

An Overview of Microplastic Pollution: Origins, Movement, and Effects in Marine Ecosystems

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Abstract Over an extended period, the ocean has been utilised as a convenient sink for the disposal of various waste materials, including plastics. The presence and accumulation of plastics and microplastics in marine environments, including both open seas and coastal systems, are primarily driven by increased population growth and human activities. Once it has been dumped in the environment, plastic debris disperses in the sediment throughout the water column and has been documented in marine organisms via ingestion and entanglement. Microplastic debris is frequently ingested by marine organisms, including seabirds, whales, fish, and turtles, which often results in starvation due to gastrointestinal blockage. Moreover, floating plastics serve as vectors for the dispersal of invasive marine species, posing significant threats to marine biodiversity and the stability of the aquatic food web. The ingestion of microplastics also leads to the transfer of toxic pollutants such as heavy metals and Polycyclic aromatic hydrocarbons (PAHs) from the environment into the food chain and eventually into the human bodies which accumulate those toxins. This research compiles the most recent studies on microplastic (MP) pollution in the global marine environment and is

further strengthened by a bibliometric analysis of Scopus-indexed publications over the past five years. The analysis highlights the rapid growth and increasing visibility of this field, thereby providing empirical depth to the review. Three key sections are emphasized: (1) sources, distributions, and major pathways of MPs in the marine environment, (2) interactions of MPs with heavy metals and PAHs contamination, and (3) the impacts of MPs and associated contaminants on marine ecosystems as well as Small Island Developing States (SIDS). Additionally, the global strategies for mitigating this issue have been outlined, with an emphasis on the roles played by various stakeholders. This includes the involvement of industries, government, non-government organisations (NGOs), stakeholders and consumers. The input in this study will serve as a foundation for future marine management and promote greater awareness of the impact of MPs on the marine environment.

Keywords Microplastic Pollution, Transport and Pathway, Polymer Risk

1. Introduction

Plastics have been an important aspect of human life since their first production. The demand for plastic products was increasing gradually in basic need items and so the production from the industries also increased. The production of plastic increased rapidly in the year 2009 to over 250 million metric tonnes with an annual increasing rate of 9%. In the year 2015, the global intake of plastic was reported to be more than 300 million metric tonnes and is expected to increase more or double in the upcoming years (Figure 1) [1]. The contribution of ocean-based sources, such as fishing operations and maritime transport, significantly amplifies the volume of plastic pollution entering marine ecosystems. It was reported that total amount of floating plastic debris larger than 0.33 mm in the world's oceans reaches approximately 0.27 million tonnes, representing around 5.25 trillion individual particles. Notably, MPs within the size range of 0.33 to 4.75 mm account for 92% of the total particle count, while contributing only 13% to the total mass. These figures underscore the pervasive presence and disproportionate abundance of MPs in the marine environment, raising concerns about their ecological and biological impacts [2]. It is estimated that the weight of plastics in the ocean will exceed that of fish by 2050. Nowadays, plastics are always chosen over traditionally used materials such as ceramics, glass, metals, and wood because of their high durability and lack of susceptibility to loss of strength when they get wet. Plastic is used daily in almost all industries including packaging, construction, consumer goods, transportation, textiles, electrical and electronic equipment and industrial machines [3]. However, most of the plastics that are being used today are single-use which have low-value recovery and difficulty in degrading. Microplastic particles (MPs) are produced by environmental degradation and subsequent fragmentation of larger plastics by physical, chemical, and biological processes. This small size of MPs (< 5mm) is present in a variety of products such as personal care,

cosmetics, clothing and other textiles [4]. Urban and stormwater runoff, sewer overflows, littering, inadequate waste disposal and management, industrial activity, tire abrasion, construction, and illegal dumping are the main causes of MPs debris detected in the ocean [5]. Microplastic (MP) pollution in marine environments is largely attributed to activities such as fishing, naval operations, and aquaculture. Due to hydrodynamic forces and transport mechanisms involving wind and ocean currents, MPs have become widely dispersed throughout the marine ecosystem. The presence of MP in the environment can lead to various ecological disruptions such as physical harm, chemical contaminant and ecosystem imbalance. For instance, MPs can inflict physical harm on the digestive systems of organisms, resulting in impaired feeding efficiency, stunted growth, and, in severe cases, mortality. MPs often carry toxic chemicals or attract pollutants from the environment, which can further harm organisms. As MPs disrupt individual organisms, they can affect predator-prey relationships, reproductive success, and overall ecosystem health. Therefore, addressing these issues requires a comprehensive strategy to reduce plastic waste and mitigate its impact on the environment. The goal of this paper is to highlight the current understanding of the MP pollution towards the marine environment. This research helps to identify knowledge gaps and address three main perspectives of MPs: the abundance and distribution of MPs considered its primary and secondary sources; the accumulation of different types of MP polymer and the effects of MPs pollution in the marine environment, particularly concerning wildlife and human health. Furthermore, an overview of the various international initiatives and actions taken by governmental and non-governmental organizations to address and reduce MP pollution in the marine environment is provided. This comprehensive study aims to highlight the progress made and identify areas where further action is needed to achieve a cleaner and healthier marine environment.

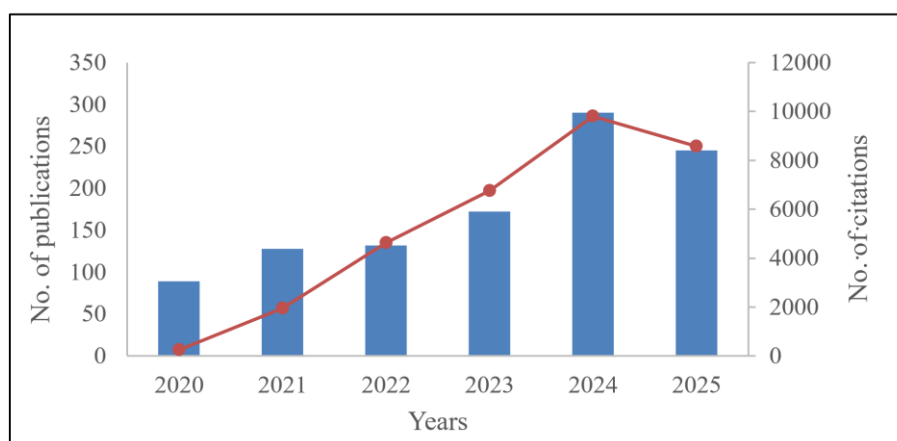


Figure 1. Number of annual publications and citations on MP in marine ecosystem articles from the global region indexed in SCOPUS from 2020 to 2025

1.1. Publication Trends on Microplastic Pollution in Marine Ecosystem Research (2020–Present)

Based on Scopus data, a total of 1057 research articles on MPs in marine ecosystems have been published for the past five years, reflecting growing global concern and academic attention to this issue (Figure 1). In 2020, fewer than 100 papers were indexed, but the number rose steadily through 2021–2023, reaching about 170 publications. A significant peak occurred in 2024 with nearly 300 outputs, representing the highest annual volume and highlighting the consolidation of MP research as a mainstream field. In fact, when compared to that year, the number of publications increased by more than 2-fold starting from year of 2020. It is expected that the annual publication will increase continuously by end of 2025 in line with the rapid increase in the number of outstanding publications. However, most of these articles are not freely available and users have to pay to access the information in them. Most likely a published article will receive more citations if it is published in an open-access journal.

Analysis of the subject field indicating that 40% of publications on MPs in marine ecosystems fall under the subject field of Environmental Science, demonstrates that research in this area is primarily framed as an environmental issue, with emphasis on pollution sources, ecological impacts, and ecosystem management. While this reflects the dominant role of Environmental Science in advancing knowledge on MP contamination, the remaining 60% of publications distributed across disciplines such as marine biology, chemistry, engineering, health sciences, and policy highlight the cross-disciplinary nature of the topic. This distribution underscores the urgent need for broader integration of perspectives, as addressing MP pollution effectively requires not only ecological insights but also technological, social, and governance solutions. Citation trends reflect a parallel trajectory to publication growth: from fewer than 2,000 citations in 2020, the number surged to nearly 10,000 by 2024 before moderating to about 8,500 in 2025. This pattern demonstrates that, in addition to rising research output, the visibility and scholarly impact of MP studies have expanded markedly. The sharp increase in both publications and citations highlights the rapid development of the field, propelled by methodological innovations, cross-disciplinary

collaborations, and the pressing need to address ecological and human health challenges linked to MP pollution in marine ecosystems. By documenting this temporal progression, the review emphasizes the dynamic character of the field and provides empirical evidence of how research momentum has advanced in step with technological progress, policy initiatives, and growing global awareness of the risks posed by MPs.

