-FTIR) may be employed when samples with very small particle sizes are available. In order to analyze MPs, phenomena including attenuated total internal reflectance (ATR), transmission, and reflectance modes are utilized as IR spectroscope operational modes [36,111].

In addition to using FTIR, many of the investigations mentioned above have also used Raman spectroscopy to identify MPs. In contrast to FTIR, which only permits the identification of the polymer, Raman spectroscopy provides a composition of the polymers in addition to identifying the plastic. Given the high expense of the equipment, Raman spectroscopy also provides a comparable tool for identification to the FTIR. It is possible to employ FTIR and Raman spectroscopy in conjunction with one another. The Raman Spectroscope's extremely narrow slit beam makes it feasible to characterize particles with sizes as small as a few microns using the Raman spectroscopy methods [36,128].

However, in some studies, the identification made by the selective sampling in situ refers to the collection of plastic trash from the sandy beach surface that can typically be seen with the unaided/naked eye. Due to their spherical shape and relatively big sizes (up to several millimeters), which make it easier to identify them on a sandy surface, plastic granules are a good candidate for this technique. The likelihood of missing plastic, however, increases if it is combined with other trash or has an odd shape [129].

Regarding their collection, microplastics from surface seawater were often gathered for samples using trawls, nets, pumps, and stainless-steel equipment. Moreover, glass bottles are frequently used to collect surface seawater samples. Plastic buckets are also common collection tools. Some of the several sampling locations are coastal regions and open sea regions. Sediments are collected using stainless steel samplers, foil bags, or glass bottles as sampling equipment. Fish were the most often employed research target in all of these investigations, and the sample methods used differed depending on the different organisms [40].

In general, a number of sample processing procedures, including sieving, density separation, purification, filtration, and visual sorting, are used in the determination of MP abundance and type. Following these procedures, the Fourier transform infrared spectroscopy (FTIR) or Raman quantification and identification process is carried out [40,52]. Figure 9 shows the different detection methods and how often they are used.

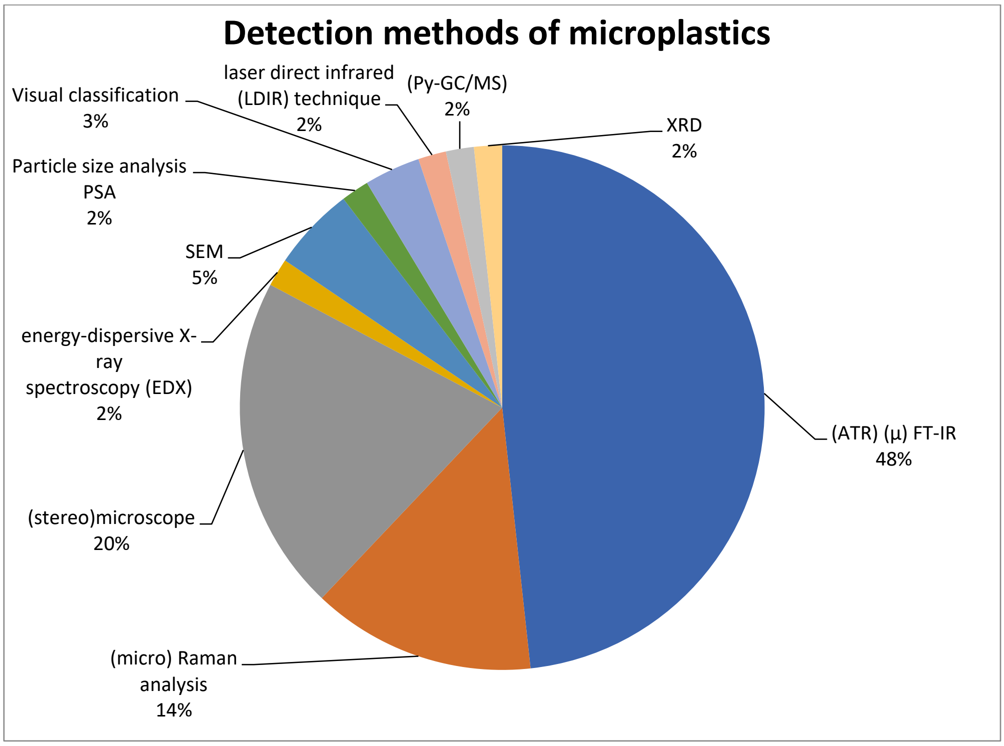


Figure 9. Detection methods of microplastics.

6.3. Status of Microplastics (Size, Shape, Color, Polymer Type)

6.3.1. Polymer Type

In maritime ecosystems, microplastics mostly consist of PE, PP, PS, PVC, PA, and PET. PE and PP are typically floating microplastics because of their lower densities than water [8]. Because they are denser than water, PVC, PS, PET, and PA have a tendency to sink in the water column. It is clear from the categorization of the original publications and the review papers that microplastics are frequently found in inland lakes, estuaries, oceans, ports, and beaches. There is evidence that surface water contains more microplastics than the water column does. There are more small microplastics (0.02–1 mm) than large ones (1–5 mm) [35].

