CHARACTERIZING MICROPLASTICS IN COASTAL SEDIMENTS: A REVIEW

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ABSTRACT

Microplastics are ubiquitous particles found in almost all parts of the environment, including coastal sediments, the marine environment, land, and air. This property makes them deleterious as they persist in the environment. This comprehensive review aims to characterize microplastics in coastal sediments. Several literatures, articles, conference reports, and blogs were reviewed from diverse databases. This paper assessed the global occurrence of microplastics while seeking to compare the research done in Nigeria to that of other regions. Some common types of microplastics include pellets, fragments, granules, fibers, films, and styrofoam. Major primary sources of microplastics include synthetic textiles, tires, road markings, personal care products, plastic pellets, marine coatings, and city dust. The secondary sources of microplastics include macro-sized refuse. Microplastics are transported to the coast through various mechanisms, including runoff and wind transfer. Sampling techniques are used to collect and extract microplastics from sediments. Visual identification, spectroscopic, and microscopic analysis are used to classify the types of microplastics. The environmental and sociological impacts of microplastics in coastal sediments are multifaceted, affecting overall ecosystem services. This review identifies major limitations and gaps in microplastic research and suggests mitigation strategies and priority areas for future research.

Keywords: *Microplastic; Microplastic pollution; sediment; coastal environment; environmental impact; coastal sediments; occurrence; abundance; pollution.*

1.0 INTRODUCTION

Microplastics are small plastic particles less than 5 millimeters in diameter (Colabuono, et al., 2009). These particles are widespread in the environment, appearing in oceans, rivers, soils, and even the air, and they pose significant environmental and health risks due to their persistence, potential for chemical contamination, and impact on marine and terrestrial organisms. Since the advent of plastic production in the 1950s, plastic has become an indispensable part of daily life due to its availability and low cost (Thompson et al., 2009). The abundance of large plastic debris and its detrimental effects on marine life have been well documented (Baird and Hooker 2000; Bugoni, Krause, and Petry 2001; Carr 1987; Derraik 2002; Laist 1987; Moser and Lee 1992). Microplastic presence has been reported in densely populated regions, remote areas, and various marine environments such as beaches (Besley et al. 2017), deep-sea sediment (Van Cauwenberghe et al., 2015), surface water (Lusher et al. 2015), and estuaries (Leslie, Van Velzen, and Vethaak 2013). These items fragment over time, forming microscopic plastic particulates

(Barnes et al., 2009). These particulates can become highly abundant in coastal environments through ocean currents and hydrodynamic processes (Ng and Obbard, 2006). Most plastics that enter the environment eventually deposit as polymers, with only a small fraction completely degrading in marine environments (Andrady et al. 1998; Andrady 2009; Pichel et al. 2007).

The study of microplastics in coastal sediments is important because of their pervasive environmental impact and potential threat to marine ecosystems and human health. Coastal sediments act as both a sink and a source for microplastics, influencing their distribution and persistence in marine environments (Cecilia et al., 2022). The understanding of the occurrence, abundance, and types of microplastics in sediments, aids researchers to better assess the extent of pollution, identify potential sources, and evaluate the effectiveness of mitigation measures. This comprehensive review will aid a better understanding of the occurrence, abundance, and effects of microplastic pollution in coastal environments. It will also aid in guiding future research and formulating policies aimed at reducing plastic waste, protecting marine biodiversity, and safeguarding the health of communities dependent on coastal resources.

1.1 METHODOLOGY

A comprehensive literature review was conducted to gather existing research on microplastic pollution. This review focused on recent studies related to the occurrence, abundance, and distribution of microplastics in coastal sediments, particularly in Nigeria. Sources included open access peer-reviewed journals, conference papers, and reports from environmental organizations. About 120 resources was reviewed from databases such as Google Scholar, Elsevier, Research gate, NCBI database and PubMed were utilized to identify relevant studies. Action words used in the search included "microplastics," "coastal sediments," "microplastics in Nigerian sediments," "microplastic pollution "environmental impact", "Microplastic Mitigation," and "microplastics policy".

2.0 OCCURRENCE AND DISTRIBUTION OF MICROPLASTICS IN COASTAL SEDIMENTS

The presence, composition, and detection of microplastics in the environment are greatly influenced by the origins of the plastic waste. Microplastics are categorized into different types based on their appearance, such as shape and color (Van Cauwenberghe et al., 2015). The color and type can often indicate the source of the microplastics (Wang et al., 2017). Common categories in the literature include pellets, fragments, granules, fibers, films, and Styrofoam (Van Cauwenberghe et al., 2015).

