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ARTICLE

A Comprehensive Review on Microplastic in Beach Sediment

Yong-Hong Wang [1,2*], *Abiola John Osanyintuyi* [1], *Jing Luan* [1]

[1] *Key Laboratory of Submarine Geosciences and Prospecting Techniques, College of Marine Geosciences, Ocean University of China, Qingdao 266100, China*

[2] *Laboratory for Marine Geology, Qingdao Marine Science and Technology Center, Qingdao 266237, China*

ABSTRACT

Microplastics (MPs) have been recognized as one of the biggest environmental challenges in marine ecosystems. Despite the extensive existing research knowledge on MPs, the origin, transport and deposition of MPs in beach sediment is still unclear. This review highlights the global occurrence, spatiotemporal distribution, sources, transport and accumulation of MPs on about 1700 world's beaches, exploring the existing connotions on the influence of external mechanisms, internal mechanisms and local beach characteristics on MPs found in beach sediment. This review further highlights the challenges and future research potential of MPs in beach sediment. The review revealed 59.4% of studies were using "n/kg" as a unit, 30.8% using "n/m^2" as a unit, and 9.8% using both units. Most paper on beach microplastics are published from Asia (45.1%) with India having a global percentage of 13.8. The summary of this review indicated that the distribution of microplactic abundance in beach sediment < 100 n/kg (39.5%) and 100–500 n/kg (36.4%), 1000–5000 n/kg (12.3%), 500–1000 n/kg (6.8%) and > 5000 n/kg (4.9%) with beaches in Africa, Asia, Europe and North America recorded high MP abundance (> 1000 n/kg). This review clarifies the need to improve the research knowledge of MPs in beach sediment by creating a global database to access the existing threat; using a standard measuring method and unit for identification of

*CORRESPONDING AUTHOR:
Yong-Hong Wang, Key Laboratory of Submarine Geosciences and Prospecting Techniques, College of Marine Geosciences, Ocean University of China, Qingdao 266100, China; Laboratory for Marine Geology, Qingdao Marine Science and Technology Center, Qingdao 266237, China; Email: yonghongw@ouc.edu.cn

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results. Ultimately, we suggest the implementation of holistic management strategy for MP pollution in beach sediment, most importantly, by focusing on the elimination of fibre to drastically reduce the MP pollution.

Keywords: Microplastics (Mps); Beach Sediment; Global Distribution; Occurrence Characteristics

1. Introduction

Plastic fragments smaller than 5 mm in size are referred to as microplastics (MPs), which was first proposed in 2004 [1]. In 2017, the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) redefined MPs as plastic fragments with diameters between 5 mm and 1 nm. Depending on their origin, MPs can also be classified into primary and secondary MPs. Primary MPs are produced in microscopic sizes for specific purposes and are usually found in toiletries and cosmetic products. Secondary MPs are formed by the long-term physical, chemical, and biological degradation and fragmentation of larger plastic debris in the environment [2]. Approximately 15%–31% of MPs are estimated to originate from primary sources [3], while the rest are from secondary sources.

Studies have shown that global plastic production has increased from 1.5 million tonnes in 1950 to approximately 390.7 million tonnes in 2021 [4]. Global annual plastic production is projected to reach 1.1 billion tonnes by 2050 [5]. Approximately 10% of plastic waste enters the marine environment through various pathways, including drainage, direct disposal, etc [6]. As a result, the marine environment is considered a significant sink for MPs. In 2015, MP pollution was identified as one of the biggest environmental challenges, along with global climate change, ozone depletion, and ocean acidification [7].

Beaches are in the transitional zone between the ocean and land and are particularly susceptible to garbage pollution due to frequent human activities such as recreation and tourism that promote their littering [8]. Additionally, MPs can be sourced offshore and quickly accumulate in beach sediments. Moreover, beach litters, the primary type of plastics, are prone to mechanical abrasion on beaches due to the coarser sediment particles, action of wind, waves, oxygen, and degradation by sunlight, causing fragmentation of the plastics into smaller MP fragments [9,10].

Currently, there are some review articles on beach MPs. Mesquita et al. [11] have systematically reviewed the spatial distribution and the methods applied in assessing MP contamination on beaches in Latin America and the Caribbean. Uddin et al. [12] reviewed the spatial variability in MP inventories within marine sediment cores. Van Cauwenberghe et al. [13] reviewed the techniques, occurrence and effects of MPs in beach sediment. Other review articles on beach MPs focused on analytical methods and techniques of MPs. For example, Soursou et al. [14] reviewed the separation, extraction, identification, and quantification techniques of MPs in beach sand and discussed the expectations and challenges regarding instrument innovation. Hanvey et al. [15] reviewed the sampling, extraction, quantification, quality control and quality assurance methods for MPs in sediments.

However, a comprehensive understanding of MPs quantification, sources, transport, degradation, and accumulation, pathway and potential implementation in future research in beach sediment remains incomplete. Hence, we make the first comprehensive database for the situation of MPs in beach sediment from globally available research articles. We further highlighted the usage of MPs in sedimentary dating and the potential of organism in beach sediments as MPs biomarkers.

This review focuses on the research status of beach MPs beyond technical methods. Workflow of the methodology used in this review is as follows (**Figure 1**).

(1) We retrieve research articles using the Web of Science and Science Direct databases with the keywords "microplastic/microplastics" and "beach/beaches" to retrieve scientific literature. Only studies that provided original data on microplastic accumulation in natural or semi-natural beach sediment environments were considered.

(2) We systematically identified the characteristics of MPs (abundance, shape, color, size, polymer compositions) in beach sediment, and then summarize the sources of MPs in beach sediment based on their characteristics.

(4) We presented the clear understanding of spatial (surface and vertical) and temporal (Monsoon, aeolian and tourism season) distribution change of MPs in beach

sediments and their external and internal mechanisms.

(5) We presented the potential usage of MPs for sedimentary (age dating) and ecological (bioindicators) of MPs in beach sediments.

(6) We summarize the current issues associated with sediment MPs research and provided solutions and valuable references for determining future research priorities and management strategies for beach MPs.