The degradation of plastic polymers occurs as a result of numerous weathering/aging processes that microplastics go through in marine and coastal environments, including sun exposure, thermal aging, biofilm formation, and oxidation [130]. According to the various weathering processes, degradation is defined as a series of chemical reactions that destroy the structural integrity of plastic polymers. It is frequently divided into photodegradation, thermal degradation, biodegradation, and thermos-oxidative degradation. Degradation causes secondary microplastics to enter the environment and fragments of macroscopic plastic debris to become garbage [131]. The key characteristics that are altered by degradation are their color, surface morphology, crystallinity, particle size, and density [35].

In this review, analyzing the polymer type of microplastics helps confirm the polymer composition of questionable materials and confirm the precision of visual recognition. For determining the polymer type of microplastics, infrared (IR), Fourier transform infrared (FTIR), and Raman spectrometers were utilized. Instrumental analysis was used to determine the polymer type of MPs in most of the harbors. Polypropylene (PP), polyethylene (PE), polystyrene (PS), and polyethylene terephthalate (PET) were the most common polymer compositions. Specifically, PET is a significant class of synthetic polymer that is frequently utilized in textiles and packaging. Moreover, several unusual polymers such as nylon, rayon, polyurethane (PU), and polyvinyl chloride (PVC), among others, could be found. The graph below (Figure 10) gathers all the results of the classification.

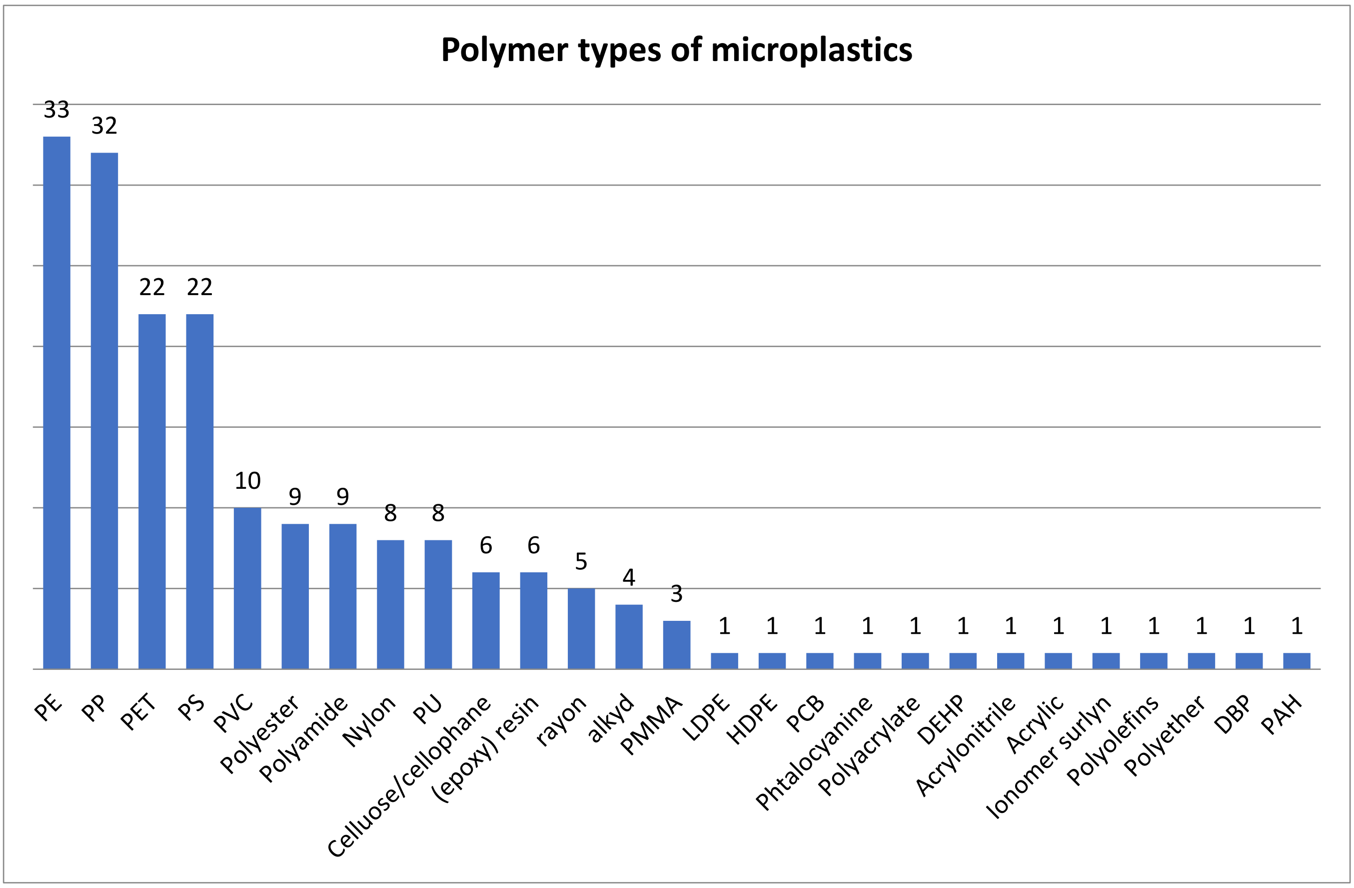


Figure 10. Different polymer types found in sediments and samples numbers show the frequency of every type.

6.3.2. Size

The bulk of the microplastics were thought to be between 0.001 and 5 mm in diameter. The statistics derived from our analysis show that the mesh size, sieve apertures, or filter pore sizes utilized throughout the collection and extraction processes—which ranged from 0.001 to 0.5 mm—determined the smallest size. In general, distinct size fractions can be identified based on the properties of the size distribution of microplastics. The maximum length of each particle or the mesh sizes of a cascade of screens employed during MPs extraction were also used to determine the size category [9,40,91].