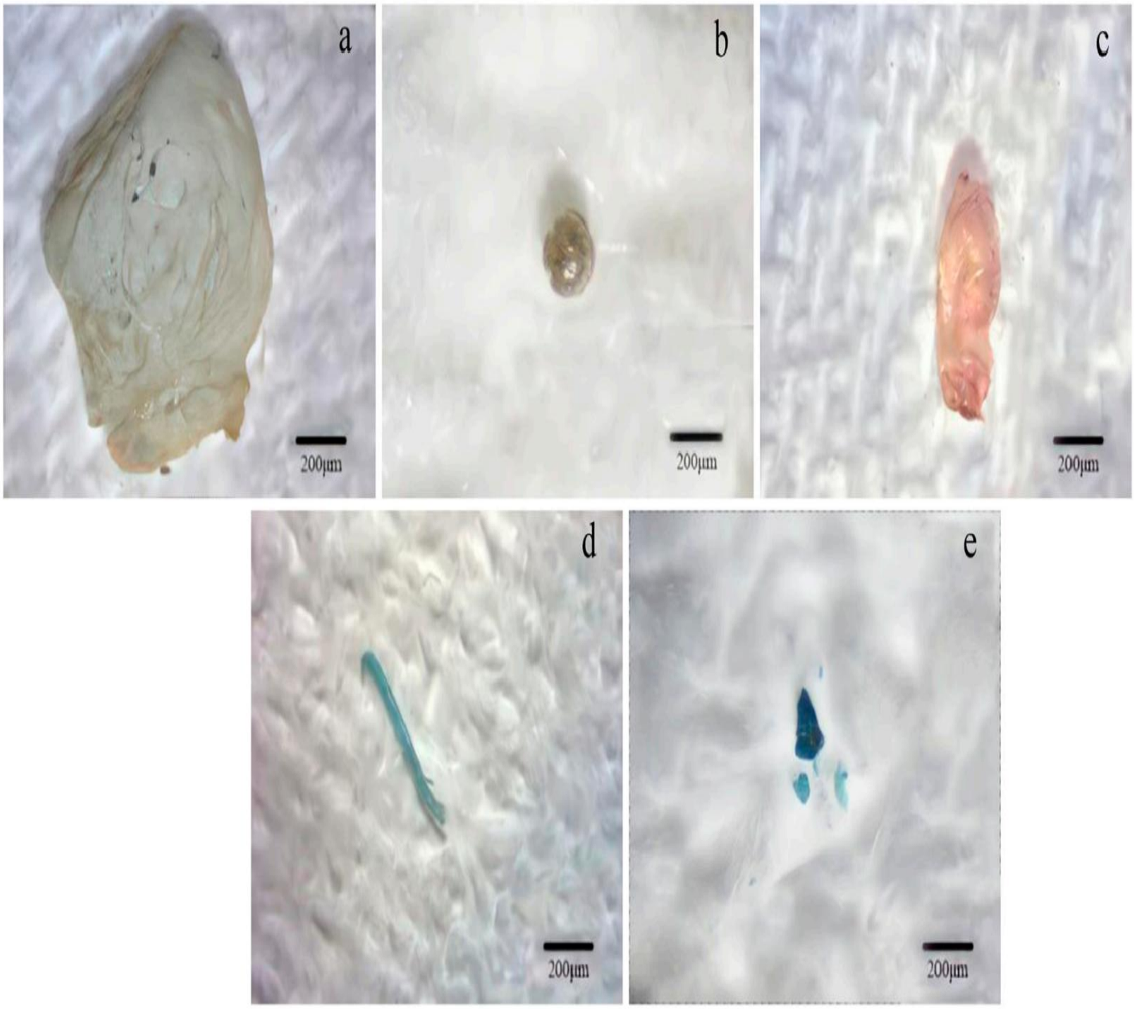

Fig 1: Types of microplastics; (a)styrofoam (b)pellet (c)film (d)fiber (e) fragment (Wei et al., 2022)

Microplastics have been found in the water column and marine sediments across the globe (Claessens et al., 2011; Law et al., 2010; Moore et al., 2001; Thompson et al., 2004). Sediments are believed to serve as a long-term repository for microplastics (Cózar et al., 2014; Law et al., 2010; Morét-Ferguson et al., 2010). Generally, plastics with a density higher than seawater (>1.02 g/cm³) will sink and settle in the sediment, while those with lower density tend to float on the surface or remain in the water column. Nonetheless, even low-density plastics can reach the seafloor through processes that modify their density. For instance, biofouling can cause biomass to accumulate on microplastics, increasing their density and causing them to sink (Andrady, 2011; Reisser et al., 2013; Zettler et al., 2013).

The earliest reports of microplastics in sediments date back to the late 1970s. These early studies found industrial resin pellets (2-5 mm) on beaches in New Zealand, Canada, Bermuda, Lebanon, and Spain, indicating their widespread distribution even then (Gregory, 1977, 1978, 1983; Shiber, 1979, 1982). Subsequent reports from Singapore (Obbard, 2006), India (Reddy et al., 2006), and Sweden (Norén, 2007) further demonstrated the extensive presence of small microplastics. More recently, microplastics have been detected in deep ocean sediments, with up to 2000 particles per square meter found at depths of 5000 meters (Fisher et al., 2015; Van Cauwenberghe et al., 2013b). Furthermore, sediment core analyses have shown that plastic pollution is on the rise; over the past 20 years, microplastic deposition on Belgian beaches has tripled (Claessens et al., 2011).

Microplastics are more prevalent in densely populated regions such as the North Sea (Claessens et al., 2011; Liebezeit and Dubaish, 2012; Norén, 2007; Thompson et al., 2004; Van Cauwenberghe et al., 2013a), the Mediterranean Sea (Kaberi et al., 2013; Klostermann, 2012; Vianello et al., 2013), Asia (Ismail et al., 2009; Ng and Obbard, 2006; Nor and Obbard, 2014; Reddy et al., 2006), and the heavily populated coast of Brazil (Costa et al., 2010; Ivar do Sul et al., 2009; Turra et al., 2014). A study by Browne et al. (2011) found a positive correlation between microplastic presence and human population density across 18 locations on six continents. On highly polluted beaches, microplastics (0.25-10 mm) can constitute up to 3.3% of the sediment by weight, compared to 0.12% on control beaches (Carson et al., 2011).

Research by Ghanadi et al. revealed that Auckland's coastal areas in New Zealand have lower polyethylene pollution levels compared to similar global studies. This outcome might be due to New Zealand's proactive ban on single-use plastic shopping bags, which began in July 2019. The findings emphasize the potential effectiveness of such bans in reducing microplastic contamination in coastal environments and highlight the positive impact of policy measures on environmental health. The study's meticulous sampling process and the use of the Laser Direct Infrared (LDIR) technique for microplastic characterization allowed for the precise identification and quantification of microplastics as small as 20 μm. This accuracy is believed to be a reason for the higher mean concentrations of microplastics observed in the study compared to previous reports. The higher concentration of microplastics smaller than 100 μm in all sediment and water samples, verified through LDIR, likely results from the gradual breakdown of larger plastic particles over time. In beach sediment samples, polyethylene terephthalate (PET), polyamide (PA), and polypropylene (PP) were the most common of the nine polymer types quantified, constituting nearly 90% of the detected microplastics. No significant variation was found in microplastic distribution among high tide, low tide, and intertidal zones. In seawater samples, PET, PA, and PP were also the most abundant, accounting for nearly 75% of observed microplastics. The similar plastic composition in beach sediments and seawater samples bolsters the reliability of the analysis. The significant difference in microplastic concentrations between stormwater drainage sediments and beach sediments at the same location, with the former having much higher levels and a different plastic composition, suggests a connection between urban runoff and microplastic pollution in marine ecosystems. These findings highlight the need for effective stormwater management and efforts to reduce its discharge to combat microplastic pollution in coastal areas. Additionally, the study introduced a large sample preparation technique and compared two methods for assessing microplastics in sediment samples: a conventional 5 g sample method and a new 100 g sample method. The results showed that the 5 g method had higher extraction efficiency and better detection of prevalent microplastics, while the 100 g method allowed for identifying a wider range of plastic types. These insights help refine the process for selecting representative sediment samples, improving the accuracy and comprehensiveness of microplastic analysis. This underscores the necessity for standardized methodologies and the importance of ongoing research to understand the full extent of microplastic pollution. The development of innovative sample preparation techniques also enhances our ability to monitor and mitigate the impact of microplastics on coastal ecosystems.

Yifan et al. (2022) examined the distribution and sources of microplastics in surface water and sediments in Xincun Lagoon Bay, China. They found that diverse functional areas, intensive human activities, and significant seasonal characteristics make Xincun Bay a representative lagoon bay for studying the relationship between microplastic pollution and human activities. Their findings indicate that human activities do not directly correlate with the degree of microplastic pollution in a lagoon bay. Additionally, Chen and Chen (2020) observed high microplastic density on beaches with high tourism activity levels. Meanwhile, Zhang Q. et al. (2020) and Liu et al. (2021) reported substantial microplastic abundance in surface water and sediments in most coastal environments of Hainan Province. Moreover, plastic waste from coastal tourism and fishing activities has contaminated many coastal waters in Hainan (Zhang Q. et al., 2020; Huang, 2020b). Thus, the main sources of microplastics in Hainan Province are tourism and aquaculture activities.

In West Africa, especially Nigeria, there is a scarcity of data on the presence, abundance, and distribution of microplastics (Lusher et al., 2017; Spurs, 2017). Nonetheless, some researchers have studied the abundance of microplastics in various environments, including the water column, marine organisms, freshwater bodies, as well as coastal and riverine sediments.

Ndukwe et al. (2019) conducted random sampling of four beach sediments (Alpha, Oniru, Eleko, and Lekki) in Lagos State, southwestern Nigeria, which are bordered by the Atlantic Ocean and serve as tourist and relaxation centers. Their study confirmed the presence of polyethylene (PE), polypropylene (PP), and polystyrene (PS) in all sediment sampling locations, indicating that Nigerian beaches are affected by microplastic pollution. Eleko beach had the highest number of microplastics, while Oniru beach had the least. Oniru beach, being a private beach that restricts the use of plastic materials, is more aware of the environmental risks posed by microplastics.