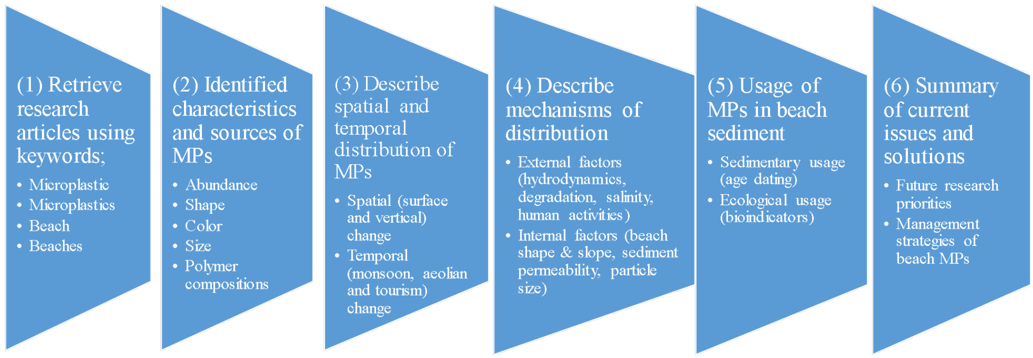


Figure 1. Flow chart of workflow of the methodology used in this review.

2. Literature Review on Global Beach Sediment Microplastics

This review paper considered scientific literature published from 2011 until February 2025. To quantify the global MPs data in beach sediment, we manually retrieved articles from the Web of Science and Science Direct databases using the keywords search of "Microplastic/Microplastics", "beach/beaches", and "sediment/sediments". These keywords are inevitable for articles in that include the scope of microplastic in beach sediment. We curated the outcomes in an Excel spreadsheet. Only studies that provided original data on MP accumulation in "n/kg" (number of MPs per kilogram of sediment) and "n/m^2" (number of MPs per meter square of sediment) units in beach sedimentary environments were considered. The reported content of most of the research articles mainly includes the concentration, spatial and temporal distribution, morphology, polymer composition, sources, methods for risk assessment, potential hazards, applications, and prevention and management measures of MPs in beach sediments. More than 1700 beach data were retrieved from 235 relevant papers from 54 countries and the Antarctic and Arctic regions. Some literature focused on a single beach as the research objective, while others researched multiple beaches within a particular region.

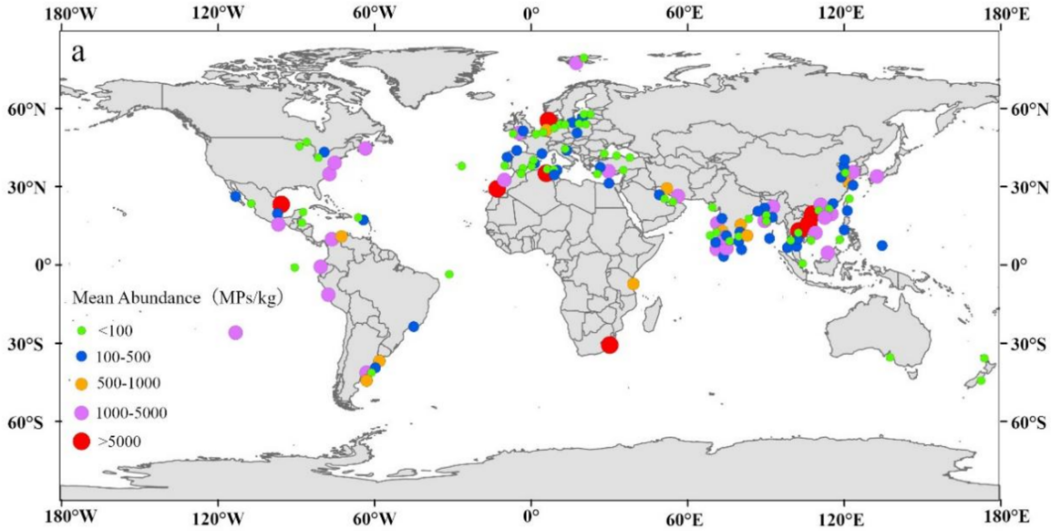
We discovered that the number of characteristics described by the authors of the research considered varies depending on the research goal and access to equipment/resources. All articles considered in this review did present the abundance of MPs in beach sediment. However, about 30% only reported the colour, 40% described the colour characteristics in their research, 60% of the articles in this research indicated the size characteristics of the MPs they studied, and less than 20% were able to include polymer properties in their articles.

In terms of distribution, the highest number of published papers is from Asia (45.1%), followed by Europe (23.8%) and the Americas (21.7%), and the lowest from Africa (5.5%), Oceania (2.6%), Arctic (0.9%) and Antarctica (0.4%). In terms of countries, a significant proportion of the literature is from India (13.8%), China (11.4%), Spain (4.9%), Brazil (4.6%), Germany (3.7%), Mexico (3.2%), and the United States (3.2%). These articles were published in various journals, mainly including "Marine Pollution Bulletin" (47.7%), "Science of The Total Environment" (11.5%), "Environmental Pollution" (5.5%), and "Environmental Science and Pollution Research" (4.3%).