6.3.3. Shape

The shapes of microplastics range from amorphous to spherical and long, thin strands, and all of them are shown in Figure 11. Plastic pellets come in a variety of shapes, primarily spherical to ovoid with rounded ends, but they can also be tablet-like, oblong, cylindrical, spherical, and disk-shaped [52]. Pellets, fragments, fibers, films, granules, flakes, ropes, microbeads, sponges, foams, lines, and particles were the most common categories for nanoplastics [35]. The morphologies of microplastics were present in all 75 test sites and included fibers, pieces, films, pellets, foams, sponges, lines, and particles. Regardless of the various sampling sites, the classification results demonstrate that fibers, pieces, films, and pellets were the predominant morphologies.

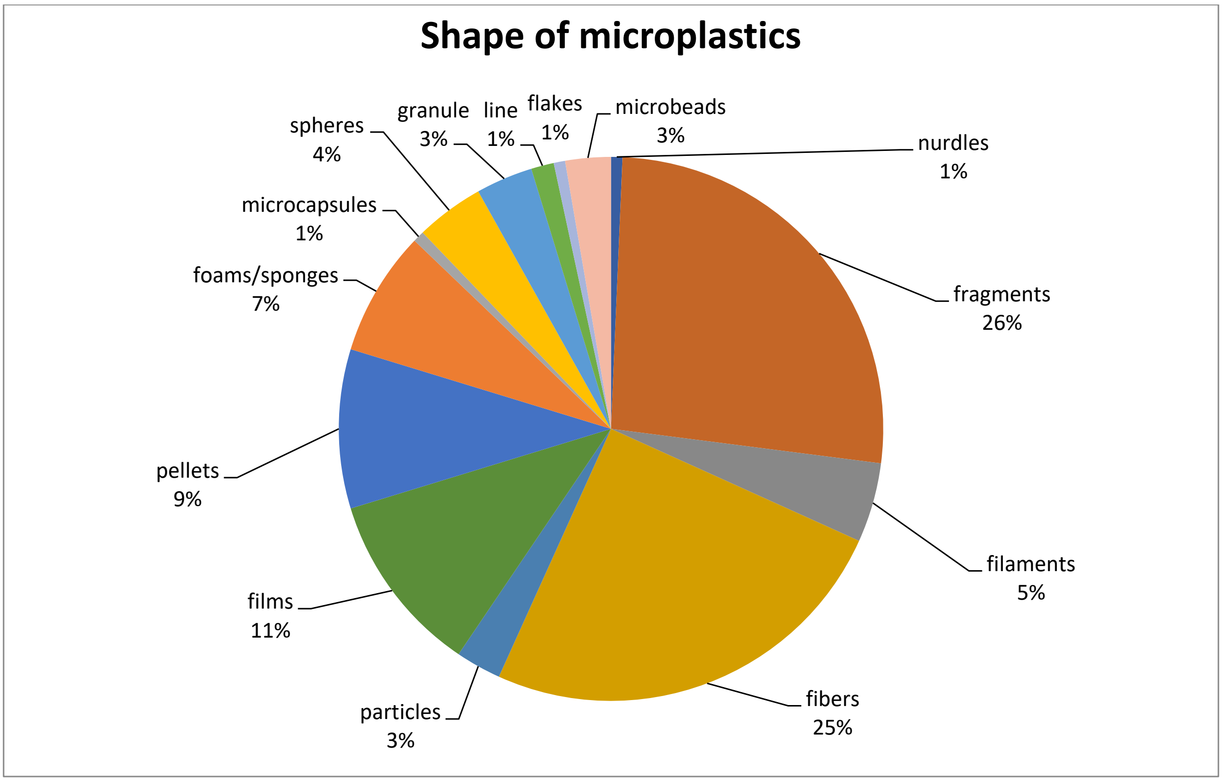


Figure 11. Shapes of microplastics.

6.3.4. Color

Color classification of the microplastics' source is crucial and presented in Figure 12. In circumstances when microplastics are dispersed among numerous different pieces of detritus, color can help with sorting. As opposed to those with dull hues, which are readily missed and may introduce bias, eye-catching particles have a high possibility of being isolated for later detection as microplastics. For a preliminary identification of the chemical make-up of the most popular pellets, colors were used [52]. For instance, blue and green fibers typically come from clothing and fishing nets. Transparent, black, white, red, yellow, blue, green, gray, and brown were the most prevalent microplastic colors among the 75 sampling locations that examined the finds' color. Brightly stained and pigmented MPs can be seen and identified visually. Nonetheless, it is possible to undervalue the problem if transparent microplastics are neglected. In addition, marine species may recognize colored microplastics more readily than transparent ones [40,132].

6.4. Ecological Risk

Microplastics with densities greater than seawater collect in sediments, while those with densities below seawater float on the water's surface. Microplastics may sink due to an increase in density brought on by biofouling by marine creatures [133,134]. As the density of the plastic material exceeds that of seawater, which happens when biofouling develops, the plastic material sinks to the bottom of the ocean [8]. Marine sediments are shown to be long-term sinks for microplastics and have the capacity to accumulate small pieces of plastic [27]. Microplastics are known to accumulate in deep sea regions, underwater canyons, and marine coastal shallow deposits [133].