1.2. Country Contributions and Co-Authorship Networks in Microplastic Research

The bibliometric trends in Figure 2 highlight that research on MPs in marine ecosystems has gained significant global traction, with China and India emerging as the top contributors, supported by strong outputs from the United States and several European nations. The presence of countries such as Malaysia and Brazil in the top ten further reflects the growing recognition of MP pollution as a pressing issue in both developed and developing regions. The co-authorship network map illustrates extensive international collaborations, with 54 nodes and 8 clusters linking research communities across Asia, Europe, and North America. Such collaborative patterns are critical for standardizing methodologies, advancing analytical techniques, and broadening ecological comparisons across diverse marine environments. Importantly, these findings also signal that the depth of the MP problem requires urgent global concern and coordinated action. While the growth in publications and cross-country linkages indicates rising awareness, the reality remains that MPs are already pervasive across all depths of the marine environment, from surface waters to deep-sea sediments that can threaten biodiversity, ecosystem stability, and human health through bioaccumulation in the food web. The leadership shown by highly publishing countries must now translate beyond academic contributions into actionable strategies, including stronger policy frameworks, regional monitoring programs, and transboundary mitigation measures. By embedding scientific progress with proactive governance and community-level interventions, the international research community can help transform knowledge into tangible solutions to curb MP pollution before its long-term impacts on marine ecosystems become irreversible.

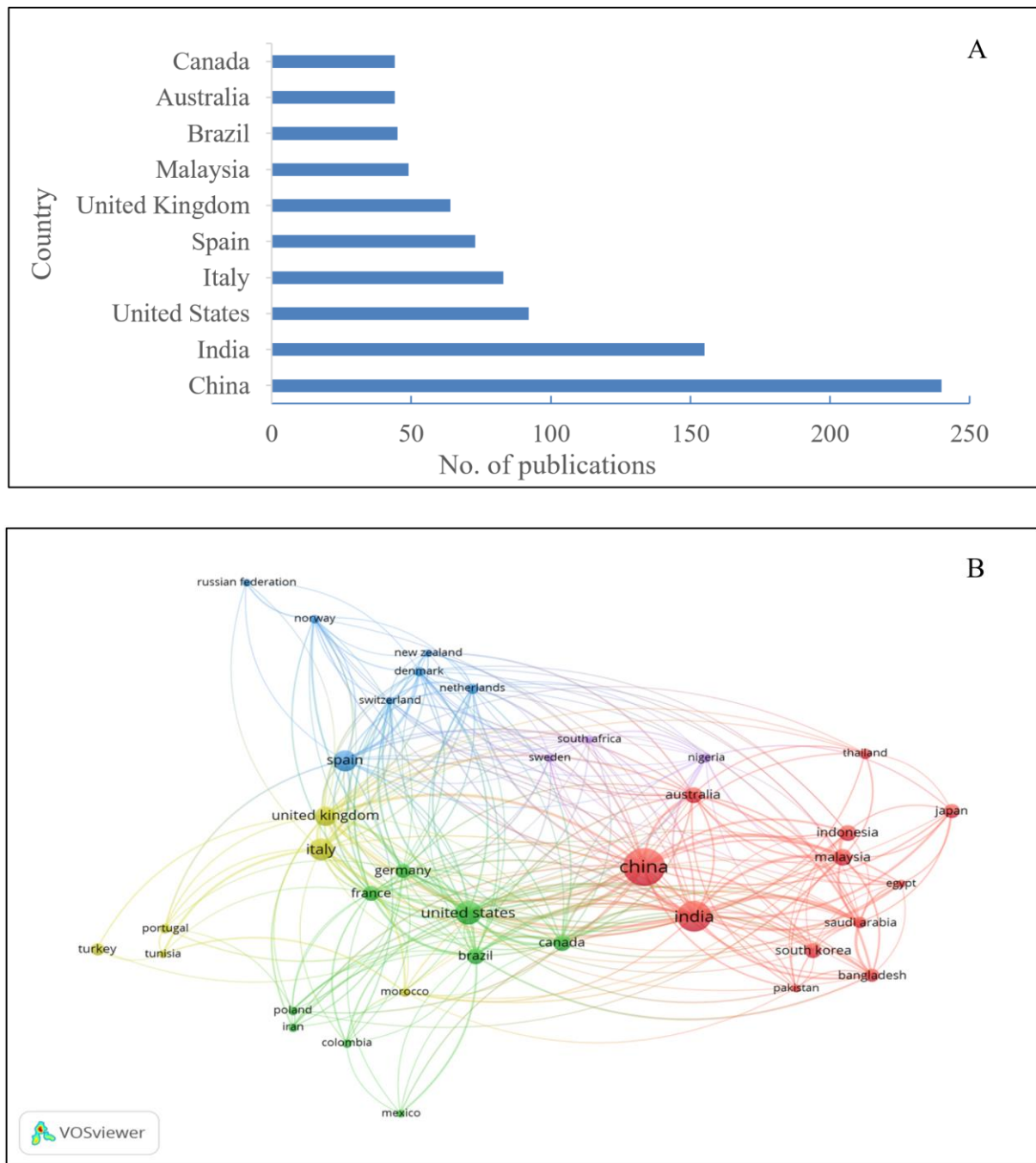


Figure 2. Countries actively publishing research on microplastics in marine ecosystems. (A) Bar chart showing the top ten countries with the highest number of publications indexed in the Scopus database. (B) Country co-authorship network map comprising 37 nodes and 5 clusters, illustrating collaborative linkages among contributing nations

2. Sources of Microplastics Pollution

Plastic waste accumulates in aquatic environments both directly and indirectly, from a variety of sources. Land and ocean-based sources contribute significantly to plastic pollution in coastal and marine ecosystems via both in-situ and ex-situ routes (Figure 3). In ocean basins, plastics are generally grouped into four types based on their size: megaplastics, macroplastics, mesoplastics, and microplastics. About 80% of the littered plastic waste that

is found in marine and coastal environments arises from terrestrial sources, such as street litter that is washed or blown into nearby waterways, public littering, inadequately covered containers, sewage treatment, and combined sewer overflows, and recreational fishing [6]. Incoming freshwater intake, residential and domestic activities, tourism, and other kinds of economic activities, such as port operations also contribute to land-based plastic litter, and over 75% of all items of marine plastic garbage derive from these land-based sources. High population density

and human activity in the coastal zone also have a significant contribution to developing plastic litter from residential, commercial, and industrial sources [7]. Consumer products used by near-coastal people, such as air fresheners and cosmetics, reach the coastal environment directly from land-based sources on account of illegal disposal or stormwater runoff. Not only that, but plastic trash entering wastewater treatment systems is not fully contained, resulting in the discharge of microfibrils from clothes and microbeads from personal care items into coastal seas [8]. Furthermore, in urban coastal areas, drainage systems help transport plastic wastes and MPs from land-based sources right into the sea, contributing to the already awful situation of plastic pollution in such sensitive areas. Activities related to commercial fishery, navigation, waste disposal, and shellfish/fish culture are among the offshore activities that add up to the load of

plastic waste in marine and coastal zones [9]. Plastic pollution is also created because of fishing and aquaculture-related operations since damaged/dispersed fishing nets and abandoned fishing nets enter the offshore. Maritime and navigation activities also add their share of plastic accumulation; wherein marine vessels are reported to dump plastic litter into the ocean at a rate of about 6.5 million tonnes per year as of early 1990. Plastics can also enter the sea through inadequate disposal of products, or loss during production and transport. Plastic litter formation in aquatic ecosystems and ocean systems also results from mismanaged application of plastic packaging materials. Observations of synthetic polymers have been made in sub-surface plankton samples around the Saint Peter and Saint Paul Archipelago in the Equatorial Atlantic Ocean, with increasing mean plastic densities [9].