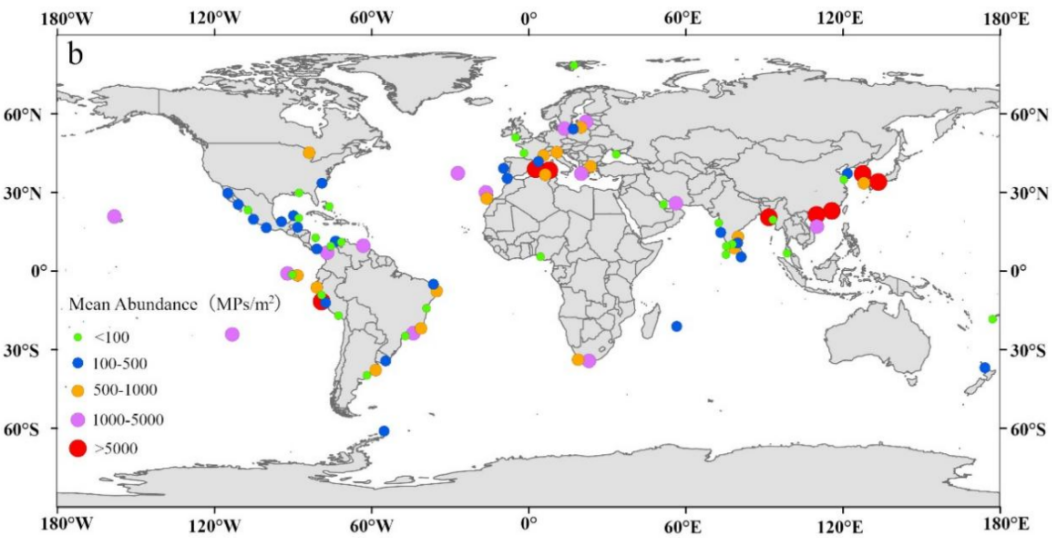
3. Characteristics of MPs in Beach Sediments

3.1. Abundance of Beach MPs

MPs are present in beach sediments worldwide with a wide range of abundance (**Figure 2**). In our analysis, "n/kg" and "n/m^2" are the considered units for the description of the abundance of beach sediment MPs, with 59.4% of studies using "n/kg" as a unit, 30.8% using "n/m^2" as a unit, and 9.8% using both units. The information on MPs on beaches is well published, with researchers preferably using n/kg rather than n/m^2 in Europe, Asia, Africa and Australia. In the Americas, the MP research concentrated on the use of n/m^2 as the favourable unit of result presentation.



(**a**)



(**b**)

Figure 2. The mean distribution of MP in the sediment of different beaches worldwide: (**a**) The unit of MP abundance is "MPs/kg" (mean distribution of MPs particles in a kilogram of sediment—data from beaches that reported results in n/kg); (**b**) The unit of MP abundance is "MPs/m^2" (mean distribution of MPs in a square meter of sediment—data from beaches that reported results in n/m^2).

Beaches with lower MP abundance (< 1 n/kg) in "n/kg" include beaches of Holbox Island in Mexico [16], Adriatic Sea, Mediterranean, Slovenia [17], and Adelaide Beach in South Australia [18]. Beaches with higher MP abundance (> 200,000 n/kg) include beaches in the eastern Gulf of Thailand [19]. The abundance of MPs in most study sites are <100 n/kg (39.5%) and 100–500 n/kg (36.4%), while in a few study sites, the abundance ranges are 1000–5000 n/kg (12.3%), 500–1000 n/kg (6.8%) and >5000 n/kg (4.9%). With this unit, beaches in Africa, Asia, Europe and North America recorded high MP abundance (>1000 n/kg), with only beaches in South America having moderate levels (500–1000 n/kg).

3.2. Shapes

Only 93% (amounting to 319) of articles considered in this review indicated the shapes of the MPs in their research. MPs in beaches come in various shapes, including fibres/lines, fragments, foams, pellets, films, microbeads/microspheres, blocks, etc., of which fibres/lines and fragments are the most common two shapes. From the 319 research papers, 97% of beaches have fibres-shaped MPs on them, 69% of beaches have fragmented MPs present, about 55% of beaches have fragments present, 37% of beaches have reported pellets present, and the remaining 8% of beaches have reported other shapes such as ellipsoids, blocks, and microbeads accounted for the most significant proportion. Some beaches have multiple shapes of MPs; for example, foams, fibres, fragments, films, and granules were found on the coastal beaches of Sishili Bay in the northern Yellow Sea [20]. On the other hand, some beaches only have one MP shape; for example, fibre is the only identified MP shape on Tampico Beach along the Gulf of Mexico [21]. We discovered that, on average, fibre usually constitutes more than 50% of the shapes of MP found on a particular beach [22]. For example, fibre was 93% of the total MPs found on selected beaches in Virginia and North Carolina, USA [23].

3.3. Colors

Globally, the colour of MPs found on beaches is diverse, with over ten different colours, but primarily transparent/white, blue, and black. According to statistics, among 178 articles that included the colour of beach MPs in their research, 96% of beaches show that white/transparent/colourless colour present on the beach, 73% of beaches show blue is the primary colour of MPs, 71% beaches show black MPs account for the most significant proportion, and 36% beaches show other colours (red, yellow/orange, green, beige) account for the most significant proportion.

White and transparent MPs were recorded to be the most abundant due to the long-term disintegration and weathering process of another type of MPs [24,25]. For instance, on the Brazilian coast, up to 60% of MPs in their research were white [26]. On Quilon Beach, India, white and transparent colours account for 64% of the total MPs in the beach sediment [24]. In Qingdao of China, transparent MPs were high when observed in multiple seasons, with an abundance as high as 65% in Autumn and 60% in Spring [25]. Although still the dominant colour recorded, Shaji et al. [27] discovered that only 27% of transparent MPs were present in the beach sediment samples from Andhra Pradesh, India. On some beaches, white or transparent MPs were the only MP colours recorded [28,29]. Some articles did not record white/transparent. For example, Pasolini et al. [30] recorded only green colour MPs on a beach in Svalbard, Arctic.

3.4. Size

Different studies have different ranges of observed MP particle sizes, which depend on the experimental equipment and identification techniques researchers' use. Currently, the most minor detectable limit in research is one μm [31,32], as plastic particles below one μm are called nanoplastics, requiring more advanced detection techniques. Only 234 articles considered in this review conducted size analysis, while the remaining 20 articles didn't present the result due to limitations in observation technology. From our review, we observed that the most common range of MPs often discovered are those with sizes between 300 and 5000 μm with 70% of the articles considered in this research detecting MPs in this range. Moreover, Chaudhary et al. [33] have corroborated that more than 40% of MPs in marine environments exist in this size range. Interestingly, fibre, the most abundant shape of MPs, exists in this range. Nearly 80% of the articles that indicated the size of MPs in this review identified the existence of fibre MPs in their research.