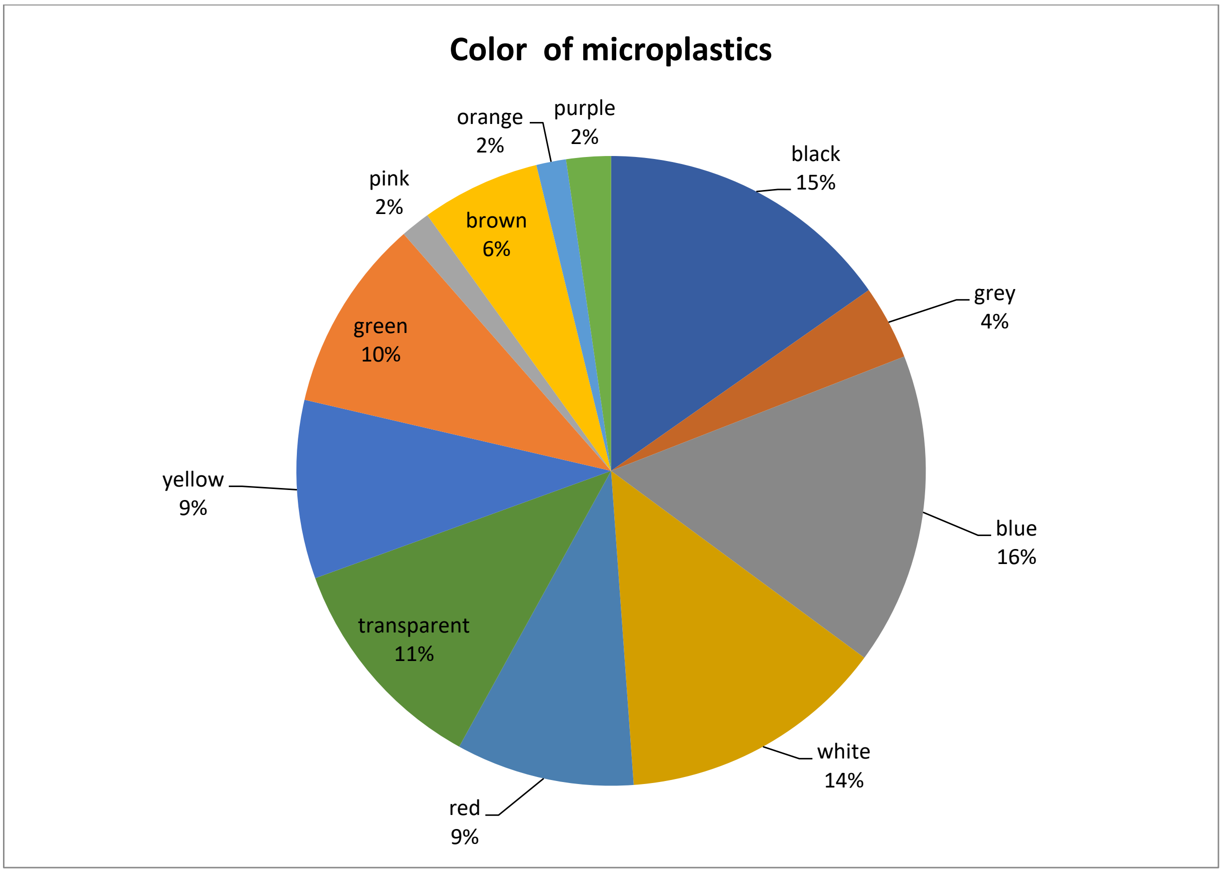


Figure 12. Colors of microplastics.

Microplastics are becoming more bioavailable to marine life as their quantity rises. These microscopic plastic particles' potential bioavailability to marine animals depends on their color, density, shape, size, charge, aggregation, and abundance. When consumed by marine species, microplastics injure them chemically and physically [135]. The intake of microplastics by marine species may have chemical or mechanical impacts, such as inflammation, hepatic stress, or diminished growth. Mechanical implications include the polymer attaching to external surfaces and impeding motility and blocking the digestive tract [27,136].

Research has revealed the presence of compounds that are used to make plastic in fish tissues. While hazardous substances from various sources can accumulate in the organism, predator–prey interactions facilitate the transfer of the toxins in higher quantities. Laboratory studies to show the effects of microplastics on marine biota were conducted as a result of worries about the movement of microplastics and dangerous substances between trophic levels [8,41]. Several studies were also conducted to demonstrate that fish are at risk from ingesting microplastics since mortality occurs frequently before fish reach maturity [27].

Although it is clear that microplastics are pervasive and widespread, the knowledge of the biological effects of this pollution on marine organisms is still in its infancy [9,24]. The scientific worry about the prospect that microplastics, which are available to a variety of marine species due to their small size, could be harmful to biota is growing [14].

Marine species, including zooplankton, mussels, oysters, corals, fish, etc., may consume microplastics that are present in the environment. Once consumed by marine species, microplastics pose dangers to those organisms. Microplastics cause mechanical harm to organisms on a physical level. Microplastics, for instance, may obstruct the digestive tract, harm the intestinal lining, and even change how organisms filter substances and engage in phagocytosis [35].