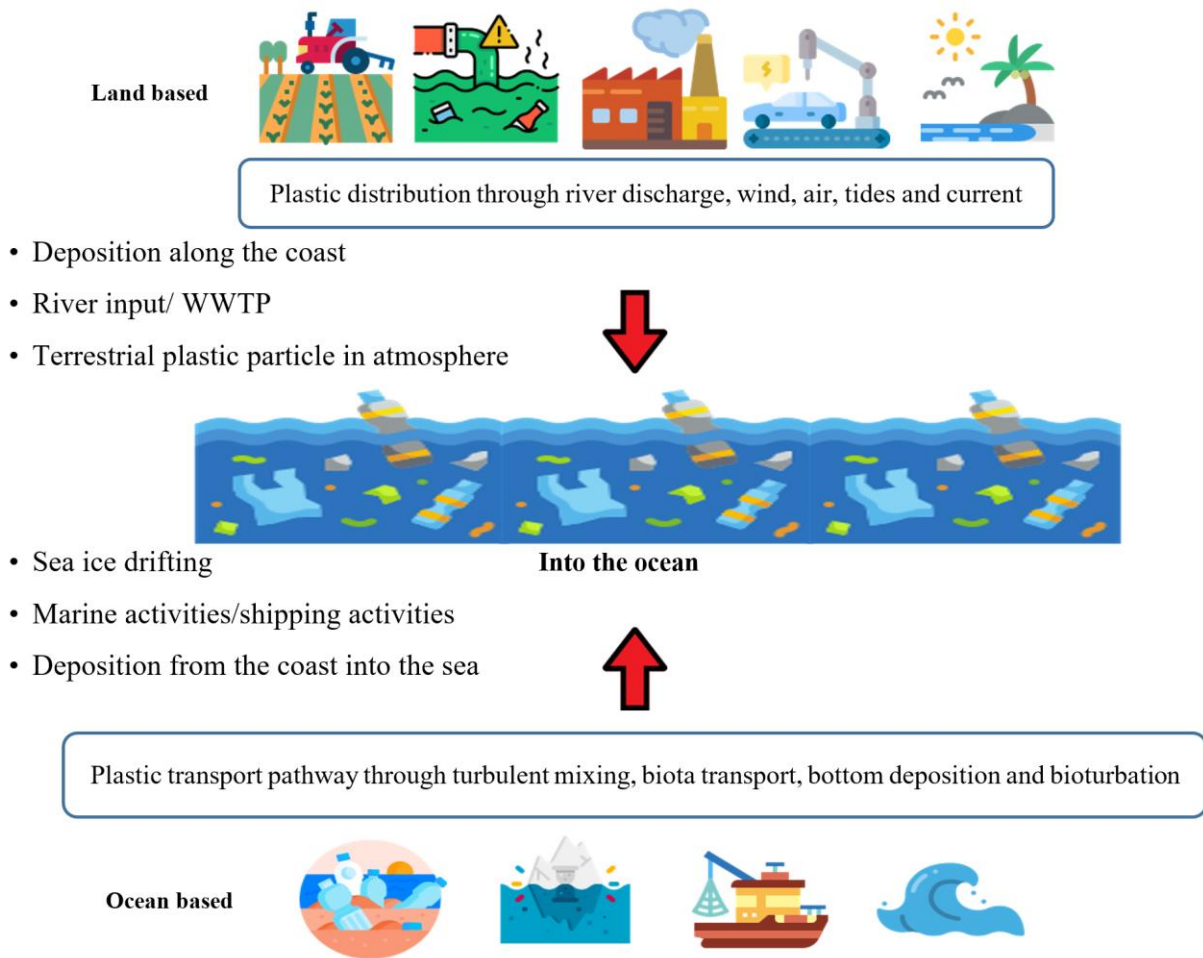


Figure 3. Pathway distribution of microplastic into the marine environment

3. Primary and Secondary Microplastics

In marine environments, MPs are generally classified into two categories: primary and secondary MPs. Primary MPs are intentionally manufactured at microscopic sizes, whereas secondary MPs originate from the degradation of larger plastic debris through physical, chemical, or biological processes. The primary form of MPs can be found as small plastic beads manufactured specially for cosmetics, hand cleansers, and plastic pellets which were accidentally or purposely spilled into the environment during manufacturing [10]. Primary MPs are mostly manufactured for certain industrial and domestic applications. There are a lot of forms of primary MPs such as pellets, fibres, capsules, and microbeads. The usage of MPs in many branded cosmetics and facial products has gained the attention of researchers worldwide. Virgin plastic production pellets as shown in Figure 4 are also considered as primary MPs. Another form of primary MPs can be found in personal care products such as face wash and body scrubs where the MPs act as exfoliators in the

products. Secondary MPs are derived from the fragmentation of MPs into plastic particles with a microsize. The fragmentation process can be induced by mechanical intrusion or weather. Both mechanical and chemical weathering are present at beaches, creating a naturally optimal environment for plastic fragmentation. For example, plastic debris at the beaches is exposed to atmospheric oxygen, abrasion, turbulence, and wave action simultaneously and is fragmented into MPS, which is one of how secondary MPs form. Besides, secondary MPs can also be formed by receiving ultraviolet radiation from the sunlight and lead to plastic polymer oxidation by breaking the chemical bonds. Synthetic clothes also contribute to the formation of secondary MP. Surprisingly, secondary MPs are mostly found in the ocean rather than primary MPs. As primary MPs degrade into secondary MPs, their quantity in the water ecosystems grows, potentially increasing ecological damage. As a result, smaller pieces of plastic are more easily consumed, increasing the susceptibility, leaching, desorption, and adsorption potentials of MPs in the environment.

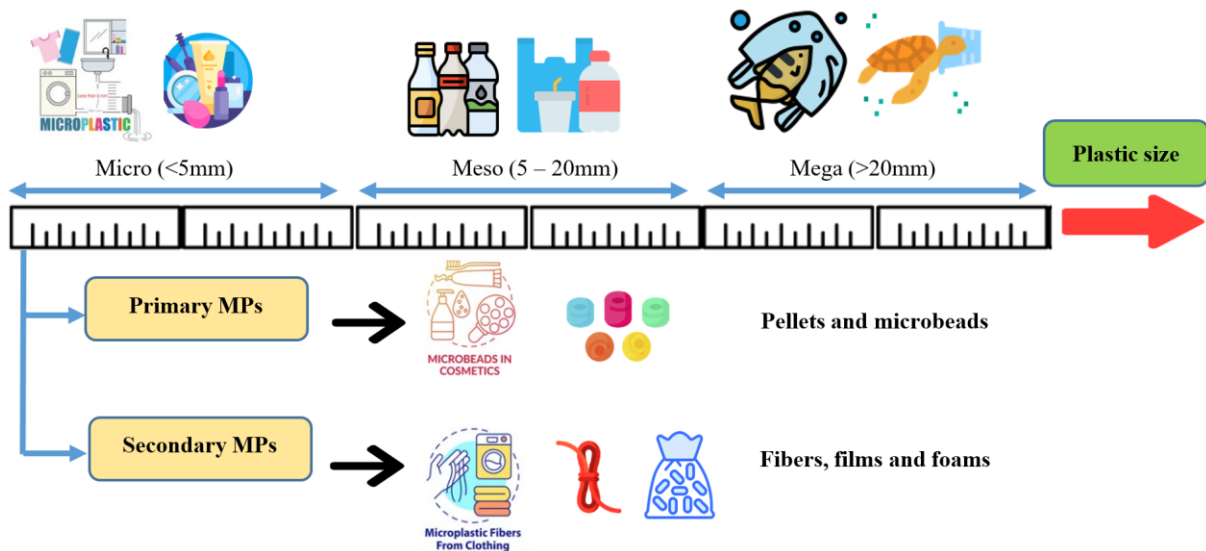


Figure 4. Size range of plastic objects observed in the marine environment

4. Degradation and Fragmentation of Microplastics

There is substantial controversy regarding the lifetime of plastics; estimates range from hundreds to thousands of years. All ordinary plastic that has ever been released into the marine environment is thought to still be there today, either in its entirety or in pieces, with the exception of things that have been burned. Despite the durability of these polymers, extended exposure to UV light and physical damage are causing plastic objects to fracture in the environment [11]. This is especially true towards the coast, where plastic products become more fragile due to photodegradation and wave-induced abrasion [12]. It appears likely that the pieces are developing from the breakdown of a wide variety of common plastic products, including rope, packaging, and apparel, as these materials have a wide range of residential and industrial uses. Generally, the degradation of MPs can be classified as either abiotic or biotic pathways. The biotic degradation involves the process of fragmenting plastic into smaller particles with the aid of digestive processes by microorganisms. These microbes interact with the molecular structure of the polymer and convert the organic substances into carbon dioxide (CO₂) and water (H₂O). However, the entire process proceeds very slowly, and plastic may not completely decompose for 50 years or more [13]. Abiotic degradation involves being exposed to high temperatures, solar radiation, pH, salinity, and oxidising conditions. These processes generate carbonyl groups that boost the polymer's hydrophilicity and hence raise its