3.5. Polymer composition

Among the 201 articles reporting the polymer composition of MPs on beaches, polyethene (PE) was identified on 94% of beaches, polypropylene (PP) was identified on 89% beaches, polystyrene (PS) was identified on 88% beaches, polyethene terephthalate (PET) and polyvinyl chloride (PVC) was identified on 30% and 28% beaches respectively. Other polymer types of MPs such as polyester and nylon were identified on about 28% beaches. Corroborated from our work, other research has also shown that PE and PP are the two most widely produced polymers globally [34,35]. They are commonly used in disposable and short-lived products such as shopping bags and plastic bottles. Poor waste management has resulted in the widespread presence of these polymers in various environments [36].

4. Sources of MPs Found in Beach Sediments

4.1. Sources

The sources of MPs in beach sediment are still complex. It is found that the source of MPs is from the land, the open sea [37] and air. Plastic products undergo weathering and disintegration to form MPs. Eventually, most MPs initially originate from land, then are transported by different pathways (air, water bodies) and in most cases, find their way into the open ocean/sea (except direct dumping/discharge) before being reworked, transported and deposited in beach sediments by the actions of wave, tide, current, longshore transport and storm conditions.

Air-sourced MPs are often from sea spray and resuspension from tyre wear, landfill, nail salons, clothing materials, vented mechanical drying of synthetic material, human movement when wearing synthetic clothing, etc, transported by wind and can be deposited to beach sediment by rain [38]. Land-sourced plastic waste includes various types of plastic waste (such as degradation from packaging bags, plastic bottles, and foam boxes) directly discarded on the beach, as well as degraded plastics washed away by rainwater, discharged from land-based sewage outlets, or river runoffs. Sea-sourced MPs migrate and accumulate on beaches under the influence of ocean currents and tides [39]. This includes degradation from discarded fishing gear such as damaged fishing nets, ropes and fishing lines in fishery production, foam plastics and buoys from aquaculture, domestic waste, ropes, and maintenance waste from various ship activities and offshore platforms. Conclusively, MPs in beach sediments are primarily sourced from offshore source. It should be noted that land-sourced MP can be firstly deposited in the open ocean and further re-deposited in beach sediment as a sea-sourced MP. The abundance and where MPs are deposited in sediment are affected by different factors, including the number of MPs from various sources, the transport mechanism from land, nearshore dynamics aiding deposition, degradation of plastics into MPs, and beach characteristics influencing the deposition.

4.2. Shapes and their Indication for Sources

Researchers have attempted to specify MP shape to some particular sources. For example, fragmented MPs have the broadest range of sources, as they are sourced from cracking and crushing of industrial, agricultural, and household plastic wastes [9]; Films mainly come from everyday plastic food packaging bags, as well as waterproof film layers of various woven bags such as fertilizer bags and cement bags [40]; Microbeads are usually derived from personal care products and medications [41]; Fibers typically originate from fishing activities [42] and clothing [43,44]. Pellets typically originate from industrial inputs [45]; Foams, having many uses, often originate from packaging, construction and fishery waste [46].

4.3. Colors and their Indication for Sources

Previous studies have proposed that the different colors of MPs can indicate their different sources in the environment [47,48]. A large amount of white and blue MPs in research may originate from fibres released by fishing nets, ropes, clothing, packaging, and kitchen utensils [49–51]. Blue MPs may also come from the degradation and weathering of blue plastic packaging used for food, cosmetics, and toys [52]. Generally, the clothing worn by beach tourists may be the main source of various coloured fibres on the beach [43,44]. Ultrafine fibres with bright blue, purple, red, or green colours are typically made of polyester (PES) and acrylic acid (AC) [44,48].

Overall, determining the source of MPs with the colour is a daunting task since MPs/marine litters will undergo mechanical abrasion and discolouration on long-term exposure to ultraviolet light and high temperature, creating white and/or transparent MPs [53–55]. Also, the colour of MP particles is essential in visual identification, among other debris. It is also crucial in identifying the potential to be swallowed by a visual predator and provides information on chemical composition, potential sources, and the level of degradation [56].

4.4. Size and their Indication for Sources

Scientists have attempted to determine the MPs' source in beach sediments based on their size. For example, Gül [57] concluded that a seaward decline in the average size of MP during the tourism season could indicate that the primary source of MPs is direct dumping from tourists. In general, numerous studies have concluded that the abundance of MPs decreases as their particle size increases [20,53]. This is backed to be a result of the environmental degradation of larger plastic fragments into smaller ones [26]. Since larger plastic fragments are broken down into smaller ones due to high temperature, ultraviolet light and mechanical stress, thus the MPs sources are related to the source of larger plastic [53,54].

4.5. Polymer composition and their Indication for Sources

Identifying the source of MPs based on its polymer has been mostly done based on extrapolation of activities on and/or near a beach. For example, Shaji et al. [27] conclude that the PET, PP and PS found on Andhra Pradesh, India beaches could be sourced from tourist waste and damaged fishing gear/nets. Eventually, the source of multiple polymers usually found on a particular beach can be linked to multiple sources, including human sources (urban, domestic, industrial and tourism waste disposal), sea-based activities (shipping and fishing) and atmospheric fallout [58,59]. Specifically, polymers such as PS are used in packaging fishing and industrial materials and can be sourced from styrofoam, toys, CDs, toothbrushes and food containers [59]. PA/NY type of MPs might be sourced from sea-based sources, including fishing nets, ropes and trawls [59,60]. PVC polymer in beach sediment most likely originates from the construction industry through pipes. PET is usually sourced from commercial and/or recreational fishing materials [59]. Pegado et al. [61] concluded that polystyrene foam fragments on a tropical beach proximate to a river outlet are most likely sourced from land and transported by river and surface current before deposition by wave and tide with factors like the MP lightweight and rain discharge complementary to the process.

Eventually, the redistribution of polymers to the beach is complex. Normally, polymers are light materials whose existence in beach sediment is affected by the combination of effects of hydrodynamic condition, biofouling and UV light [54]. For instance, it might be difficult to accurately determine the source of some MP polymers such as LDPE, HDPE, PE, and PP since they are often more susceptible to the disintegrating effect from excessive heat oxygen content, mechanical effect (wind, waves), high temperatures (activates higher resistivity and cleavage formation for degradation) and biological activity (water) [62,63]. The occurrence of different polymer compositions, especially in concomitant with high abundance, suggests the role of beach morphodynamics and local disturbance of the sediment bed in shaping MPs distribution [64].