Moreover, predation may cause microplastics to accumulate in the food chain. Microplastics can, therefore, accumulate in organisms through a variety of different pathways. Microplastics in seafood, a source of protein, may also pose health hazards to people. Chemically, contaminants would be absorbed and accumulated by microplastics in aquatic environments. In this way, microplastics serve as carriers for hazardous contaminants. However, there is still no conclusive proof of the link between microplastics and pollutants in the food chain and human health. Microplastics are nevertheless significant transporters of pollutants to marine animals, and under some circumstances, they may collect more contaminants in the environment than other media [35,137].

The effects of paint MPs on the biota are not well studied. It is possible to anticipate that both MP kinds acting physically have an identical impact on the impacted species. The presence of MPs in cormorant chicks was most likely caused by transfer from fish that the mother birds had consumed, according to one of the rare studies on MPs in animals in which paint particles were detected. However, MPs from antifouling paints exhibit enhanced toxicity not only when they come into touch with organisms but also when they release their toxins into the environment. At pleasure boat harbors, where many of the toxins found were reportedly connected to paint additives, the ecotoxicological consequences of sediments are investigated. Romeo et al. discovered that a site near grit-blasting activities was the most polluted with heavy metals (particularly Pb, Cu, and Zn) and organotins in their relatively detailed investigation of microplastic pollution in the Grand Harbour in Valetta, Malta. Since the port is near busy shipping lanes, they assumed that this was a result of the heavy maritime traffic [37,109,138]. In other words, the toxicity of the paint particle itself may be increased by the emission of potentially harmful metals from boat paints, such as Cu, Zn, Sn, and Pb, which raises environmental issues in port and maritime areas. With their mobilization into the water above and encouragement of antifouling paint burial, deposit feeders may be able to contribute to the chemical cycle of compounds related to antifouling paints [46].

As in other environments, the amount of MP pollution in the environmental compartments (i.e., the water, sediments, and organisms) of coastal lagoons varies depending on the proximity to and the intensity of the pollution sources, which typically include subpar waste management techniques for both residential and industrial waste, as well as tourism, fishing, aquaculture, port activities, and river discharges, among other things [44]. The creature class in which MPs were most extensively researched in coastal lagoons, as well as other marine, estuarine, and freshwater habitats, is fish. Fish from coastal lagoons had higher MP abundances in their digestive tracts than fish from bays, estuaries, lakes, rivers, and the open ocean [139,140].

6.5. Monitoring Microplastics

All varieties of marine species suffer from plastic garbage. Many marine animals, such as cetaceans, seabirds, sea turtles, fish, and invertebrates, consume and accumulate plastic waste and microplastics, or they become entangled in plastic fibers. Different studies have now revealed that ingestion and/or entanglement are the main ways that marine wildlife is exposed to plastic trash. This is in line with early observations that suggested a correlation between the amount of plastic ingested by seabirds and their physical states [19]. Following that, studies revealed that scientists were using marine creatures more and more as sentinel organisms to keep an eye on marine plastic waste. Seabirds, for instance, serve as an effective sentinel to track the increase in marine plastic trash contamination [141].

Early in the 1990s, the emphasis of study moved from describing these effects to coming up with answers to the "problem" of marine trash [142]. The effectiveness of mitigation strategies intended to lessen the amount of waste plastic entering the environment can only be evaluated by detecting a change in the volumes and types of debris [19]. Although there are presently no international guidelines for levels of plastic contamination, monitoring can also be used to assure compliance with requirements, such as those levels of microplastics in seafood remaining below acceptable ranges [143].

Marine spatial planning (MSP) is an effective method for observing marine litter. MSP has gained recognition for its emphasis on the financial aspects of marine conservation in addition to its potential to promote sustainability in the marine ecosystem. In order to enable policy makers and strategy planners to take economic factors into account before planning on environmental objectives, this dichotomous role ensures that MSP use is specialized both in environmental and economic aims [48,144].

Microplastics' quantity, distribution, and characteristics in many worldwide ecosystems require statistical monitoring and evaluation based on accepted standards or criteria. Environmental monitoring can investigate and assess the sorption characteristics of microplastics, their impact on marine species, and their interactions with other contaminants. Environmental monitoring has recently researched the amounts of contaminants on microplastics in marine and coastal habitats around the world [35]. Standardized monitoring is necessary to determine whether or not plastic contamination of the seafloor is rising and whether it is having an impact on the marine ecosystem in order to better understand plastic accumulation on the seafloor [53].

The effectiveness of implemented measures to reduce the abundance of plastic debris must be monitored, but this is difficult due to the large spatial and temporal heterogeneity in the amounts of plastic debris and due to our incomplete knowledge of the pathways taken by plastic debris and its long-term fate. The majority of monitoring up to this point has centered on beach cleanups of stranded plastic and other trash. Crude estimates of debris kinds and abundance are provided by infrequent surveys of the standing stock of trash on beaches, but they are biased by the varying rates at which trash is removed by beachcombing, cleanups, and beach dynamics. Although it is expensive to do, monitoring the buildup of stranded trash gives an index of trends in debris in nearby seas [17].

Large amounts of monitoring data and simulation data could be gathered to update the MP abundance in sediments that were previously expected to have no influence. To examine the biotoxicity of various polymers, further monitoring and simulation data may also be gathered. In fact, analytical indicators must be added to increase the precision of the study of the sources of microplastic pollution [145]. To establish a connection between the analysis indicators and the sources of microplastic contamination, there must be enough monitoring data. The development of a method for analyzing the sources of microplastic contamination is crucial for preventing their pollution of sediments. To lessen the release of microplastics from pollution sources, managers can create tailored pollution management methods. Thus, it is necessary to perform ongoing monitoring in order to gain a comprehensive understanding of microplastics pollution [38].