susceptibility to biodegradation [14]. The polymer is broken down into its monomers during biodegradation, and the monomers are then mineralized. This degradation type can be classified as photodegradation, photo-oxidative, auto-oxidative, thermos-oxidative, and hydrolytic degradation [11]. However, both biotic and abiotic pathways processes contribute significantly to the chemical breakdown of polymer structure. The breakdown of the polymers primarily depends on the types of plastic polymer used and the environmental factors to which MPs are exposed (Figure 5). Plastic polymers that contain length and the backbone carbon chain such as (PP) are more resistant to degradation [15]. However, adding heteroatoms, such as in PU and PET, where oxygen is included in their polymers, makes the plastic susceptible to thermal and biological degradation. The presence of additives such as antioxidants and stabilizers inhibits the degradation of the polymer [16], while pro-oxidant additives make it more sensitive to degradation. Jenkins and Harrison [17], reported that the more crystallinity of the plastic polymers, the more oxygen (O₂) and water (H₂O) are required to degrade the plastic. Furthermore, the morphological properties of the plastics have the potential to accelerate the degradation process. Rough surfaces are the best surfaces for forming a biofilm. As a result, the pace of plastic degradation will increase [18]. The descriptions below outline the concepts and specifics of degradation and fragmentation processes, covering photodegradation, biodegradation, thermal degradation, and mechanical degradation.

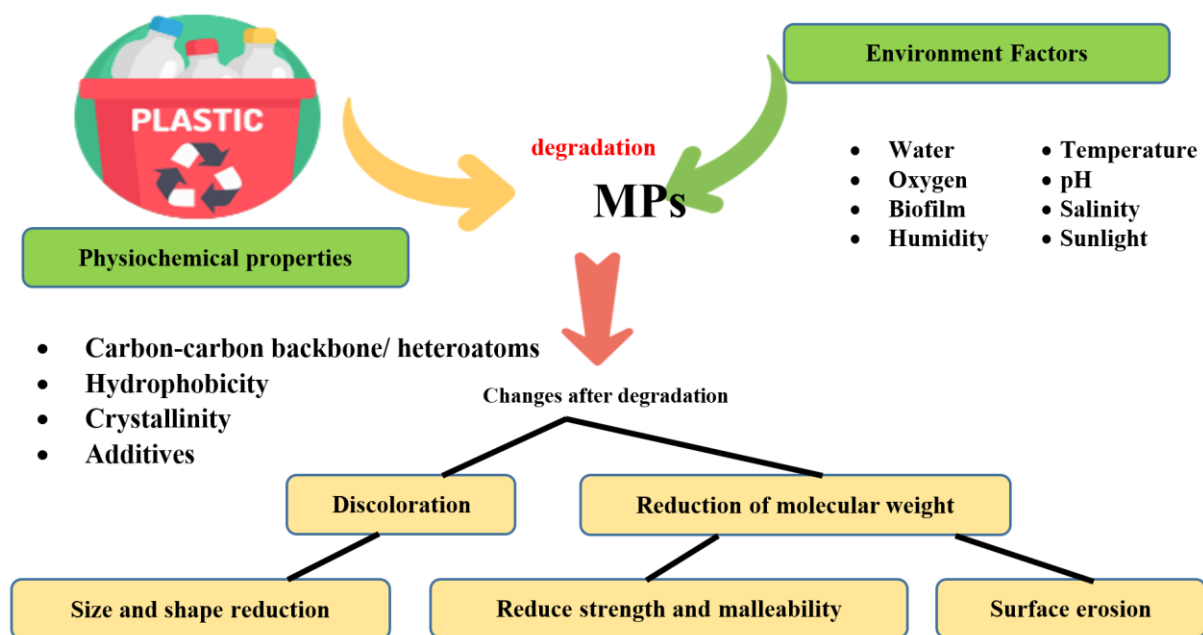


Figure 5. Factors that influence the MPs degradation in the marine environment

4.1. Photodegradation

Photodegradation of plastic materials into smaller particles involves the reaction of the plastics with sunlight and oxygen. It will cause polymer chains to break which will then make them more brittle which will then produce MPs [19]. This process involves the formation of free radicals and the oxidation of plastic polymers, leading to the creation of peroxides, which eventually break down into alkoxy and hydroxyl radicals, akin to the thermal degradation process. In the atmosphere, photodegradation produces free radicals that break down various plastics depending on their chemical structures. For instance, in polypropylene (PP), polyethylene (PE), and polyvinyl chloride (PVC), chromophores (alternating or conjugated carbon double bonds) facilitate free radical formation. In polystyrene (PS), phenyl rings play a similar role, while in polyethylene terephthalate (PET), ethylene glycolate and terephthalate groups linked by ester bonds mediate these reactions due to photodegradation.

4.2. Biodegradation

In the marine environment, microorganisms contribute to the biodegradation process of plastic waste. This process involves (1) biodeterioration, (2) biofragmentation, and (3) bioassimilation and is influenced by environmental conditions such as microbial growth and communities' presence [20]. In the first stage, biodeterioration, environmental factors such as ultraviolet (UV) radiation, saltwater exposure, temperature fluctuations, and oxidative reactions initiate physical and chemical changes on the plastic surface. These changes, including cracks and roughened textures, enhance microbial adhesion and promote the formation of biofilms [21]. This phase is critical because it increases the surface area available for microbial colonization, making the plastic more susceptible to enzymatic attack. The second stage, biofragmentation, involves the secretion of extracellular enzymes by microorganisms such as bacteria and fungi. These enzymes catalyze the cleavage of long polymer chains into shorter oligomers and monomers. The efficiency of biofragmentation is influenced by the type of plastic, the degree of polymer crystallinity, and the presence of functional groups that affect enzyme binding and hydrolysis [22]. The final phase, bioassimilation, occurs when the fragmented plastic molecules are small enough to be taken up by microbial cells. Within the cells, these compounds are further metabolized through microbial catabolic pathways, producing carbon dioxide and water under aerobic conditions or methane and other byproducts under anaerobic conditions [23]. This phase

effectively mineralizes plastic-derived compounds, reducing their persistence in the environment.

4.3. Thermal Degradation

Plastic waste on coastal shorelines is subjected to high temperatures, which leads to thermo-oxidative breakdown. This process involves polymer's molecular deterioration due to high temperature conditions (100 °C). This form of degradation plays a significant role in the transformation of macroplastics into smaller fragments, particularly in sun-exposed, dry beach environments. The mechanism begins with heat absorption by the polymer material, which weakens covalent bonds along the polymer chains, resulting in chain scission and the generation of free radicals. These radicals react with atmospheric oxygen to form hydroperoxides, which are thermally unstable and decompose into hydroxyl ($\bullet\text{OH}$) and alkoxy ($\text{RO}\bullet$) radicals. These secondary radicals further accelerate the oxidative degradation process, ultimately producing low-molecular-weight compounds such as aldehydes, ketones, esters, alcohols, and carboxylic acids [24]. These chemical changes significantly alter the physical and mechanical properties of the plastic, making it more brittle and prone to fragmentation. The cumulative effect of thermal degradation, combined with mechanical stress from environmental factors such as wave action and sand abrasion, enhances the production of microplastics and nanoplastics, which persist in the environment and contribute to pollution.