5. Distribution of MP in Beach and its Mechanism

5.1. Spatial Distribution Characteristics

5.1.1. Surface Distribution Characteristics

Numerous studies attempted to show the distribution of MPs on a beach. They often have discovered that the concentration of MPs near the high tide line is higher than that near the low tide line. For example, Zhang et al. [65] identified up to 60 MPs in the high tide while only 2 MPs in the low tide zone of Yugang Park Beach in Southern China due to low tidal power. Wave and tide are typically considered the redistribution and sorting mechanisms for MPs in beach sediment. Initially, MPs in the nearshore open ocean can easily undergo tidal mixing, especially in summer [66]. The MPs are often transported to the backshore during high tide and deposited when the tide recedes [67]. Malli et al. [68] have demonstrated that neap tides favour the retention of MPs in sediment more than spring tides.

5.1.2. Vertical Distribution Characteristics of MPs

Considering only the top 10 cm of beach sediment cores, researchers have shown that MPs in beach sediments generally exhibit an increasing trend in abundance with increasing depth. For instance, Veerasingam et al. [58] investigated the vertical distribution of MPs in beach sediments around the Ras Rakan Island of Qatar. Samples were taken at nine locations vertically, at depths of 30 cm with 5 cm intervals. The surface layer (0–5 cm) had the highest abundance of MPs, with a maximum concentration (average 320.7 n/kg) that was 25 times higher than the sediment in the bottom layer (10–15 cm). The study concluded that the MPs are transported by the winds, currents, and stokes drift since none of the cores shows MPs below 20 cm. Yao et al. [69] collected sediment column samples at the top 30 cm depth of five beaches in Xiamen Bay to analyze the vertical distribution characteristics of MPs and their influencing factors. They concluded that waves, tides, shoreline shape, tourism activity, and cleaning of marine debris removal. The highest abundance was found in the 0–10 cm layer, significantly higher than the 20–30 cm layer, followed by the 10–20 cm layer. The MPs in the top two layers accounted for over 70% of the total abundance in all layers, indicating a significant decrease in abundance with increasing depth. The study also found that coloured MPs were present in all layers of the sediment cores, but the proportion of coloured MPs in the 10–20 cm and 20–30 cm layers was higher than that in the 0–10 cm layers. This may be due to the higher density of most pigments than MPs, which increases the density of coloured MPs and makes them more likely to sink when the sediment is disturbed.

5.2. Temporal Change of Beach MPs

The concentration of MPs can change with time on several beaches in a particular area. Often, the seasonal conditions of monsoon, wind, and particular tourism activity, such as sunbathing in summer, could be linked to the temporal changes of MPs in beach sediment.

5.2.1. Monsoon Season

Rainfall conditions promote the deposition of more MPs than non-rainfall conditions. High monsoon activity has been tied to increase MPs on beach backshore in Chennai and Puducherry, India[66]. The increased rainfall activities can aid in the transportation of massive MPs via other mediums, such as river input, after the dry season. Oftentimes, the abundance of MPs in beach sediment is expected to double during the monsoon season when compared to the dry season. For example, along several South African beaches, de Villiers[70] attributed the effect of monsoon to river run-off aiding the deposition of more land-sourced MPs. They measured about a 50% increase in the level of microfibre in May–June 2016 when they compared their result to February–March 2017. Similarly, in Tsing Lung Tau, Hong Kong, sediment MPs were about 5 times more in the monsoon season when compared to the dry season[71]. They attribute the increase to typhoons and stormwater associated with the area's monsoon season. Since storm waves are common in the monsoon season, they tend to push MPs backshore, while summer waves are calmer and swash zones are restricted to the high tide line[66]. This further facilitates that rainfall can redistribute MPs from terrestrial sources via stormwater and open ocean because of its influence on nearshore storm conditions such as typhoons.

5.2.2. Aeolian Season

Aeolian transport could affect MPs' characteristics with season. Garello et al.[72] have suggested that wind with a velocity above 24km/h can rework the sediments and redistribute the MPs within the sand grain column, especially in the dry season. Also, the transport of MPs by wind can be aided by a beach's geometry and morphological features[73]. The orientation of a beach affects the direction of the prevailing wind, thereby causing the re-suspension of MPs transported. The low-density characteristics of MPs can also facilitate long-distance aeolian transport, which will affect its source and abundance on a beach[74]. The intensive wind-weather force can induce the redistribution of MPs in beach sediment by other mediums, such as wave and longshore currents, since wind plays important roles in the manifestation of these factors. Besides, increased wind and storm surge activities have been attributed to the redistribution of MPs on the beach[75].

5.2.3. Tourism Season

During the summer, recreational activities such as camping and swimming, which are more frequent on the beach, can result in more MP pollution[76]. In Qingdao, Luan and Wang[25] reported human activities (tourism) contributed to the temporal distribution of MPs in beach sediment. Seasonal variations of MPs due to tourism (source of MP) are often controlled by the hydrodynamic conditions (reworking mechanism) peculiar to those periods. When compared to winter, summer (tourism season) is documented to have more light-coloured and diverse types of MPs[53]. Pellets of PE were more abundant during wet seasons, likely due to backwashing during storm events, while fragments and pellets of both PE and PP characterized dry seasons[77]. On several Turkish Black Sea sandy beaches, a major contributor of MPs was the short-term seasonal tourism activities[57].

5.3. Distribution and Transport Mechanism

The distribution, transport mechanism and driving mechanism of MPs in beach sediment exhibit considerable complex behaviour. MPs undergoes both mechanical and chemicical disintegration as the particles migrate through different medium including (water and air). The direction of migration of MPs starts with plastic fragments from the land/air to the the open sea[78]. The plastic products then undergo weathering and disintegration to form MPs. Eventually, most MPs initially originate from land, then are transported by different pathways (air, water bodies) and in most cases, find their way into the open ocean/sea (except direct dumping/discharge) before being reworked, transported and deposited in beach sediments by the actions of wave, tide, current, longshore transport and storm conditions.