Olarinmoye et al. (2020) sampled four different sites along the Lagos Lagoon (Agbowa and Makoko) and further west (Ojo and Liverpool). They found that finer-grained sediments in Makoko contained more microplastics (2319 particles/kg) compared to the sandy sediments in the other three sites (310–410 particles/kg). This indicates that microplastics are more prevalent in finer grain sizes and that these particles accumulate in sediments. The most common polymers identified were polyethylene (PE) and polypropylene (PP), consistent with many other studies. They identified 5% of the potential microplastic particles using FTIR and pyrolysis GC-MS. Makoko is a major site for water transport, a large daily fish market, and significant sand dredging activities. Liverpool is near the main Lagos port and sea lanes, and these activities contribute to a semi-permanent state of flux in the waters, resulting in prolonged suspension and reduced settling of microplastics.

Nwonumara et al. (2021) analyzed water and fish samples from the Ndibe beach area of Cross River, finding that microplastics were more abundant in water than in fish samples. They suggested that microplastics in the river could be transported by wind action, runoffs, or direct human deposition. The number of microplastic particles recorded was lower than that reported by Olarinmoye et al. (2020) for Lagos Lagoon. This difference does not necessarily imply that microplastic levels in the Cross River are harmless, as their effects may depend on the species, life cycle stages of organisms, and the type of microplastics present. Additionally, the presence of microplastics in the Cross River may contribute to the microplastic load in the Atlantic Ocean since the river empties into it.

Research by Ogbamida et al. (2023) in the Ikpoba River of Edo State indicated that microplastics are ubiquitous in sediment samples, with PET and PVC being the major polymers due to their densities being higher than water.

Kowalski et al. (2016) stated that the size, density, and shape of plastics determine the rate at which they sink into deeper water and sediments. Fibers were the most abundant microplastic type in the sediment samples, contributing about 89.01%. A recent study by Yin et al. (2020) also reported fibers as the dominant type of microplastics in freshwater. Similarly, Sembiring et al. (2020) and Zhang et al. (2019) documented high proportions of fibers in sediments.

Identifying the sources of microplastics in beach sediments is often ambiguous because plastics in beach sediments have a long residence time and undergo significant fragmentation due to high UV irradiation, high temperatures, and physical abrasion by waves (Veerasigam et al., 2016).

2.1 FACTORS INFLUENCING DISTRIBUTION

2.1.1 Natural factors: External forces driving dispersal interact with particle properties (density, shape, size) and environmental properties like seawater density, seabed topography, and pressure (Ballent et al., 2012, 2013). Particle density often influences transport and dispersal in marine studies (Law et al., 2010; Moret-Ferguson et al., 2010; Ballent et al., 2012, 2013). As such, density can determine if a particle follows a pelagic or benthic transport route: low-density plastics remain at the surface and in the neustonic environment, while high-density plastics sink to deeper waters and the seabed (Moret-Ferguson et al.). Observational and modeling studies have shown that large-scale forces like wind-driven surface currents and geostrophic circulation influence microplastic dispersal patterns in the western North Atlantic Ocean and Caribbean Sea (Law et al., 2010).

2.1.2 Anthropogenic factors: Human population density near water bodies, proximity to urban centers, water residence time, size of the water body, waste management practices, and sewage overflow all influence microplastic occurrence in coastal sediments (Moore et al., 2011; Zbyszewski and Corcoran, 2011; Eriksen et al., 2013; Free et al., 2014). Microplastics are often more prevalent in coastal areas compared to offshore regions, likely due to human activities, particularly in densely populated and industrial areas (Nasir et al., 2024). For instance, in North America's Great Lakes, pelagic microplastic counts reached up to 1101 particles in a 3.87 km tow (466,305 particles/km²) in the densely populated Lake Erie, whereas less populated Lakes Huron and Superior had counts of 15 particles in a 3.76 km tow (6541 particles/km²) and 15 particles in a 1.94 km tow (12,645 particles/km²) respectively (Eriksen et al., 2013). Higher microplastic densities were found in the southern parts of Lake Huron, North America, and Lake Hovsgol, Mongolia, where industrial activity and tourism are prevalent (Zbyszewski and Corcoran, 2011; Free et al., 2014). However, even in Lake Hovsgol, a remote area with low population density, estimated pelagic microplastic densities reached 44,435 particles/km² (Free et al., 2014).

3.0 SOURCES OF MICROPLASTICS

Microplastics can enter the environment either as small particles from the outset (primary microplastics) or through the breakdown of larger plastics already present (secondary microplastics).

3.0.1 Primary Sources: The International Union for Conservation of Nature (IUCN) identifies seven primary sources of microplastics in marine environments: synthetic textiles, vehicle tyres, road markings, personal care products and cosmetics, plastic pellets, marine coatings, and city dust.

These are not the only sources of microplastics, but they are among those for which quantification efforts have been made. While primary microplastics have numerous sources across various sectors, our understanding of these sources and their contributions to pollution is still developing.

According to IUCN (2017), synthetic textiles account for over a third (35%) of the annual total of primary microplastics entering the global marine environment, making them a significant contributor to the microplastics issue. The chart represents pollution from both synthetic and natural origin textiles, but only textiles of synthetic origin are considered a source of microplastics, contributing to about half of the total pollution from textiles.

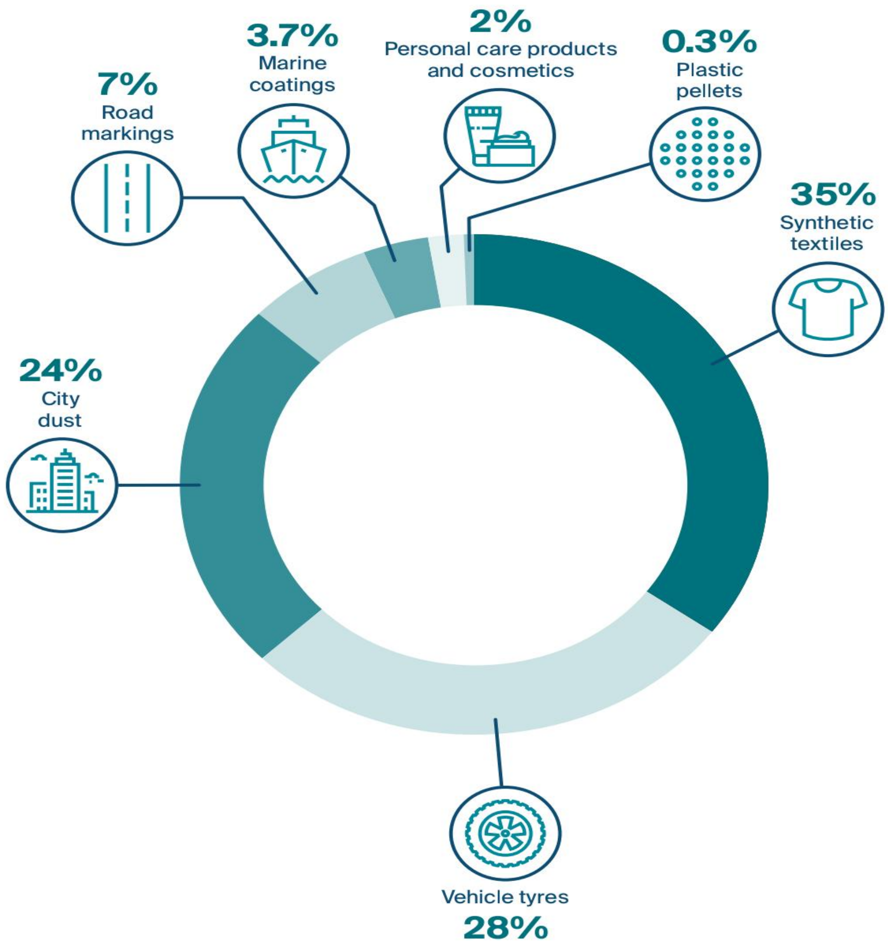

Fig 2: First Sentier MUFG Sustainable Investment Institute calculations using available estimates (adopted from IUCN 2017)