4.4. Mechanical Degradation

Mechanical degradation or weathering can occur due to grinding, collision, abrasion, compression, extrusion, shear and stress forces, and even tension. This form of degradation occurs when plastics are subjected to repeated mechanical forces such as grinding, abrasion, shear stress, impact, compression, and tensile forces [19]. Unlike chemical or biological degradation, mechanical degradation does not alter the chemical structure of the polymer but instead causes physical breakdown into progressively smaller fragments, often resulting in MPs or even nanoplastics. In coastal environments, plastic debris is frequently exposed to mechanical stress due to wave action, tidal forces, and wind-driven movement. Plastics that accumulate along beaches are subjected to repeated collisions with rocks, sand particles, and other debris, which act as abrasive agents. This constant friction weakens the polymer structure, leading to surface wear, cracking, and eventually fragmentation [25].

5. Types of Microplastic Polymer in Marine Environment

According to Aurani [26], the most prevalent MP polymers detected in Malaysian marine environments include polypropylene (PP), polyethylene (PE), polystyrene (PS), and polyamide (nylon). These polymers are widely used in consumer products and industrial applications, and their persistence in marine settings is attributed to their low degradation rates and buoyant nature. Polypropylene and polyethylene, being less dense than seawater, tend to remain afloat and are often found in surface waters, while polystyrene and polyamide may settle in sediments depending on their physical state and environmental conditions. This finding is significant to Erni [27], who reported that those polymer types were commonly found in aquatics environment (Table 1). Additionally, Chouchene [28] reported that 31% of PE was

found in Barra beach, Portugal and a study by Prata [29], found 69% of PE in sandy beach, Aveiro, Portugal. This is not surprising as these materials are primarily used in the production of packaging materials and fishing equipment. PE is one of the most widely used polymers in consumer goods and fishing operations, and its low density allows it to float on the sea surface and traverse great distances. Meanwhile, PA (or nylon) can be found on beaches due to its toughness and low density (Figure 6). It was reported that about 18% of the marine plastic debris found in the ocean environment is attributed to the fishing industry [25]. Most MPs are retained in the environment for up to a century due to hard-to-degrade materials of their strong resistance to corrosion [30]. Microplastics with a high density are inherently non-buoyant and are found in sediments from coastlines to the deep ocean as reported by Li et al. [3].

Table 1. Types of microplastics commonly in the marine environment [31]

Polymer Types	Common Applications	Density (g/cm ³)
Polyethylene (PE)	Plastic bag, storage containers	0.91-0.95
Polypropylene (PP)	Rope, bottle caps, gear, strapping	0.90-0.92
Polystyrene (PS)	Cool boxes, floats, cups	1.04-1.09
Polyvinyl chloride (PVC)	Film, pipe, containers	1.16-1.30
Polyamide or Nylon (PA)	Fishing nets, rope	1.13-1.15
Polyethylene terephthalate (PET)	Bottles, strapping, textiles	1.34-1.39
Polyester resin + glass fibre	Textiles, boats	>1.35
Cellulose Acetate	Cigarette filters	1.22-1.24
Polyurethane (PU)	Sponges, furniture cushioning, life jackets	0.80-1.05
Polytetrafluoroethylene (PTFE)	Non-stick kitchen utensils	2.10-2.30
Polycarbonate (PC)	Compact discs, eyeglass lenses, and water bottles.	1.20
Low density polyethylene (LDPE)	Trays, containers, food packaging film	0.91-0.94
High density polyethylene (HDPE)	Toys, milk bottles, shampoo bottles, houseware	0.94-0.97

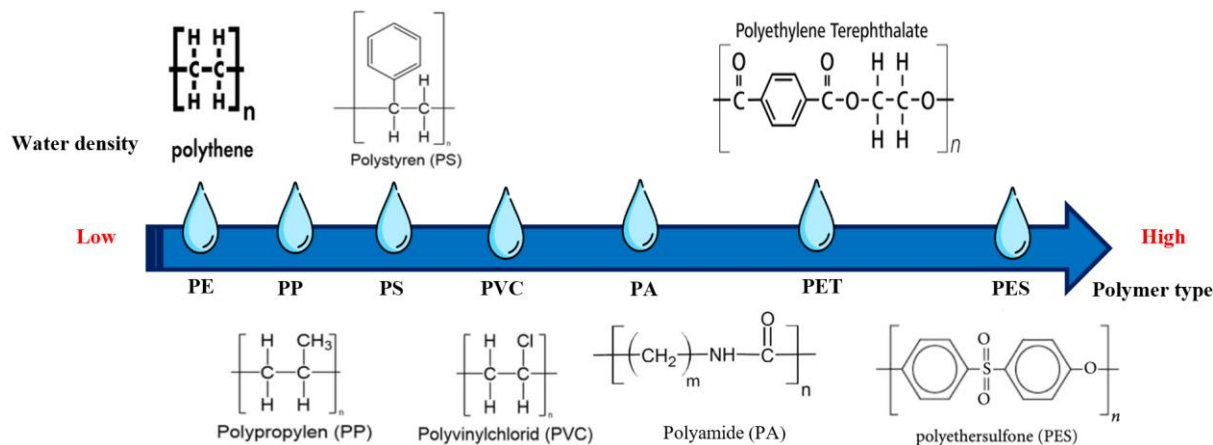


Figure 6. Density of different polymers in the water column

The heterogeneity of MP sources was examined through meta-regression analysis by Erni [27] who found that factors such as debris size, water type, and sampling zone significantly influence the variability in polymer distribution. Their findings indicated that low-density polymers like polyethylene (PE) and polypropylene (PP) were more prevalent at the sea surface (PE: 42%; PP: 25%), compared to the water column. In contrast, denser polymers such as polyester, polyamide, and acrylics were more frequently detected in subsurface waters, likely due to their higher specific gravity causing them to sink below the surface. The distribution and composition of MP polymers in aquatic environments are influenced by a variety of environmental and methodological factors. Previous studies by Erni [27], highlighted that the variability in polymer types is significantly affected by the size of debris, the type of water body, and the sampling zone. Their study revealed that low-density polymers such as polyethylene (PE) and polypropylene (PP) were more abundant at the sea surface (PE: 42%; PP: 25%), whereas denser polymers like polyester, polyamide, and acrylics were more commonly found in subsurface waters. Additionally, the concentration and prevalence of plastic polymers are closely linked to geographic factors. These include regional sources of pollution, particularly in densely populated coastal areas as well as the distance from the coastline, the shape, the density of plastic particles and the sampling methodology employed [32]. These spatial and methodological variations underscore the complexity of assessing MP pollution and the need for standardized approaches in environmental monitoring. In summary, the various synthetic polymers contribute significantly to the issue of MP pollution in the marine environment. Many synthetic polymers contain additives like plasticisers, flame retardants, and colorants, which can leach into the environment. These chemicals can be toxic to marine life and disrupt biological processes and lead to broader ecological impacts.

6. Major Pathway and Fate of Microplastic Pollution to the Marine Environment

Plastic pollution has emerged as a critical environmental concern, with a large proportion of plastic waste originating from land-based sources before reaching aquatic ecosystems. Most plastic debris is produced, used, and discarded on land, where it accumulates in terrestrial areas and inland water bodies. Only an estimated 12% of globally produced plastics are effectively recycled, while the remaining majority are either incinerated, disposed of in landfills, or dispersed by wind and water into remote locations including the ocean floor. Once introduced into the marine environment, plastics can persist for extended periods, posing ecological threats to marine biodiversity