5.3.1. External Mechanism

The external mechanisms governing the transport and deposition of MPs to the beach can be categorized into 4 primary aspects: hydrodynamics (e.g., wave & tide, nearshore current, and river), degradation, salinity and human activities (**Figure 3**).

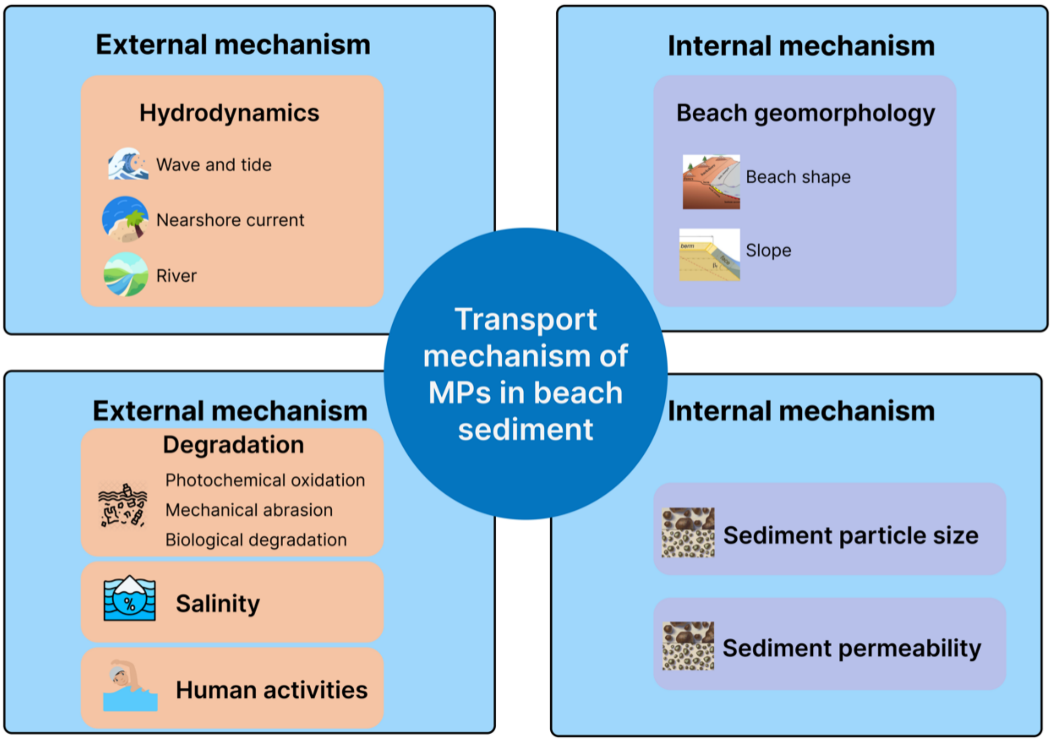


Figure 3. Internal and external mechanisms affecting the transport of microplastics in beach sediment.

Hydrodynamics

Hydrodynamic factors such as waves, tides, ocean currents significantly determine the characteristics (abundance, color, shape and size) of MPs found in beach sediments[45]. These factors do not only serve as a transport medium but as well as determine the rate of deposition and where MPs are found on the beach.

(1) Wave and tide

Studies have attempted to show the distribution of MPs on a beach. They often have discovered that the concentration of MPs near the high tide line is higher than that near the low tide line. For example, Zhang et al.[65] identified up to 60 MPs in the high tide while only 2 MPs in the low tide zone of Yugang Park Beach in the North Yellow Sea basin due to low tidal power. Wave and tide are typically considered the redistribution and sorting mechanisms for MPs in beach sediment. Initially, MPs in the nearshore open ocean can easily undergo tidal mixing, especially in summer[65]. The MPs are often transported to the backshore during high tide and deposited when the tide recedes[67]. Malli et al.[68] have demonstrated that neap tides favour the retention of MPs in sediment more than spring tides. Moreover, factors like flood-ebb and spring-neap variations concomitant with sea circulation, mixing, and stratification can affect the net transport of MPs at transitional zones[29].

(2) Nearshore current

Nearshore currents transport MP and deposit them on beach sediment in a process called "beaching". Nearshore currents have been recognized as a transport mechanism of terrestrial MPs into the open ocean and redistribution alongshore [29]. Gao et al. [53] confirmed that westward moving nearshore currents in Qingdao, China, which led to the higher MP content in the sediment of May Fourth beach and the lower MPs contents in the sediment of Shilaoren bathing beach. Gedik et al. [79] examined the sediment samples from several Turkish beaches. They concluded that the Mediterranean current causes MPs upwelling gyre to gather water nearshore and deposit in beach sediment. Their record revealed higher values (1688 ± 746 MPs kg^{-1}) of MPs in sediment found in the areas corresponding to the upwelling region when compared to 118 ± 97 MPs kg^{-1} recorded in a region not influence by the current. Constant et al. [80] explained that alongshore current favoured the accumulation of MP on Fourat beach when compared to La Crouste beach. The two beaches are located in Mediterranean's Gulf of Lion, a located dominated by the Northern Current. It should be noted that the extent of MPs transport by nearshore currents may depend on the characteristics of the MP, as well as the direction and strength of the current [29,37,81] The buoyancy property of MP (density, size, and shape) is often important in the open ocean. Surface currents may move buoyant MP much faster in the open ocean [29].

(3) River

Rivers can effectively transport medium size MPs (2000–5000 μm) from land to the sea [66]. In fact, the transport of MPs in the rivers has been cited to be similar to the well-known transport of suspended sediment [73].

Around the world, river discharge has been reported to be a significant source of MPs found in the sediment of beaches adjacent to rivers. River sourced MPs are initially transported into the open ocean increasing the risk of trasboundary movement. After transport into the open ocean, it takes approximately 3 years for the MP to be transported by nearshore currents before "beaching" [82,83]. Matsushita et al. [83] showed that the MPs released from the Pearl River, Mekong River, and Pasig River tend to be transported to the East China Sea and the northwest Pacific Ocean through the Luzon Strait and Taiwan Strait during the prevailing southwesterly monsoon. If the MPs remain in the South China Sea, many of them are transported to nearby shore and beached, depositing in beach sediment.