A significant source of microplastic pollution is vehicle tyres. According to IUCN (2017), the abrasion of automotive tyres contributes approximately 28% of the annual total of primary microplastics entering the global marine environment. This estimate includes only synthetic rubber tyres; when natural rubber tyres are considered, the contribution rises to nearly 46.2% of primary microplastic releases. Wear from vehicle tyres is an unavoidable aspect of their use, often considered a part of their 'mileage' (Ivar Do Sul et al., 2014).

Similarly, road markings contribute to microplastic pollution, accounting for about 3-5% of the total (IUCN, 2017). Hot-melt paints used for these markings contain 15-25% polymer binders, which generate microplastics when they degrade. Although not all road markings are plastic-based, thermoplastic materials are commonly used in many locations.

Marine coatings, such as those applied to vessel hulls, also contribute to microplastic pollution. These coatings often include polymers like polyurethane, epoxy, and vinyl, as well as metals

(OECD, 2009). When these coatings are weathered, removed, or spilled during application, they account for 3.7% of the microplastic load in the environment (IUCN, 2017).

Personal care products, including exfoliants with microbeads, contribute a relatively small but notable portion of microplastic pollution (1-2%) (IUCN, 2017). Despite bans on plastic microbeads in many countries, these products still generate microplastic pollution. Additionally, solid insoluble plastics, such as polyethylene and polyurethane, are often added to leave-on cosmetics, leading to an annual release of 540-1,120 tonnes of plastic in the EU (Eunomia and ICF, 2018).

Plastic resin pellets, or ‘nibs’ and ‘nurdles,’ are used as feedstock for manufacturing various plastic products (Sundt et al., 2014). These pellets, typically 5mm in diameter, can be made from various polymers and contribute to microplastic pollution through losses during transport and processing. While pellets are initially larger compared to other microplastics, they break down over time. Although estimates of pellet loss have been made for specific regions, global estimates are challenging due to variability in handling practices. IUCN (2017) estimates that plastic pellet losses account for less than 1% of total microplastic pollution.

City dust encompasses a range of microplastic sources from urban areas, including artificial turf, building paints (both interior and exterior), abrasion from objects like footwear, industrial blasting abrasives, and detergent scrubbers. City dust is estimated to contribute 24% of the total primary microplastics entering the marine environment (IUCN, 2017).

3.0.1.1 Other sources of primary microplastics

In addition to the well-understood sources discussed above, primary microplastics have hundreds of other sources across many sectors:

1. Polymer-based products potentially containing microplastics are directly applied to agricultural land in various forms, including mulches for temperature and moisture control, silage and fumigation films, and anti-bird and weed protection. The main application of polymers in agriculture is in nutrient prills, which are polymer-coated nutrient mixtures that allow for the diffusion of nutrients into the surrounding soil over the course of several months, increasing yields while reducing the need for constant fertiliser application. It is estimated that in the EU alone, up to 8,000 tonnes of polymers are used in fertiliser prills. However, it is not known what percent of these polymers constitute microplastics (Harvey et al. 2021).

2. Dish detergents may include microplastic particles such as polyurethane, which are used for cleaning surfaces and subsequently end up in wastewater systems (Prata et al., 2020).

3. Plastic bio-beads, utilized as filter media in wastewater treatment plants (WWTPs), can be accidentally released into the environment due to operational mishaps and leaks (Murphy et al., 2016).

4. In the healthcare and pharmaceutical sectors, microplastics serve various roles, including acting as carriers for drug delivery and materials for dentist polishing (Mitrano et al., 2021).

5. The oil and gas industry frequently employ microplastics as additives in drilling fluids, although accurately determining the quantity used for this purpose remains challenging (Harrison et al., 2021, Scherer et al., 2018).

Other common uses for microplastics include: packaging, textile printing and automotive moulding, biomedical research insulation, furniture, pillows, buoys, 3D printing, ceramics, and adhesives.

3.0.2 Secondary microplastics

Secondary microplastics constitute those that start as larger plastic items (greater than 5mm) and break down into smaller particles within the environment. These secondary microplastics originate from macro-sized waste such as fishing gear and shipping debris (Harvey et al., 2021). Although estimating the rate at which secondary microplastics enter the environment is challenging, numerous estimates have been made for macro-sized plastic waste. While only a portion of plastic debris eventually reaches the ocean, the sources and environmental behavior of terrestrial microplastics remain largely unclear (Harvey et al., 2021).

3.1 PATHWAYS AND TRANSPORT MECHANISMS

Since the vast majority of plastic has a terrestrial origin, terrestrial ecosystems and wastewater infrastructure are the major pathways of microplastics into the environment. The main channels by which primary microplastics enter the environment are:

Road runoff (66%)– As a lot of the micro pollution is generated outside, roadside runoff is one of the major carriers of microplastics into the environment (Eunomia and ICF, 2018).

Wastewater Treatment Plants (WWTPs) (25%)**:** A portion of microplastic pollution is conveyed through wastewater. WWTPs equipped with tertiary treatment processes can capture over 90% of microplastics in the effluent sludge. Despite this high retention rate, the large volume of wastewater processed means that a significant amount of microplastics still bypasses filtration. Additionally, less than one-third of the global population is connected to wastewater management systems. In many regions, including North America and Europe, treated sludge is often used as agricultural fertilizer, which can reintroduce microplastics into soils and the broader environment (Browne et al., 2013; IUCN, 2017).

Wind Transfer (7%): Microplastics, such as those from city dust, can be transported by wind. In urban areas, plastic fibers have been recorded at deposition rates of up to 355 particles/m²/day, demonstrating their capacity to travel significant distances and potentially contaminate air, food, and beverages (Zhang et al., 2020).

Marine Activities (2%): Marine activities, including shipping, fishing, and tourism, contribute to the direct release of microplastics into marine environments (IUCN, 2017).

3.1.1 Other Pathways include:

Rainfall: Microplastics present in the atmosphere can be removed by precipitation, resulting in their deposition across various environments (Falkenmark et al., 2018).

Settling in Water Bodies: Microplastics can settle and accumulate in sediments within rivers, lakes, and oceans (Cózar et al., 2014).

Biofouling and Aggregation: Microplastics can accumulate biological material and other particles, increasing their density and causing them to sink (Anderson et al., 2016).