and ecosystem functioning. Lightweight single-use plastic items such as plastic bags, straws, cotton swabs, and wrappers are particularly prone to being transported from terrestrial areas into marine environments. These plastics are easily carried by wind or washed through river networks and drainage systems, eventually entering the ocean via wastewater discharge, rainfall, surface runoff, or flooding events. McDonnell [33] investigated the sinking behavior of marine particles and reported sinking rates ranging from 10 to 150 meters per day. Based on these rates, particles traveling through the deep ocean could take anywhere from one month to a full year to reach the seabed from the surface, illustrating the prolonged residence time and wide dispersal potential of MP debris in marine systems. Most horizontal currents move at a rate of 1 m/s, but at 1000 m they have decayed to a trickle. As a result, a sinking particle's horizontal travel distance can vary from 1 kilometre (fast sinking rate) to 35 kilometres (slow sinking rate). Other than that, MPs can get stuck in sediments for a long time, and thus can be taken up and retained for certain periods by marine organisms. Because they are small and less dense than natural sediment. Microplastics (MPs), due to their small size and low density, are more likely to be re-suspended from bottom sediments compared to larger plastic debris. One of the primary pathways through which MPs enter both marine and freshwater ecosystems is via wastewater treatment plants (WWTPs) or sewage treatment plants (STPs) [34]. These facilities often lack filtration systems specifically designed to capture microfibrils, allowing significant quantities to pass through and be released into aquatic environments. Recent research has shown that microfibrils remain among the most dominant types of MPs in treated effluents, even after advanced treatment processes. Globally, WWTPs are estimated to contribute approximately 25% of total MP pollution, encompassing both terrestrial and marine inputs, with about 71% of this waste eventually entering the ocean. This translates to an estimated 37% of all oceanic MP pollution, underscoring the critical role of wastewater systems as a major conduit. Additionally, road runoff accounts for an estimated 44% of marine MP pollution, while atmospheric and ocean-based sources are believed to contribute less than 20% [35]. The dynamics and the fate of MPs in the marine environment are largely determined by their material density. However, shape, size, and stiffness are also important characteristics since different particle types have distinctive transport paths to the water column. However, experiments revealed that biofouling can accelerate sedimentation and result in up to 81 % higher sinking rates of particles [36]. In dynamic coastal environments such as tide-dominated estuaries and wave-influenced beaches, fine-grained particles, MPs, may escape the coastal zone and be transported offshore. Plastics with densities greater than seawater typically accumulate on the seafloor. However, due to their finite sinking time, these particles can remain suspended within

the water column for extended periods. The MPs end up in sediment when the less dense MPs are being pushed by the waves and the MPs' debris stays on or gets into the sediment by the ocean wave. Less dense MP particles (or fiber-shaped particles with a large surface area) are transported independently of sediments because they only sink to the ocean bottom through biofouling, ingestion, or other mechanisms. When MP particles are large and dense enough to be transported in bedload and are thus able to be hydraulically sorted with sediment grains, correlations between sediment size and MPs occurrence will occur [37]. The descriptions below outline the fate of MPs in the marine environment, specifically within the water column, seabed, beaches and biota respectively.

6.1. Water Column

The water column is a conceptual vertical profile that extends from the ocean surface down to the seabed, encompassing all water layers in between. Plastic debris has been detected throughout this entire vertical space, from surface waters to deep-sea sediments, indicating its widespread distribution and persistence in marine ecosystems. The vertical movement and positioning of plastic particles within the water column are largely governed by two primary factors: buoyancy and particle characteristics. Plastics with densities lower than seawater tend to float, while those with greater densities are more likely to sink. However, the process of tracking and capturing sinking plastic particles is logistically challenging and resource-intensive, leading to a scarcity of observational data. The sinking behavior of plastic particles is influenced by their size, shape, and relative density compared to seawater. McDonnell [33] reported that the sinking rates of marine particles can range from 10 to 150 meters per day. Based on this rate, particles released at the ocean surface could take anywhere from one month to a full year to reach the seafloor in deep oceanic regions.

6.2. Seabed/Seafloor

Plastics and MPs have been detected in marine sediments across a wide range of geographical locations, highlighting their extensive and persistent distribution in benthic environments. Recent studies have revealed that deep-sea sediments also serve as significant accumulation zones for MPs. Interestingly, the composition of microplastics in these deep-sea sediments differs markedly from that found in surface waters. For instance, Woodall [38] reported that MP fibres were up to four orders of magnitude more abundant in deep-sea sediments than in surface waters, suggesting distinct transport and deposition dynamics at depth. Sediments are now increasingly recognized as a long-term sink for MPs, where physical, chemical, and biological processes limit their resuspension and contribute to their persistence. The transport pathways that deliver MPs to the deep ocean differ from those at the

surface and are generally weaker, governed by slower currents, gravity-driven sedimentation, and particle aggregation. Furthermore, submarine topographic features, such as trenches, canyons, ridges, and seamounts, influence the deposition patterns of both macro- and MPs by acting as traps or accumulation zones.

6.3. Beach and Shorelines

While many studies have documented the presence of large plastic debris on beaches, increasing evidence also highlights the widespread occurrence of MPs on shorelines across the globe [35]. This plastic debris is typically a combination of locally generated waste and materials transported over long distances by wind, wave action, and ocean surface currents, in some cases travelling thousands of kilometers before reaching shore. In addition to human-related activities, natural environmental factors also contribute significantly to the accumulation of plastic debris on beaches. For instance, rainstorms and seasonal changes have been shown to influence the quantity and distribution of plastic waste along shorelines. Sulaiman [7] observed that MP concentrations in beach sediments were substantially higher after the rainy season compared to pre-rainy season conditions, suggesting that stormwater runoff and intensified water flow may mobilize and deposit plastics along coastal zones. Moreover, wind direction and prevailing ocean currents serve as important determinants of where and how much plastic accumulates on a given beach, shaping both spatial and temporal contamination patterns. On a broader scale, aesthetic degradation caused by stranded plastics can negatively impact coastal tourism and recreation, which are economically important sectors for many regions. Additionally, large items such as abandoned fishing nets and ropes pose entanglement risks to marine fauna, including seabirds, turtles, and marine mammals. At the same time, smaller MP particles continue to accumulate unnoticed, contributing to long-term contamination of the shoreline environment [39].

6.4. Biota and Sediment

Macro and MPs have been found associated with a wide variety of organisms, from small zooplankton to the largest whales, from worms burying in the seabed to seabirds feeding in the upper ocean. Microplastics are widely recognized for their ability to be ingested and retained by a variety of marine organisms over extended periods, enabling their transport across significant distances within marine ecosystems. In some cases, mobile species such as seabirds and seals may inadvertently carry MPs back to terrestrial environments, highlighting the transboundary nature of plastic pollution. Once ingested, MPs can cause both chemical and physical harm to marine organisms, including damage to internal tissues, disruption of feeding behavior, and reduced reproductive success. Furthermore, they can impair algal growth and disrupt primary

productivity, thereby interfering with the broader marine food web. Marine sediments serve as a major sink for MPs, particularly those with densities greater than that of seawater, which tend to sink and accumulate on the seafloor. Studies have shown that MPs can be present in sediments at very high concentrations, with some contaminated beach sediments containing MPs comprising up to 3.3% of the total sediment weight [40]. Due to their small size and relatively low density compared to natural sediment particles, MPs may remain buried in sediments for prolonged periods, yet they are also more susceptible to resuspension. Physical forces such as wave action, currents, and bioturbation can readily disturb and mobilize MPs, making them more dynamic and persistent pollutants in benthic marine environments than larger plastic debris.

7. Microplastics as a Vector of Heavy Metals and Polyaromatic Hydrocarbons (PAHS) in the Marine Environment

Heavy metals that are found in the marine environment are a natural part of the earth's crust through rock erosions, weathering, and atmospheric deposition. However, anthropogenic sources due to human activities also contribute to the high level of heavy metal released into marine environment. The sources of metals to the marine environment are diverse, though many arise from the irresponsible dumping of sewage, industrial and household waste and many other sources [41]. The occurrence of organic chemical pollutants on plastic debris items is detected globally but the existence of heavy metals on plastic debris items has only lately been studied. Like other chemical pollutants (e.g. polybrominated diphenyl ethers), some heavy metals are reported on plastic debris like lead which sources from the manufacturing production process and also from environmental adsorption. However, some organic chemical pollutants (e.g. DDT), and several heavy metals are found on plastic debris merely as a result of environmental adsorption [42]. Previous studies deployed the virgin of polyethylene pellets in a port in Southwest England for 8 weeks and discovered several heavy metals such as Al, Fe, Mn, Cu, Pb, Zn, and Ag adsorbed from oceans [43]. It was reported that the polymer production of plastic pellets on the coastline of Southwest of England had similar and higher concentrations of heavy metals such as Zn, Fe than local sediments, despite sediment customarily presenting a higher surface area and being composed of charged minerals capturing adsorption of heavy metal ions [42]. A study by Zahari *et al.*, [44], found that the MPs collected from Kebagu beach, Sabah Malaysia presented higher trace metal contents (specifically Zn). This is due to the long-term sorption of metals by MPs and the comparative metal burden between MPS, macrolitters and fresh plastic products in the marine environment. However,

the results are remarkable compared with data from Beijing River, which showed that the concentration of Zn in MPs was greater than that in plastic bags due to, for example fragmentation of macroplastics or micro-size plastic production, which have different metal burdens added as additives [45].