Rivers Brenta and Adige, as well as the Venetian lagoon, were linked to be the major source of MPs with an abundance of up to 672 to 2175 MPs per kilogram DW at the catchment basin of the Po River in Northwest Italy [84]. On the North Yellow Sea coast of Sishili Bay, Li et al. [20] suspected that river discharge could have caused an increase in MPs on the beaches they studied.

On the Praia Grande (Torres/RS—Brazil) beach, Pelegrini et al. [85] attributed the Mampituba River for the supply of up to 1500 MPs/kg found in the sediment of the up section of the 2 km beach. The up section of the beach is in proximity to the river. Their compared result with the down section of the beach shows a lower average of result of <500 MPs/kg. On Jureia Beach, bordered by the river in São Paulo State of Brazil, longshore current, wave action and River Iguape were linked to have sourced the MPs found [39].

Degradation (Photochemical oxidation, Chemical degradation and biological degradation)

The Carbonyl Index is used to measure the degree of weathering of MPs by photooxidation [86]. The light-induced oxidation of MPs has been reported to be faster in order of magnitude when compared with other types of degradation processes in the terrestrial environment (e.g. mechanical abrasion) [87]. Through this method, PVC pipe and plastic bags are easily degraded to form MPs in beach sediment [86]. Song et al. [88] have demonstrated that different type of MPs undergoes surface fragmentation by photooxidation under simulated sunlight exposure at different rates, namely; PS (< 1 year); PP (< 2 years); LDPE (> 3 years).

In concomitant with mechanical abrasion, chemical degradation reduces the structural integrity of larger plastic particles and causes their fragmentation over time, promoting the appearance of secondary MPs [56]. The mechanical degradation in the swash and surf zones, under the energetic action of breaking waves and moving sediments, can be linked to the generation of MPs from larger objects [37]. Song et al. [87] demonstrated that the UV exposure duration of 12 months followed by 2 months of mechanical abrasion could produce 8.7 ± 2.5 (mean ± SE) and 20 ± 8.3 particles/pellet, respectively.

Biological degradation also occurs along with weathering conditions on the beach especially in MPs of secondary source [89]. Secondary plastics within superficial sand layers can exchange their materials with seawater and organisms. This can cause different type of harmful MPs to be deposited in different layer of the sediment.

Salinity

During the transport of MP in nearshore water, the sinckability, flocculation and dispersion of MPs is greatly affected by the salinity of the water and density of the MP [37,73]. High salinity will cause an electric double layer of MPs to be compressed, resulting in repulsive energy barrier between the MP particles, which affects the dispersion capacity. A strong dispersion capacity especially with large-size MPs particle polymers with densities ≤ 0.9 g/cm³ will cause MP to ascend to the surface regardless of velocity of the transporting water [90]. In presence of other form of impurities (such as oil), this can make MPs to be easily transported in nearshore waters and deposited in beach sediment [90–92]. Furthermore, a measured salinity of 30.7‰ in seawater can aid the suspension of fine-grained silt for extended periods, contributing to the deposition of MPs in beach sediment [48]. Moreover, Li et al. [93] has corroborated that finer sediments contribute to the increased deposition of 27–32 µm PE MPs. This suggest that PE MPs can be easily deposited on beaches by seawater. Zhang et al. [94] have also described that the permeability of MP in sediment as a factor of salinity can be reciprocally affected by the pore space in the sediment. They also specified that the salinity of 35 PSU (practical salinity unit) would decrease the mobility of MPs in the sand column by more than 20%. Oftentimes, the transport is stopped at this threshold.

Human activities

The distribution pattern at different beaches can be affected by the functional design of the beach. Nguyen et al. [64] have identified that tourism activity (such as direct dumping) increased the number of MPs (up to 2653 particles.kg^{-1} recorded) on Vietnam's Binh Tien beach. Several tourism-related activities, such as beach resorts, restaurants, and water sports facilities at different beaches in India, were linked to the increase in MPs [95]. Higher MP abundance (up to 2458.2 items/kg) has been linked to intense human activities such as tourism, mariculture, and port construction on Shandong beaches of China [96]. Tourism-related activities, such as drink bottles, plastic film, and microwave packaging, were linked to the higher MP contents in beach sediment of the Thai island of Phuket [97]. Yaranal et al. [98] did show the significance of tourism and industrialization when they recorded MP abundance up to 264 ± 62 MP kg^{-1} and 1002 ± 174 MP kg^{-1} on Kapu and Malpe beaches respectively. In India's Bheemapally area of Thiruvananthapuram beach, religious and commercial activities were held in a certain zone on the 76 km long beach. This resulted in a high level of MPs recorded when compared to the rest of the beach [99].

5.3.2. External Mechanism

MPs transport to the beach is influenced by various internal mechanisms, including the geomorphological characteristics of the beach and the sediment properties of the beach.

Beach geomorphology characteristics

The shape of a beach could play an important role in the abundance of MPs found on it when compared to other beaches subjected to other similar properties. The geomorphology characteristics of a beach, alongside with other factors (such as wave characteristics, human population) will affect the amount of MP deposited.

(1) Beach shape

For example, an enclosed beach (La Herradura beach—45.0 ± 24.7 particles/kg) was demonstrated to have more MPs than an open beach system (La Rábita beach—22.0 ± 23.2 particles/kg), considering that they are both affected by similar population and hydrodynamic characteristics along the Granada coast [100]. A semi-enclosed bay, with shallow water, gentle slope, small headlands and islets in front of a restrain wave will facilitate the accumulation of MP [101].

(2) Beach slope

Ferreira et al. [102] confirmed that a section of Enseada beach in São Paulo with altitudes higher than 2.06 m, slope ~ 3° and face facing the direction of high energy waves were more susceptible to pellet (larger MP) deposition.