Ryan et al. suggested that monitoring is crucial for determining whether mitigation efforts to lower the amount of waste plastic entering the environment are successful in the context of managing marine anthropogenic debris. It is necessary to evaluate whether mitigating strategies to lower waste plastics at sea are having an impact. The ideal place to monitor plastic leakage from land-based sources is on land (for example, in storm drains and river run-off). This will prevent the plastic from entering the ocean. The greatest way to combat illegal ship dumping is to keep an eye on how port garbage reception facilities are used. Fish and other invertebrates can serve as bioindicators for bigger microplastic pieces in sampling plastic consumed by biota [50].

Monitoring plastic interactions with biota can be a useful strategy, especially if the interactions take into account exposure to plastics over time and geography (such as plastic ingestion by animals that frequently store ingested plastic for long periods of time) [146]. The percentages of biota that consume plastic, become entangled in marine trash, or use plastic to create structures or shelters (such as seabird nests, hermit crabs, tube-building annelids, and echinoderms) are among the parameters that can be tracked. It is also possible to monitor plastic-related contamination levels, which may directly affect people's health. The large range of potential interactions is one of the difficulties in monitoring through biota [50,147]. Monitoring interactions with biota (such as plastic ingestion by some species and trash in seabird nests) might be a helpful and affordable auxiliary for tracking ecological impacts in the area [50].

Given the considerable geographical and temporal heterogeneity, at-sea sampling requires large sample numbers in order to have statistical power to detect changes in abundance. Another strategy is to keep an eye on the effects of plastics. A practical technique that Ryan et al. suggest to track the amount and make-up of tiny plastic trash is to use seabirds and other marine creatures that store plastics in their stomachs. Because they are sensitive to changes in the population numbers of the affected species, changes in entanglement rates are more difficult to assess. Because it identifies the primary sources of plastic debris entering the sea and can guide mitigation measures, monitoring garbage disposal on ships and plastic debris levels in rivers and storm-water runoff is useful [17].

Monitoring was used in different cases with positive results. A characteristic example is that when Gorokhova et al. used monitoring in their study, they managed to demonstrate the heterogeneity in the distribution of microplastics caused by biotic and abiotic factors and to propose the use of samples gathered for other purposes for measuring the amount of microplastics in the Baltic Sea, making it easier to incorporate the evaluation of microplastics into current monitoring programs [148]. Zhang et al. suggested an alternate strategy to routinely monitoring microplastics in all environmental media in order to gain a better knowledge of their quantity, distribution, and accumulation to reduce potential dangers in the future. Environmental policy-makers can use the results to monitor microplastic pollutants while also addressing the urgent need to comprehend the spatiotemporal pattern of microplastic pollution [31]. Another study from Valente et al. presents results from an Italian pilot operation to examine the appropriateness of a monitoring method based on a multispecies approach, indicating a connection between the bioavailability of microplastics and the distance from cities and river flows. Furthermore, the eating habits of the species under study had an impact on microplastic intake [149]. A paper from Bauerlein et al. provided a microplastic monitoring and data analysis approach that may be employed with the Marine Strategy Framework Directive (MSFD) and OSPAR policy framework. By choosing areas with little microspatial variation, it offers a chance to improve the sensitivity of trend detection in microplastic monitoring networks [32]. According to a different study, Mytilus species are suited for monitoring MPs in coastal waters on a semi-quantitative and qualitative basis. However, several questions remain, such as the impact of depuration and other processes connected to fate, the size of the mussel as a confounding factor that may affect swallowing, and this calls for additional investigation [150]. Bivalves are beneficial bioindicators of microplastic contamination in the marine environment for a number of reasons; therefore, a study was conducted that monitored microplastic pollution across the whole Korean coastline. Cho et al., in their study, used filter-feeding bivalves as bioindicators to determine the extent of national contamination and the properties of microplastics, including oyster, mussel, and Manila clam [151]. Last but not least, three different types of mussels were used in a study made by Staichak et al. to look into the filtration and prevalence of microplastic in them. The soft tissues, feces, and pseudofeces of bivalves were found to contain several types of microplastics. All three of the investigated bivalve species have demonstrated the potential to be employed in monitoring programs for various forms of microplastic in aquatic habitats with various salinity levels [152].

All in all, it is generally suggested that future studies on microplastic pollution in coastal lagoons concentrate on methodological issues, pollution assessment and monitoring, the dynamics and effects of microplastic pollution, and preventative strategies as part of effective environmental management [44]. Many authors emphasize the necessity of routine microplastic monitoring in order to establish reliable time series on their prevalence, traits, and sources. Understanding how microplastics cycle in coastal lagoons and how long they stay there—whether for a few days, many months, or decades—requires an understanding of the differences in their composition and concentration in sediments from various sub-environments [44]. Beach and coastal lagoons surveys can be used to learn more about the origins of plastic waste by choosing beaches that are various distances from the main sources of litter. In order to gauge the amount of trash at sea, the monitoring of stranded litter should focus on determining the rate at which debris accumulates on beaches [17]. A Technical Group on Marine Litter (TGML) was established by the European Commission as part of the MSFD Joint Implementation Strategy. The Guideline on Monitoring of Marine Litter in European Waters, one of the documents created by this organization, offers the European Union's member states advice on how to implement the same tactics for microplastics examination in a maritime environment [153].