For PAHs, the most prominent and noticeable discharges of this pollution come from oil spills, atmospheric deposition, river and urban runoff and anthropogenic activities such as shipping and boating activities. When oil spills occur from tanker accidents or offshore drilling operations, PAHs are released into the water. These PAHs can dissolve in the water or form oil slicks on the surface, thus potentially affecting marine organisms. Previous studies by Mara [46], showed that there is high variability of PAH in PE and PP collected from the sandy beaches of Santos Bay, located in São Paulo State, Brazil. He mentioned that the highest concentration of PAH was seen for PE given that this is the most widely used polymer and appears to be particularly prone to picking up organic molecules [47]. The ability of plastic particles to absorb organic contaminants has previously been found to vary with polymer (resin) type, additive presence, and end product grade [48]. Rochman [49] reported that polyethylene (PE) and polypropylene (PP) resins exhibit a significantly higher capacity to absorb hydrophobic organic pollutants such as polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs), compared to other plastic polymers like polyethylene terephthalate (PET) and polyvinyl chloride (PVC). In a related study, Hirai [50] observed that PCB accumulation was notably greater in PE fragments than in PP, indicating that polymer type plays a critical role in contaminant sorption behavior. Research conducted on Portuguese beaches by Frias [51] revealed that the concentration of PAHs in plastic pellets ranged from 0.2 to 319 ng/g, while PCBs ranged from 0.02 to 15.56 ng/g. These pollutants were attributed primarily to maritime sources, particularly oil tankers and freight vessels operating in the area. The variation in pollutant concentrations and chemical compositions among different plastic types is of particular concern due to their implications for marine biota and ecosystem health. Plastics that accumulate higher levels of toxic substances can act as vectors for the transfer of hazardous chemicals into the food web, potentially leading to bioaccumulation and biomagnification. Understanding these sorption dynamics is essential for assessing the environmental risks associated with microplastic pollution in marine environments.

8. Effects of Microplastics Pollution on Marine Environment

Microplastics also represent an emerging threat to coral reef ecosystems, compounding the pressures already imposed by climate change, overfishing, and pollution.

Corals, being both habitat-builders and sensitive organisms, are directly and indirectly affected by the presence of MP particles in reef environments. Recent experimental evidence has revealed that MPs, particularly polyethylene terephthalate (PET) particles, can become physically embedded within the aragonitic skeletons of coral polyps during calcification processes. This skeletal incorporation is alarming because it not only compromises the structural integrity of corals but also suggests that MPs may become a long-term component of reef carbonate frameworks. Such alterations could weaken skeletal density, reduce resilience to wave action, and exacerbate the vulnerability of coral reefs to climate change stressors such as ocean acidification and thermal bleaching [52]. The presence of foreign particles within the skeletal matrix may also disrupt normal mineralization pathways, potentially altering growth rates and skeletal morphology. Beyond physical incorporation, MPs may also affect coral polyps physiologically. Ingestion of MPs can obstruct feeding, reduce energy budgets, and impair reproductive success. The chronic presence of MPs may further disturb the delicate coral-algal symbiosis (zooxanthellae), reducing photosynthetic efficiency and exacerbating coral stress under environmental pressures [53]. These impacts highlight the dual threat MPs pose, both as physical intruders in skeletal frameworks and as disruptors of physiological functions critical for reef survival. At the ecosystem level, the chronic presence of MPs may alter reef community structure. Reduced coral growth and survival compromise reef complexity, which in turn diminishes habitat availability for associated organisms such as fish, mollusks, and crustaceans. Given that coral reefs support roughly 25% of marine biodiversity and sustain coastal livelihoods through fisheries and tourism, MP pollution represents not only an ecological threat but also a socio-economic challenge.

Microplastics have been found in tap water, sea salt, and bottled water, demonstrating how many ways they can enter the human body. Studies have shown that particular chemicals in plastic can leach into the food and beverages that we consume. Some of these substances have been associated with metabolic diseases (including obesity) and decreased fertility [54]. There are research findings on the presence of chemicals utilised in plastic in the human body, and this research was conducted using laboratory animals as the model organism to demonstrate the harmful effects of the chemicals contained in plastic [55]. Recently a study conducted by Ragusa [56], reported the presence of pigmented MPs in the human placenta. Ingestion, inhalation, and skin contact can all cause the poisonous chemical to spread rapidly to the surface of the human skin [57]. Plastic that has been discarded will affect the local ecosystem by altering the soil structure and so influencing the microbes and plants that thrive there [58]. Microplastics can degrade the soil nutrition content or obstruct the flow of nutrients, causing the soil's moisture to diminish and ultimately affecting the plantation industry [59]. Excessive

disposal or accumulation of MPs will block sunlight from reaching the soil surface, destroying essential bacterial pathways for soil fertility.

Additionally, MP pollution poses a serious threat to economic and industrial development, with tourism being one of the most affected sectors. The presence of MPs in marine environments can lead to visible pollution on beaches, degrade the aesthetic appeal of natural landscapes, and negatively impact recreational activities [60]. This, in turn, can deter tourists and reduce the revenue generated from tourism-related businesses such as hotels, restaurants, and tour operators. The economic consequences extend beyond the immediate loss of tourism revenue. The costs associated with cleaning up polluted beaches and marine environments can be substantial, placing a financial burden on local governments and communities. Moreover, the potential contamination of seafood with MPs can affect the fishing industry, further impacting coastal economies reliant on tourism and seafood [61]. Additionally, the decline in marine and coastal health due to MP pollution can diminish the attractiveness of destinations, leading to longer-term economic repercussions. This degradation can undermine efforts to promote sustainable tourism and conservation, ultimately affecting the overall growth and development of the tourism industry. Addressing MP pollution is thus crucial for safeguarding economic interests and ensuring the long-term viability of tourism and related industries.

9. Impacts of Microplastic Pollution on Small Island Developing States (SIDS)

Small Island Developing States (SIDS) are recognized for their rich biodiversity and are often habitats for endemic species that exist nowhere else on Earth. They also hold remarkable cultural diversity and heritage, making them globally significant from both ecological and socio-cultural perspectives [62]. However, SIDS are disproportionately affected by marine plastic pollution. Despite their relatively low levels of consumption and small populations, these islands experience high concentrations of plastic debris. Marine plastic litter represents a critical challenge for Small Island Developing States (SIDS), largely due to their geographical proximity to ocean gyres where floating plastics accumulate, coupled with waste management systems that are frequently inadequate. Although SIDS contribute only marginally to global plastic production and consumption, they face a dual burden of receiving transboundary debris from distant nations while also contending with their own mismanaged local waste. Other than that, structural challenges such as the high costs of inter-island transport, dependence on landfills as the primary means of disposal, and limited recycling facilities further reduce the ability of SIDS to manage the escalating

plastic waste problem [63]. These challenges are projected to escalate with increasing urbanization, population expansion, and shifts in consumption patterns.