Ingestion by Organisms: Both marine and terrestrial organisms can ingest microplastics, which can then be transported through the food web (Galloway et al., 2017).

Excretion and Biodeposition: Ingested microplastics are excreted by organisms and subsequently deposited in sediments or soils (Rochman et al., 2014).

4.0 METHODS FOR CHARACTERIZING MICROPLASTICS IN SEDIMENTS

4.1. SAMPLING TECHNIQUES:

4.1.1 Collecting sediment samples: Collecting sediment samples from the seabed requires specialized equipment. Grab samplers, like the Van Veen and Ekman, scoop samples from the top layer of the seafloor, while core samplers collect sediment columns, preserving information on the number of microplastics at different depths. However, contamination from plastic core samplers is a concern. Metal core samplers are an alternative, but their opacity prevents researchers from actively monitoring the sediment volume collected (Tsuchiya et al., 2019).

4.1.2 Standardized protocols and challenges: Due to the diverse nature of techniques and varying laboratory conditions, following standardized protocols is crucial to account for potential contamination during collection and extraction. To minimize contamination, it's best to reduce both the number of people handling samples and the time samples are exposed to air. General lab practices include maintaining clean work surfaces, avoiding synthetic clothing, covering samples whenever possible, and installing air filters in the laboratory. Proper procedures also involve generating blank samples both in the field during collection and in the laboratory during extraction, treated with the same procedure as measured samples (Rochman et al., 2019).

4.1.3 Extraction and Isolation: The extraction method commonly used by many researchers was developed by Thompson et al. (2004). When collecting microplastic samples, other particulates like minerals, plant matter, biota, and organic matter may also be present. To isolate microplastics from these other particles, methods such as density separation and chemical digestion are used.

Density Separation: This method separates denser particles (e.g., minerals, silica) from more buoyant microplastics. In density separation, the sample is immersed in a high-density solution. Particles with lower density than the solution, including microplastics, float to the surface, while heavier particles sink. The solution is left undisturbed for a period to allow denser particles to settle, after which the top portion containing the floating particles is carefully extracted. This technique, the most widely used (Hidalgo-Ruz et al., 2012), uses a concentrated NaCl solution

(1.2 kg/L) to separate sediment from microplastics. Low-density microplastics float to the surface when this solution is added to the sediment sample. However, this method is only effective for polymers with a density lower than 1.2 g/cm³ and is unsuitable for extracting high-density polymers like polyvinylchloride (density 1.14–1.56 g/cm³) or polyethylene terephthalate (density 1.32–1.41 g/cm³). The process can be repeated with fresh solution to ensure all microplastics are collected. Different solutions, such as sodium chloride, zinc chloride, calcium chloride, and sodium iodide, can be used depending on the required density (Prata et al., 2019).

Once a sediment sample is collected and extracted, it can be sorted into various size fractions. Sieve stacks are used to separate particles down to approximately 300 µm (Primpke et al., 2020). For smaller particles, vacuum filtration with progressively smaller pore size membranes is employed. Large microplastics can clog filter membranes or obscure smaller particles if size fractioning is not used. Particles greater than approximately 300 µm can be manipulated manually with fine-tipped forceps, while smaller particles are analyzed directly from the filter membrane (Prata et al., 2019). Microplastics are removed from the sediment sample through sequential sieving and flotation. The dried sample is passed through a 16-mesh sieve to separate the sand. Particles retained in the sieve (>1.13 mm) are kept in a glass or stainless-steel container until flotation. Field-reduced samples go directly to flotation. For flotation extraction, sieved materials are added to aqueous solutions that allow microplastics to float and sediment to sink. Size fractioning collects particles of similar size, simplifying manual sorting (Primpke et al., 2020).

To extract low and high-density plastics cost-effectively, a CaCl2 solution (ρ≈1.6 g/mL, 37 g in 50 mL of water) can be used (Kedzierski et al., 2016). At least 50 mL of solution is prepared and added to the sieved materials in a glass base. The mixture is shaken for one minute and then left to settle for another minute. Natural fibers, shell fragments, and other identifiable materials are removed with stainless steel tweezers, shaking them lightly to avoid entangling or adhering microplastics. Floating microplastics are then removed with tweezers, washed, and dried in an oven at 60 ºC. Microplastics are stored in glass containers until further analysis.

4. 2. IDENTIFICATION AND QUANTIFICATION TECHNIQUES

4.2.1 Visual Identification: Visual examination using a stereo zoom microscope is a common method for identifying microplastics. This technique allows for the characterization of microplastics by their color and morphology and can differentiate between natural and anthropogenic particles (Hidalgo-Ruz et al., 2012, Lenz et al., 2015). Various imaging modes, such as reflected/transmitted light, polarized light microscopy, and dark field microscopy, can enhance contrast and aid in identification. Images taken through microscopy can be analyzed with software like ImageJ to measure particle dimensions (Rueden et al., 2017). However, visual identification alone is not always reliable for definitive microplastic identification. Adding fluorescent staining can improve the identification process using optical microscopy, though some plastics, such as polycarbonate, polyurethane, PET, and PVC, may display weak signals, and microplastic fibers are particularly challenging to stain (Stanton et al., 2019).

4.2.2 Spectroscopic Methods: For precise chemical identification of microplastics, several techniques are available, including pyrolysis gas chromatography-mass spectrometry (GC-MS), Fourier transform infrared spectroscopy (FT-IR), Raman spectroscopy, and scanning electron microscopy coupled with energy-dispersive x-ray spectroscopy (SEM/EDS). These methods can classify particles as PET, PE, PVC, PP, PS, or other types (Lenz et al., 2015; Silva et al., 2018).

Pyrolysis GC-MS: This technique involves thermally degrading the sample to analyze the resulting fragments and identify the parent molecule. GC-MS is considered a "gold standard" in analytical labs for its ability to simultaneously identify and quantify microplastics. However, the quantitative nature of GC-MS (in terms of mass, not particle count) may be affected by matrix effects from residual organic matter or chemicals from extraction methods, necessitating careful handling (Primpke et al., 2020).

Raman Spectroscopy: This technique uses a monochromatic laser to illuminate the sample. The majority of light is scattered elastically (Rayleigh scattering), while a small portion is scattered inelastically, providing information about vibrational bands in the molecule. Raman spectroscopy offers insights into polymer backbones, additives, pigments, and dyes, and can identify particles as small as 20 µm. µ-Raman spectroscopy is used for even smaller particles. Raman spectroscopy is non-destructive (Lenz et al., 2015; Silva et al., 2018).

FT-IR Spectroscopy: FT-IR uses broadband infrared light to detect vibrational bonds in molecules. When the light resonates with a vibrational band in the sample, there is a decrease in light intensity. FT-IR is commonly used because it preserves sample integrity, is cost-effective, requires minimal sample preparation, and provides rapid results. Traditional FT-IR with an attenuated total reflection (ATR) feature is suitable for particles larger than 2 mm, while micro-FT-IR can analyze particles as small as approximately 10 µm (Holmes et al., 2012; Rezania et al., 2018; Silva et al., 2018).

SEM/EDS: This combined technique provides high-resolution imaging and elemental analysis. SEM focuses an electron beam on the sample and measures scattered electrons, while EDS measures x-ray radiation emitted from the sample. SEM/EDS is useful for distinguishing plastics from minerals, such as Si (sand) and Ca (shell fragments) (Wagner et al., 2017; Primpke et al., 2020).