6.6. Legislation

Many regional and international initiatives were created to prevent microplastics contamination. For instance, the United Nations Environment Organization had started a global campaign to limit the excessive use of single-use plastic by 2022 and eradicate the main causes of marine plastic litter, such as microplastics in cosmetics [47].

The 1978 Protocol to the International Convention for the Preservation of Pollution from Ships (MARPOL), which forbids or prohibits all vessels from disposing of their waste of plastic origin into the marine environment, is the most significant piece of legislation in place addressing the issue of marine pollution [154]. Moreover, the Manila Declaration was accepted in 2012 by 64 nations, including the European Union, with the goal of putting into practice the UN Global Program of Action for the Preservation of the Maritime Environment from Land-based Sources. The parties to this declaration also decided to create the Global Partnership on Marine Litter (GPML), whose major objective is to encompass sources of marine debris that are located at sea [55,155].

To lower their environmental levels, the member states of Europe must monitor microplastics and support research activities under the Horizon 2020 program [156,157]. In January 2018, the EU established the European Plastics Strategy. It focuses on how plastic goods are conceived, used, produced, and recycled in the EU and proposes innovative life-cycle economy and life-cycle evaluation methodologies. The EU has also emphasized the need for action to protect the Mediterranean Sea, a partially isolated body of water with significant contamination from the land. Due mostly to resource overuse and climate change, the Mediterranean Sea is critically contaminated [47].

The relevant regulation needs to be reinforced if marine plastic pollution is to be solved and reduced. Internationally, the Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal (also known as the Basel Convention) was established in 1989 to control the transboundary movement of hazardous waste and to regulate how those wastes are disposed of. In addition, the Basel Convention modifications that were ratified in a number of nations in 2019 showed that plastic trash would be classified as the subject of import and export restrictions, supporting the expansion of the plastic waste recycling business globally. Japan, South Korea, the United States, Indonesia, Canada, and Australia were the nations that drafted the relevant legislation [40,158,159].

6.7. Gaps

Many gaps still need to be filled despite the abundance of related studies, especially those pertaining to the origin, movement, interactions, and destiny of microplastics in the marine environment [14]. It is necessary to create more suitable indicators for assessing the ecological risk of microplastics. Furthermore, the weight coefficients of different indicators in the system for assessing the ecological danger of microplastics should be quantified [38].

It is crucial to use a precise and uniform size definition for microplastics, more effectively compare the findings from various study sites, and optimize and adopt routine, high-throughput microplastic sampling procedures. Additionally, it is important to increase the understanding of microplastic behavior and fate, especially the impact of fragmentation and biofouling; find out how eating microplastics affects marine biota in terms of death, illness, and/or reproduction; and comprehend how this contaminant moves up the food chain [14].

As we do not know enough about turnover rates in any environmental compartment to interpret changes in input rates from standing stock assessments, monitoring should instead estimate flows of materials rather than standing stocks. Sampling at sea or on beaches is not the most straightforward approach to keep track of leakage from either land-based or ship-based sources, so there is more uncertainty about the relationship between action and response. As close to the leak as is practical should be used to monitor the effectiveness of mitigating measures [50]. It is challenging to gain a thorough understanding of the pollution status of microplastics in sediments due to the lack of ongoing monitoring of microplastic pollution in the existing research. To gain a thorough understanding of microplastic pollution in sediments over the long term, the continuous monitoring of the situation is recommended [38].

According to Torres et al., observational and FTIR spectroscopic methods were used to identify environmental paint particles, but a more sophisticated investigation is needed to identify the presence of biocides. Hence, they propose microplastic investigations to complement the examination of paint particles with XRF spectrometry or HF digestion, followed by ICP spectrometry, as described in earlier studies, particularly in places influenced by marinas or significant maritime traffic. It is claimed that locations with medium and low levels of pollution with paint fragments and particles have varying degrees of toxicity. The toxicity of environmentally friendly paint substitutes in particle form has not yet been investigated in untargeted animals [46].

6.8. Practical Solutions/Future Suggestions

Solving the problem of growing microplastic contamination is incredibly challenging according to Wang et al. This calls for coordinated measures, including the development of microplastic research standards, the bolstering of relevant laws, and the implementation of doable recommendations for reducing microplastic pollution. It is important to choose common indicator organisms while investigating the toxicity of microplastics. Several standardized experimental techniques should be devised for various samples. The concentration and volume of the digestive liquids, the digestion period, as well as the use of membrane with uniform pore size, should all be controlled as part of a standard procedure to allow for comparison of the abundances of microplastics in various species. The measurement and identification of microplastics using a microscope, FTIR, and Raman spectroscopy are labor- and time-intensive processes based on statistical sampling methods, which makes it difficult to discover microplastics quickly [40]. With accuracy levels ranging from 96.2% to 99%, the fast identification and quantification of microplastics utilizing hyperspectral and machine learning technologies is currently gaining interest [64].