Sediment particle size and permeability

The particle size and permeability of beach sediment will affect the deposition of MPs on a beach. The grain size of 0.1–1.5 mm of beach sediment is considered the primary abrasive material of MPs within the sediment column [37]. The abundance of beach sediments with coarser grains tends to retain more MPs, for example, on the windward side of Kish Island (in the Gulf region), where a coarser grain size with a corresponding high abundance of MPs was recorded [103].

Misic et al. [104] indicated that the penetration of MPs into the sediment can be influenced by grain size, sorting and state of consolidation of sediments, as their result indicated higher fibre abundance in permeable sediments. Moreover, a higher abundance of MPs in the size category of fibre recorded by Fenn et al.[105] has specified that sediment grain serves as an entrapment in its interstitial spaces. Vermeiren et al.[106] measured the abundance of MP in the top sediment layer of the Barra del Chuy and La Coronilla beaches, eastern Uruguay and discovered that MP decreased exponentially with increasing grain size, indicating that more MPs can be easily retained and integrated into coarser sediment matrix.

6. Usage of MPs in Beach Sediment

6.1. Microplastics in Vertical Distribution for Sedimentary Age Dating

Due to the dynamic nature of the beach, the determination of the sedimentary age of beach sediment is extremely difficult. We suggest the use MPs vertical distribution for age dating. Generally, MPs are often well preserved in beach sediment for a long time. Determining the sedimentary history in the beach environment is challenging due to its dynamic processes. There are only few studies that have attempted to use beach sediment core in paleontology research. Pervez and Wang[55] found MP deposition in an 8 m core with an average MPs abundance of 16.6 ± 4.76 Mps/25 g DW since there were no MPs after 753 cm, they concluded that the sediments within the layer (723–753 cm) might be approximately 70 years old (1950s). Meanwhile, sediments within the layer (243–273 cm) could have been deposited 26 years ago (1996) based on the rapid plastic production change in China. Although the accuracy of dating MPs in sedimentary environments is still questionable, it is still an important means of dating in such a dynamic beach environment[107,108].

6.2. Microplastics in Beach Animals as Bioindicators

Organisms in beach sediments can be used as bioindicators for MPs. Zhu et al.[109] confirmed that bioaccumulation of microplastics occurred in the gills and lungs of oyster samples. Ingestion of MPs directly or indirectly through contaminated prey can cause physical damage and chemical toxicity resulting in bioaccumulation and biomagnification of MP particles in the food chain. Microplastics can also be associated to toxic chemicals (e.g. PAHs, PCBs, and PBDEs) and thus, act as facilitators in uptake and bioconcentration within consumers and bioaccumulation in predators.

In beach sediment, there is a risk of bioaccumulation, toxification and trophic level transfer in the food chain. The potential widespread of microplastics in marine life, such as edible oysters, may become a threat to human health not only because of its presence but also its potential adsorption of many other contaminants[109].

7. Conclusion and Prospects

This study summarises the current status of beach MP research worldwide. MPs are widely present in beach sediments worldwide, with varying concentrations. The characteristics of MPs present in beach sediments are described in detail in this article. We presented the existing information and conflicting connotations of the source of MPs found in beach sediments. Summarizing the outcome of this and recommendations this article;

(1) The regions most severely affected by MP pollution on beaches are Africa, Asia, Europe, and North America, respectively, while the Australia, Arctic region, South America, Oceania, and Antarctica have lower levels. Fibre is the most common shape of MPs found in beach sediment, with an average of 50% probability of it occurring in a particular beach. MPs within the 300–5000 μm size are also the most commonly found in beach sediment. Polyethylene polymer is the most common MP found in beach sediment. White/transparent is the most abundant MP colour.

(2) We identified that beaches serve as both sources and sinks of MPs. Shape, polymer may determine the source of a MP, but colour characteristic can not be effectively used to identify its source since it often undergoes environmental stress and abrasion by temperature and pressure in sediment. Eventually, the source and abundance of MPs to a particular beach is a complex dynamic controlled by several factors, including monsoon, grain size, storm activities, coastal hydrodynamic processes, beach usage, and beach ecosystem.

(3) There are no uniform quantitative units or standardized methods for sampling, pretreatment, analysis, and identification of MPs on beaches. Moreover, researchers currently use a conflicting range of units such as "n/kg"

and "n/m^2". These problems make it difficult to compare the results of different studies. We suggest the use of a suitable unified measuring unit such as n/kg in beach MP research since sediment samples are often quantified by weight. Moreover, from this review, we discovered that almost 59.4% of all research conducted on beach sediments use the unit n/kg to quantify the abundance of MPs.

(4) From a global perspective, we suggest including strategies that limit the abundance of fibres as an integral part of MP management practice for beach sediment. Since fibres are the main category of MPs on beaches, identifying and eliminating some significant sources of fibres/microfibres is an effective way to mitigate the abundance and risk of MPs.

(5) We recommend the creation of a global database for MPs in beach sediment data. Since the issue of an MP is similar to climate change, we recommend creating a global database for MPs in all environments for effective curation and measurement of the effect of human industrialization.

(6) Beach organisms and plants could be suitable biomarkers for MPs monitoring in future studies. Moreover, beach sediments can be suitable as a potential detoxification mechanism for MPs. Interestingly, organisms in beach sediment could also convert non toxic MPs to toxic MPs that can bioaccumulate and biomagnify in the food chain.

(7) The intensity of a factor to the abundance of MPs on a beach could be peculiar to the local characteristics of the beach. Ultimately, we concluded that the source, pathway and deposition of MPs in beach sediment are yet to be fully understood; hence, there is a need for research improvement.

Authors Contributions

Y.-H.W.: Supervision, Conceptualization, Methodology, Revision and writing, Validation, Visualization, Formal analysis, Data curation. A.J.O.: Investigation work, Methodology, Revision and writing, Formal analysis, Validation, Software, Visualization, Data curation. J.L.: Investigation work, Data curation, Formal analysis, Methodology, Software. All authors have read and agreed to the published version of the manuscript.

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No new data were created.

Conflicts of Interest

The authors declare no conflict of interest.

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