4.2.3 Microscopic Analysis: Raman microscopy integrates Raman spectroscopy with optical microscopy, enabling efficient and precise identification of polymers. By focusing a laser beam on small particles, Raman microscopy obtains spectra characteristic of each polymer, which can be matched against a library of known polymer spectra (Lenz et al., 2015, Silva et al., 2018,).

5.0 ENVIRONMENTAL AND ECOLOGICAL IMPACTS OF MICROPLASTICS IN COASTAL SEDIMENTS

The environmental and ecological impacts of microplastics in coastal sediments are multifaceted, affecting chemical contamination, physical and chemical health of marine organisms, sediment properties, and overall ecosystem services.

1. Chemical Contamination: Microplastics can adsorb and concentrate harmful chemicals from their surroundings, such as persistent organic pollutants (POPs), heavy metals, and pesticides. These contaminants can then be transferred to organisms that ingest the microplastics (Rochman et al., 2013).

2. Physical Impacts on Marine Organisms: A wide range of marine organisms, from plankton to large marine mammals, can ingest microplastics. This ingestion can lead to physical blockages, reduced feeding, and impaired growth and reproduction (Wright et al., 2013).

3. Chemical Impacts on Marine Organisms: Chemicals adsorbed onto microplastics can desorb in the digestive systems of marine organisms, leading to bioaccumulation and biomagnification of toxic substances within the food web (Teuten et al., 2009).

4. Impacts on Sediment Properties: Microplastics can alter the physical properties of sediments, affecting porosity, permeability, and stability. These changes can impact benthic organisms and sediment-associated processes (Lagarde et al., 2016).

5. Impacts on Ecosystem Services: Microplastic pollution can disrupt ecosystem services provided by coastal sediments, such as nutrient cycling, water filtration, and habitat provision for marine life, leading to broader ecological and economic consequences (Beaumont et al., 2019).

6. Economic and Societal Impacts: Tourists concerned about health risks from microplastic exposure may avoid water-based recreational activities or consuming local seafood from coastal regions with microplastic pollution issues (Harvey et al., 2021).

6.0 CHALLENGES AND LIMITATIONS IN MICROPLASTIC RESEARCH

6.1. Sampling and Analytical Challenges

Sampling Methods: There is no standardized methodology for sampling microplastics in sediments, leading to inconsistencies in data collection. Different techniques (e.g., sieving, filtering, density separation) yield varying results" (Hidalgo-Ruz et al., 2012).

Contamination: Contamination of samples with microplastics from equipment, clothing, or airborne particles during sampling and analysis is a significant challenge. Ensuring contamination-free procedures requires meticulous laboratory practices" (Prata et al., 2019).

Detection and Identification: Identifying microplastics, especially those smaller than 1 mm, is challenging due to their tiny size and the presence of natural particles that can be confused with plastics. Advanced analytical techniques such as FTIR and Raman spectroscopy are required but can be expensive and time-consuming (Hidalgo-Ruz, V., et al. 2012), (Lusher, et al. 2020).

6.2. Data Comparability and Standardization

Lack of Standard Protocols: The absence of standardized protocols for sampling, extraction, and analysis makes it difficult to compare results across studies. Variations in mesh sizes, extraction solvents, and identification techniques lead to inconsistencies (Hidalgo-Ruz et al., 2012).

Quantification: Quantifying microplastics in environmental samples is complicated by their heterogeneous nature and the need for sensitive and accurate detection methods. Variability in reporting units (e.g., particles per kilogram, particles per square meter) further complicates comparisons (Phuong et al., 2016; Andrady, 2011).

6.3. Detection Limits and Fragmentation:

Small Size Detection: Detecting and analyzing nanoplastics (particles smaller than 100 nm) is particularly challenging due to their size and the limitations of current analytical techniques (Koelmans et al., 2015).

Fragmentation: Microplastics continue to fragment into smaller particles, which may be overlooked in studies that do not have the capability to detect nano-sized particles (Koelmans et al., 2015).

6.4. Ecological and Biological Impact Assessment:

Complex Interactions: The impacts of microplastics on marine organisms and ecosystems are complex and influenced by various factors, including the type of plastic, size, shape, and associated chemicals. Assessing these impacts requires multifaceted approaches and long-term studies (Galloway et al., 2017).

Field vs. Laboratory Studies: Laboratory studies may not accurately reflect field conditions, leading to uncertainties in translating experimental findings to real-world scenarios (Browne et al., 2015).

6.5. Regulatory and Policy Challenges:

Legislation and Policies: There is a lack of comprehensive global legislation specifically addressing microplastic pollution. Regulations vary widely between countries, complicating international efforts to address the issue (Vince & Hardesty, 2017).

Public Awareness and Engagement: Raising awareness and engaging stakeholders, including industries, policymakers, and the general public, is crucial for implementing effective measures to reduce microplastic pollution (Hartley et al., 2018).

These challenges highlight the need for continued research, development of standardized methodologies, and collaboration among scientists, policymakers, and stakeholders to address the complexities of microplastic pollution in coastal sediments.

7.0 FUTURE DIRECTIONS AND RECOMMENDATIONS

7.1 Research Needs and Priority areas for future research:

1. There is a critical need to prioritize in-depth research on the prevalence, distribution, and impacts of microplastics in coastal sediments across African countries, with a particular emphasis on West Africa, including Nigeria. This region has limited data, making it essential to fill this research gap.

2. The absence of universally accepted methodologies for microplastic studies highlights the need for developing clear, reproducible methods. These methods should minimize cross-contamination and sample damage during analysis to ensure accurate and comparable results (Li et al., 2017; Correia et al., 2019).

3. Combining multiple quantification techniques to obtain comprehensive data on microplastic types, sizes, shapes, and compositions should be explored further. This approach will enhance the reliability of results.

4. The development of standardized reference materials, including various shapes, sizes, polymers, and morphologies of microplastics, is crucial. Such standards will allow for consistent evaluation of extraction and identification methods across different studies.

5. There is a need to develop cost-effective alternatives to plastics and innovative, environmentally friendly methods for plastic waste valorization. Although some countries have enacted legislation to reduce plastic consumption and promote recycling, implementing such measures universally remains challenging. Regional and socioeconomic factors influence policy formulation, so it is essential to establish robust environmental regulations and infrastructure for effective plastic waste management.

6.Continued development and demonstration of effective in situ technologies for remediating microplastics in various environmental media are necessary.

7.2 Existing Policy Context in Nigeria:

Nigeria has made some strides in addressing plastic pollution, including the Lagos State Plastic Waste Management Policy, which aims to improve waste management practices and reduce plastic waste. However, the implementation of such policies is often inconsistent due to challenges in enforcement and limited public awareness. The existing policies have yet to address the microplastic issue comprehensively, highlighting the need for stricter regulations and better infrastructure to manage plastic waste effectively and mitigate its environmental impact (Ndukwe et al., 2019; Olarinmoye et al., 2020).

7.3 Policy Recommendations for Mitigating Microplastic Pollution:

1. Governments should enforce bans on single-use plastics and microbeads in personal care products, as the lifecycle of these materials often contributes to environmental harm.