Governments, plastic manufacturers, industry users, individual consumers, waste management companies, and scientists should all work together to address plastic pollution. Controlling marine plastic pollution at the source is one useful suggestion for reducing plastic pollution. The development of plastic products should be restricted, alternative products should be encouraged, plastic waste should be recycled more often, and garbage should be treated more humanely. To develop plastic degrading technologies and consider alternatives, it is important to combine sustainable and cost-effective ways with technological advancements. Furthermore, the public should be educated and encouraged to use fewer disposable plastic items in daily life [40,158,159].

Microplastics cannot be removed from seawater or separated from sands by sieving. Even if one could collect all of these tiny particles, it would be ineffective. Microplastics continue to move slowly and intricately towards the ocean's floor, where they are eventually buried for decades in sand and muck. Scientists ought to suggest answers that can be taken into account by industry, society, and academia. Each stakeholder group is in charge of a variety of duties, including informing other stakeholders of results.

Several socioeconomic sectors engage in applied research, which has the potential to develop new methodologies for evaluating microplastic contamination, as well as new products, structures, and infrastructure that will ultimately stop plastics from entering the environment. According to Ivar do Sul et al., the ingestion of contaminated microplastics, confirmation of transference/damage by histology, and chemical characterization of pelagic and benthic microplastics to confirm its composition are some suggestions. Laboratory tests on microplastic ingestion and necropsies for verification of physical harm are also suggested. Future-oriented recommendations include the introduction of educational initiatives, collaboration between urban and rural facilities, and effective waste management. Future decision-makers, who are primarily in the public sector, can create state policies to direct the control of the sources of primary plastics and determine the environmental value losses caused by microplastic contamination [42].

Indicator species are crucial for monitoring and assessing a marine ecosystem's condition and the effects of human activity. They have shown to be effective and trustworthy methods for keeping track of changes in the marine environment, particularly to evaluate environmental and human health. A conceptual framework for choosing a collection of indicator species for microplastic ingestion monitoring is recommended as a crucial step toward the development of standardized biomonitoring protocols. The development of appropriate indicator species and widely used techniques for microplastic monitoring processes is urgently required, given the consequences on marine biota that have been reported [160,161].

Extended producer responsibility (EPR) is an effective waste management strategy that is gaining popularity worldwide, particularly in many developed nations such as Europe, Canada, Japan, and South Korea. It can help increase recycling and reduce the amount of plastic waste that is dumped in landfills. The policy makes sure that the sole legal obligation for the collection, recycling, and end-of-life management of plastic waste materials is placed on producers (plastic industries), manufacturers, and importers of goods and packaging. It is intended to hold manufacturers accountable for goods such as plastic and packaging waste that are discovered in public spaces [56]. To limit the amount of plastics discovered in the marine environment (from sea-based sources), incentives for appropriate disposal, collecting, and recycling have also been developed and adopted in several advanced countries of the world. For instance, a required retailer take-back program is in place in several locations, such as New York, California, etc., to offer customers free and convenient ways to return single-use plastic bags for recycling [162].

7. Conclusions

This paper was organized in two parts: The first one is an overview of all published review papers focusing on MPs, while the second one focuses on reviewing the existing published articles on microplastics in ports and coasts. In the first part, after conducting a thorough investigation and analysis of the previous literature reviews, the level of meta-analysis was selected. There, it was discovered that although there were quite a few review articles published concerning the existence of microplastics in the marine environment, an extensive overview of the findings of the helpful review articles released since 2010 received insufficient attention. This publication could be a reference for the published review studies of microplastics in the sea because there was interest in researching this subject at a meta-level.

Although the authors conducted their research meticulously, there are several limitations that could serve as recommendations for upcoming papers that are related. Future research, for instance, might develop an alternative strategy to monitoring, not only in the ocean environment but also in rivers and lakes. Furthermore, because this paper only examined review articles in English, future research could look for pertinent publications in other languages, even if the authors believe that because a meta-level was attained, the likelihood of finding review articles in another language is slim. Moreover, this research reviewed and categorized the review papers according to a number of criteria, including year of publication, keywords, journals, predominate topics, and most common countries.

In the second part, several papers were analyzed and specific conclusions and recommendations can be drawn. It was clear that during the past decades, there has been an increase in the study of microplastic pollution in sediments. The presence of microplastic contamination in harbors and on coastlines seems to pose serious threats to marine biodiversity and the marine carbon cycle. Higher abundances of MPs are reported in the scientific literature on marine waters where these ecosystems are subjected to human pressures such as urbanization, port industries, fishing, and other high intensity activities [38]. The majority of studies on beaches and ports deal with environmental challenges by concentrating on the physical and chemical aspects of microplastics, such as shape and color. Due to the restricted water exchange, short depth, and heavy anthropogenic pressure, ports are typically extremely prone to microplastic pollution. For this reason, future research and monitoring strategies must be adopted, as they will provide a far improved understanding of the dynamics of microplastics [44]. Moreover, managers could create specialized microplastic pollution control strategies with the help of a thorough assessment of the ecological risk posed by MPs. The analysis of the sources of pollution can be performed using the objects' colors, forms, polymer types, and land-use patterns. The improvement of the current pollution source analysis system is facilitated by the development of more precise detection and analysis technologies for microplastics. Last but not least, road markings on land and maritime and boating activities are the principal sources of paint fragments in the oceans. Because of this, even though paint particles' polymer concentration may be smaller than that of other microplastics, they are included in audits of microplastics [37].

Finally, it can be postulated that biotechnology provides a promising and reliable solution to the problem of plastic pollution that has become so pervasive in modern society.

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