The ecological consequences of macro- and MP litter for SIDS are profound. Plastics persist in the marine environment, fragmenting into micro- and nanoplastics that are readily ingested by marine organisms. This leads to entanglement, ingestion, habitat alteration, and chemical transfer, with cascading effects on biodiversity and ecosystem health. Coral reefs, seagrass beds, and mangroves, which are critical to coastal protection, fisheries productivity, and carbon sequestration, are particularly at risk. Plastic entanglement reduces coral growth and increases susceptibility to disease, while ingestion by fish, seabirds, and turtles not only threatens wildlife survival but also jeopardizes local food security [64]. From a socio-economic perspective, the dependence of SIDS on fisheries and tourism makes them disproportionately vulnerable. Plastic litter on beaches deters tourists, reduces aesthetic value, and damages national branding as pristine island destinations. Meanwhile, MPs contamination in seafood undermines fisheries markets and consumer confidence. Since these industries form the backbone of SIDS economies, marine plastic litter directly translates into lost revenues, unemployment, and heightened poverty risks [64]. The problem is further compounded by the costs of beach clean-ups and ecosystem restoration, which are significant burdens for nations with already limited resources. In sum, marine plastic pollution represents not only an environmental threat but also a socio-economic and cultural challenge for SIDS, making it an existential issue. Protecting these nations requires urgent, coordinated, and equitable global action to safeguard their ecosystems, economies, and communities.

10. Global Efforts to Reduce Plastic Pollution

The rapid increase in plastic production and consumption has made it increasingly challenging to prevent plastics from entering the marine environment. While eliminating plastic pollution entirely may seem implausible, a critical first step in mitigation involves identifying the primary sources and dominant types of plastics found in marine ecosystems. Historically, significant fractions of marine plastic debris have been landfilled due to their perceived low economic value. However, recent insights reveal that such waste holds substantial potential for recovery, particularly through chemical recycling and energy conversion technologies

[65]. The widespread prevalence of plastic debris in the ocean has attracted growing concern from scientific communities, civil society, policymakers, and both public and private stakeholders [66]. Plastic makes up an estimated 60% to 80% of all marine debris, and the financial burden of cleanup operations often falls on local authorities and maritime sectors that are not directly responsible for the pollution. The transboundary nature of marine plastic pollution has elevated it to a globally recognized issue, prompting urgent action at both national and international levels.

In response, governments around the world have begun implementing comprehensive management strategies to curb plastic pollution. These include legislative measures such as bans or restrictions on single-use plastics including plastic bags, straws, and cutlery as well as the introduction of Extended Producer Responsibility (EPR) schemes. EPR policies mandate that manufacturers take responsibility for the full life cycle of their products, including post-consumer disposal and recycling. At the international scale, collaborative efforts and multilateral agreements are emerging to tackle plastic pollution through shared objectives. Programs spearheaded by organizations such as the United Nations Environment Programme (UNEP) and regional alliances aim to establish common standards, promote responsible waste management, and set ambitious targets for plastic reduction. Furthermore, the continuous monitoring and research on marine debris are essential to quantify the scale of the problem and guide data-driven interventions. National governments should enhance initiatives that incentivize recycling behavior, such as offering rewards for waste segregation and supporting the development of recycling infrastructure. Public awareness campaigns also play a vital role. These include educational programs, community outreach, and advocacy efforts designed to raise awareness about the environmental and ecological impacts of plastic pollution. Early education initiatives, particularly those targeting school-aged children, can help foster long-term behavior change. Integrating environmental stewardship, waste reduction, and recycling practices into formal education curricula will cultivate a culture of sustainability from a young age. Ultimately, reducing plastic consumption, improving recycling practices, and encouraging sustainable lifestyles are essential components of a holistic strategy to mitigate the marine plastic crisis. Referring to Table 2, the engagement of the government in ocean governance such as by participating MARPOL will help the government to manage strategies to govern the ocean in terms of marine pollution [67]. The government can also allocate funding for marine pollution research so that there will be more comprehensive data that can be presented to the public.

Table 2. Roles of government, industry, and consumer in reducing marine debris pollution

Sector	Roles	Solutions
Government	<ul style="list-style-type: none"> Engage in ocean governance. Improve implementation of policy. Respond to climate changes. Participate in and support international agreements and partnerships aimed at reducing marine debris pollution, such as the United Nations' Clean Seas campaign. 	<ul style="list-style-type: none"> Provide more funding for the research on marine debris so that there will be more comprehensive data that can be presented to the public. Develop management guidelines. Impose fine for industry which does not obey the guidelines. Ensure the participation of the nation in tackling climate change by participating in the Paris Agreement.
Industry	<ul style="list-style-type: none"> Ensure that the industry is environmentally-friendly. Ensure proper disposal of industrial waste especially those that are of plastic origin. Adopt corporate social responsibility policies that prioritize environmental sustainability and actively work to reduce plastic waste. 	<ul style="list-style-type: none"> Stop the usage of MPs in consumer products such as facial cleansers. Practice waste minimization with modification of technology. Report transparently on environmental impacts and efforts to mitigate marine debris pollution, building trust with consumers and stakeholders.
Consumer	<ul style="list-style-type: none"> Choose products with minimal or no plastic packaging and opt for reusable items instead of single-use plastics. Dispose of plastic waste responsibly by recycling and avoiding littering. Participate in local clean-up events and programs. Support and participate in initiatives and campaigns aimed at reducing marine debris. Advocate for stronger policies and practices related to plastic use and waste management. 	<ul style="list-style-type: none"> The consumers should be educated more about the extent of plastic pollution in our ocean. Educate others about the impacts of marine debris and encourage friends and family to adopt sustainable practices. Provide feedback to companies and policymakers on environmental issues and support those taking proactive measures to reduce marine debris.

Other than that, having up-to-date data will also enable them to monitor the current status of marine pollution. Since there is still much that we do not know about this problem, continuous research and monitoring of marine litter especially plastics must be strengthened to find a way to get rid of it. The MARPOL Convention is the main international convention that focuses on the pollution of the marine environment caused by ships. This Convention includes regulation that aims to prevent and minimize pollution from ships be it accidental or from routine operations. In MARPOL, there are currently six different Annexes depending on the types of pollutants emitted from ships [67]. Annex V is the annex that deals with pollution by different types of garbage from ships. The most important feature of Annex V is the complete ban imposed on the disposal of all forms of plastics into the sea [68]. Other than that, the government can also improve their policy implementation by referring to the Sustainable Development Agenda made by the United Nations which involves 17 Sustainable Development Goals (SDGs). The SDG is a good reference for the government to improve their policy as it includes targets to prevent and reduce all kinds of marine pollution [69]. The government authority can develop management guidelines and implement them such as by imposing fines on industries which do not obey the guidelines. There should be a ban on products that contain MPs such as facial cleansers and body scrubs. The industry that produces consumer products containing MPs

should act and stricter regulation should be developed. Other than that, the industries must also practice waste minimization by modifying their technology to ensure that minimal or zero waste is produced especially those that are of plastic origin. The government can also increase fees and taxes on plastic manufacturing industries. This can be done by making the fees for recycled plastics cheaper than those for fossil. Finally, the users of plastics must be educated more about the extent of plastic pollution in our ocean. This can be started by educating young children so that they will grow up with the right attitude towards caring for the environment. Having up-to-date data on the current situation of marine pollution will convince consumers to practice proper waste management and encourage them to recycle their recyclable wastes.

11. Conclusions and Recommendations

In conclusion, this study exposes the global scenario of marine and coastal MP pollution from multiple perspectives. Based on the examined literature, it could be summarized that MP abundance and characteristics such as polymer types are influenced by anthropogenic sources, with the primary contributions originating (80-90%) from land-based activities such as water treatment plants, household supplies and personal care products. Polypropylene (PP) and polyethylene (PE) were the major

types of MP found in the marine environment. Besides, this study also investigates how MPs function as vectors for heavy metals and polyaromatic hydrocarbons (PAHs) in the marine environment, and includes examining how MPs can adsorb and transport these hazardous substances, potentially leading to their accumulation in marine organisms and ecosystems. The impact of MP pollution, including its impacts on marine life, such as ingestion by marine species and resulting health consequences is also highlighted in this study. Additionally, it addresses the disruption of marine ecosystems and food webs, the potential risks to human health through seafood consumption, and the economic implications for industries dependent on marine resources. To effectively address this urgent threat, a global effort to reduce MP pollution has been presented to coordinate international policies, enhance research, and foster collaborative initiatives. These measures include creating and enforcing stricter regulations on plastic production and disposal, investing in new technologies for waste management and recycling, and supporting global and local clean-up efforts. Furthermore, the effort involves strengthening public education and engagement to drive behavioral changes and promote sustainable practices across various sectors. The goal is to create a unified approach that integrates scientific research, policymaking, and community action to mitigate the impact of MPs on the environment.

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