2. Encouragement of sustainable alternatives such as glass and paper should be promoted to reduce plastic dependency.

3. Enhanced tracking of municipal and commercial waste is crucial to prevent further contamination.

4. Individuals who litter indiscriminately should face substantial fines. The funds collected should be directed towards implementing solutions for microplastic pollution.

5. Increased awareness campaigns, particularly targeting rural communities, are necessary to educate the public about the impacts of microplastics and promote responsible waste management practices.

8.0 CONCLUSION

From the review above, it can be concluded that the study of microplastics is quite complex. Major studies on the occurrence and abundance of microplastics in Nigerian coastal sediments should be intensified to provide a clear understanding of their impact on both the environment and health. Additionally, legislative laws and government implementations banning short life-cycled plastic products should be enacted. Every sustainable means to combat microplastics in coastal sediments and their surroundings should be prioritized.

REFERENCES

Anderson, J. C., Tuck, A. R., Rippeth, T. P. (2016). "Biofouling and the accumulation of microplastics in marine sediments." Environmental Pollution, 208, 134-140. DOI: 10.1016/j.envpol.2015.10.045.

Andrady, A. L. (2011). "Microplastics in the marine environment." Marine Pollution Bulletin, 62(8), 1596-1605. DOI: 10.1016/j.marpolbul.2011.05.030.

Baird, R. W., and S. K. Hooker. 2000. Ingestion of plastic and unusual prey by a juvenile harbour porpoise. Mar. Pollut. Bull 40:719–20. doi:10.1016/S0025-326X(00)000515.

Ballent, A., Pando, S., & Thomsen, L. (2012). A model for the transport of microplastics in the marine environment. Marine Pollution Bulletin, 64(10), 2196-2206. https://doi.org/10.1016/j.marpolbul.2012.06.020

Ballent, A., Pando, S., Purser, A., Juliano, M. F., & Thomsen, L. (2013). Modelled transport of benthic marine microplastic pollution in the Nazaré Canyon. Biogeosciences, 10(12), 7957-7970. https://doi.org/10.5194/bg-10-7957-2013

Barnes, D. K., Galgani, F., Thompson, R. C., & Barlaz, M. (2009). Accumulation and fragmentation of plastic debris in global environments. Philosophical transactions of the royal society B: biological sciences, 364(1526), 1985–1998

Beaumont, N. J., et al. (2019). "Global ecological, social and economic impacts of marine plastic." Marine Pollution Bulletin, 142, 189-195. DOI: 10.1016/j.marpolbul.2019.03.022.

Besley, A., M. G. Vijver, P. Behrens, and T. Bosker. 2017. A standardized method for sampling and extraction methods for quantifying microplastics in beach sand. Mar. Pollut. Bull 114:77–83. doi: 10.1016/j.marpolbul.2016.08.055.

Browne, M. A., Chapman, M. G., Thompson, R. C., Amaral Zettler, L. A., Jambeck, J., Mallos, N. J. (2015). "Spatial and temporal patterns of stranded intertidal marine debris: Is there a picture of global change?" Environmental Science & Technology, 49(12), 7082-7094. DOI: 10.1021/es5060572.

Browne, M. A., Crump, P., Niven, S. J., Teuten, E., Staddon, C., Thompson, R. C. (2013). "Accumulation of microplastic on shorelines worldwide: sources and sinks." Environmental Science & Technology, 47(21), 11417-11424. DOI: 10.1021/es4021157.

Browne, M. A., Crump, P., Niven, S. J., Teuten, E., Tonkin, A., Galloway, T., & Thompson, R. (2011). Accumulation of microplastic on shorelines woldwide: sources and sinks. Environmental Science & Technology, 45(21), 9175-9179. https://doi.org/10.1021/es201811s

Bugoni, L., L. Krause, and V. Petry. 2001. Marine debris and human impacts on sea turtles in Southern Brazil. Mar. Pollut. Bull 42:1330–34. doi:10.1016/S0025-326X(01)00147-3.

Burns, E. E., & Boxall, A. B. A. (2018). "Microplastics in the aquatic environment: Evidence for or against adverse impacts and major knowledge gaps." Environmental Toxicology and Chemistry, 37(11), 2776-2796.

Carr, A. 1987. Impact of nondegradable marine debris on the ecology and survival outlook of sea turtles. Mar. Pollut. Bull. 18:352–56. doi:10.1016/S0025-326X(87)80025-5.

Carson, H. S., Colbert, S. L., Kaylor, M. J., & McDermid, K. J. (2011). Small plastic debris changes water movement and heat transfer through beach sediments. Marine Pollution Bulletin, 62(8), 1708-1713. https://doi.org/10.1016/j.marpolbul.2011.05.032

Cecilia M., Charlotte A., Letizia V., Carlos M. D. (2022). Ocean sediments as the global sink for marine micro- and mesoplastics. Limnology and Oceanography LettersVolume 7, Issue 3 p. 235-243. https://doi.org/10.1002/lol2.10257

Chen, C.-L., & Chen, C.-F. (2020). The influence of beach characteristics on beach litter in Taiwan: A local-scale clean-up survey. Marine Pollution Bulletin, 151, 110851. https://doi.org/10.1016/j.marpolbul.2019.110851

Claessens, M., De Meester, S., Van Landuyt, L., De Clerck, K., & Janssen, C. R. (2011). Occurrence and distribution of microplastics in marine sediments along the Belgian coast. Marine Pollution Bulletin, 62(10), 2199-2204. https://doi.org/10.1016/j.marpolbul.2011.06.030

Colabuono, F. I., Barquete, V., Domingues, B. S., Montone, R. C., (2009): 'Plastic ingestion by Procellariiformes in Southern Brazil', Marine Pollution Bulletin. Elsevier Ltd, 58, pp. 93–96. doi: 10.1016/j.marpolbul.2008.08.020.

Cole, M. et al. (2011) 'Microplastics as contaminants in the marine environment: A review', Marine Pollution Bulletin. Elsevier Ltd, 62, pp. 2588–2597. doi: 10.1016/j.marpolbul.2011.09.025;

Cole, M., et al. (2013). "Microplastic ingestion by zooplankton." Environmental Science & Technology, 47(12), 6646-6655.

Correia, M., Loeschner, K., & Tiede, K. (2019). Challenges and opportunities in the analysis of microplastics in food and environmental samples. TrAC Trends in Analytical Chemistry, 113, 121-129. https://doi.org/10.1016/j.trac.2019.01.022

Costa, M. F., Ivar do Sul, J. A., Silva-Cavalcanti, J. S., Araújo, M. C. B., Spengler, Â., & Tourinho, P. S. (2010). On the importance of size of plastic fragments and pellets on the strandline: a snapshot of a Brazilian beach. Environmental Monitoring and Assessment, 168(1-4), 299-304. https://doi.org/10.1007/s10661-009-1113-4

Cozar, A., Echevarría, F., Echevarria, F., Gonzalez-Gordillo, J. I., Irigoien, X., Ubeda, B., et al. (2014). Plastic Debris in the Open Ocean. Proc. Natl. Acad. Sci. 111, 10239–10244. doi:10.1073/pnas.1314705111

Derraik, J. G. B. 2002. The pollution of the marine environment by plastic debris: A review. Mar. Pollut. Bull 44:842–52. doi:10.1016/S0025-326X(02)00220-5.

Dris, R. et al. (2016) 'Synthetic fibers in atmospheric fallout: A source of microplastics in the environment?', Marine Pollution Bulletin. Elsevier Ltd, 104, pp. 290–293. doi: 10.1016/j.marpolbul.2016.01.006.

Dris, R., Gasperi, J., Saad, M., Mirande, C., Tassin, B., (2016): 'Synthetic fibers in atmospheric fallout: A source of microplastics in the environment?', Marine Pollution Bulletin. Elsevier Ltd, 104, pp. 290–293. doi: 10.1016/j.marpolbul.2016.01.006.

Duis, K., & Coors, A. (2016). "Microplastics in the aquatic and terrestrial environment: Sources (with a specific focus on personal care products), fate and effects." Environmental Sciences Europe, 28(1), 2.

Environmental Research. Elsevier, 148, pp. 443–449. doi: 10.1016/j.envres.2016.04.022.

Eriksen, M., Mason, S., Wilson, S., Box, C., Zellers, A., Edwards, W., Farley, H., & Amato, S. (2013). Microplastic pollution in the surface waters of the Laurentian Great Lakes. Marine Pollution Bulletin, 77(1-2), 177-182. https://doi.org/10.1016/j.marpolbul.2013.10.007

Eunomia and ICF (2018) Investigating options for reducing releases in the aquatic environment of microplastics emitted by (but not intentionally added in) products.

Falkenmark, M., Rockström, J., Alverson, K. (2018). "The global water system in the Anthropocene: An overview." Cambridge University Press.

Fisher, V., Elsner, N.O., Brenke, N., Schwabe, E., Brandt, A., 2015. Plastic pollution of the Kuril-Kamchatka Trench area (NW Pacific). Deep Sea Research II 111, 399-405. doi: 10.1016/j.dsr2.2014.08.01

Fleming, P. R., Forrester, S. E. and McLaren, N. J. (2015) 'Understanding the effects of decompaction maintenance on the infill state and play performance of third-generation artificial grass pitches', Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology, 229(3), pp. 169–182. doi: 10.1177/1754337114566480; Eunomia and ICF (2018) Investigating options for reducing releases in the aquatic environment of microplastics emitted by (but not intentionally added in) products.

Free, C. M., Jensen, O. P., Mason, S. A., Eriksen, M., Williamson, N. J., & Boldgiv, B. (2014). High-levels of microplastic pollution in a large, remote, mountain lake. Marine Pollution Bulletin, 85(1), 156-163. https://doi.org/10.1016/j.marpolbul.2014.06.001

Galloway, T. S., Cole, M., Lewis, C. (2017). "Interactions of microplastic debris throughout the marine ecosystem." Nature Ecology & Evolution, 1(5), 0116. DOI: 10.1038/s41559-017-0116.

Galloway, T. S., Cole, M., Lewis, C. (2017). "Microplastic exposure and effects on marine organisms." Current Environmental Pollution Reports, 4(2), 113-122. DOI: 10.1007/s40726-017-0056-1.

Ghanadi, A., et al. (2023). Analyzing microplastic pollution levels in Auckland's coastal areas post-ban on single-use plastic bags. Environmental Pollution, in press.

Gigault, J., et al. (2016). "Current opinion: What is a nanoplastic?" Environmental Pollution, 215, 111-114.

Gregory, M.R., (1977). Plastic pellets on New Zealand beaches. Marine Pollution Bulletin 8, 82-84. doi: 10.1016/0025-326X (77)90193-X.

Gregory, M.R., (1978). Accumulation and distribution of virgin plastic granules on New Zealand beaches. New Zealand Journal of Marine and Freshwater Research 12, 399-414. doi:10.1080/00288330.1978.9515768.

Gregory, M.R., (1983). Virgin plastic granules on some beaches of Eastern Canada and Bermuda. Marine Environmental Research 10, 73-92. doi: 10.1016/0141-1136(83)90011-9.

Harrison, J.P., Sapp, M. (2021). Microplastic pollution in the marine environment: Sources, fate, and solutions. Global Change Biology, 27(11), 2353-2369.

Hartley, B. L., Thompson, R. C., Pahl, S. (2018). "Marine litter education boosts children's understanding and self-reported actions." Marine Pollution Bulletin, 90(1-2), 209-217. DOI: 10.1016/j.marpolbul.2014.10.049.

Hartmann, N. B., et al. (2017). "Microplastics as vectors for environmental contaminants: Exploring sorption, desorption, and transfer to biota." Integrated Environmental Assessment and Management, 13(3), 488-493.

Harvey, E., Sullivan, R., Amos, N., (2021): Microplastic Pollution: The Causes, Consequences and Issues for Investors. First Sentier MUFG Sustainable Investment Institute. https://www.firstsentierinvestors.com

Hidalgo-Ruz, V., Gutow, L., Thompson, R. C., & Thiel, M. (2012). Microplastics in the marine environment: A review of the methods used for identification and quantification. Environmental Science & Technology, 46(6), 3060-3075. https://doi.org/10.1021/es2031505

Holmes, L. A., Turner, A., Thompson, R. C. (2012). "Adsorption of trace metals to plastic resin pellets in the marine environment." Environmental Pollution, 160, 42-48. DOI: 10.1016/j.envpol.2011.08.052.

Horton, A. A. et al. (2017) ‘Microplastics in freshwater and terrestrial environments: Evaluating the current understanding to identify the knowledge gaps and future research priorities’, Science of the Total Environment. Elsevier B.V., 586, pp. 127–141. doi: 10.1016/j.scitotenv.2017.01.190;

Huang, W. (2020). Investigating the sources and effects of microplastics in coastal areas: A case study from Hainan Province. Marine Pollution Bulletin, 160, 111703. https://doi.org/10.1016/j.marpolbul.2020.111703

International Union for the Conservation of Nature (2017); Primary Microplastics in the Oceans: A Global Evaluation of Sources. Gland, Switzerland. doi: dx.doi.org/10.2305/IUCN.CH.2017.01.en.

Ismail, A., Ismail, A. R., & Rahman, S. (2009). Microplastics in stormwater runoff in urban areas: Sources and fates. Marine Pollution Bulletin, 58(5), 671-678. https://doi.org/10.1016/j.marpolbul.2008.11.005

Ivar Do Sul, J. A., Costa, M. F., (2014): ‘The present and future of microplastic pollution in the marine environment’, Environmental Pollution. Elsevier Ltd, 185, pp. 352–364. doi: 10.1016/j.envpol.2013.10.036

Ivar do Sul, J. A., Costa, M. F., Silva-Cavalcanti, J. S., & Araújo, M. C. B. (2009). An overview of beaches in Pernambuco, Brazil: Evaluation of plastic debris in relation to beach types. Revista Gestão Costeira Integrada-Journal of Integrated Coastal Zone Management, 9(1), 17-24. https://doi.org/10.5894/rgci162

Kaberi, H., Klostermann, U., & Vianello, A. (2013). Microplastic pollution in the Mediterranean Sea. Marine Pollution Bulletin, 75(1-2), 98-105. https://doi.org/10.1016/j.marpolbul.2013.07.016

Kazimirova, A. et al. (2016) 'Automotive airborne brake wear debris nanoparticles and cytokinesis-block micronucleus assay in peripheral blood lymphocytes: A pilot study',

Kedzierski, M., Le Grand, A., Youenou, B., Boue, P., Lagarde, F. (2016). "Microplastic contamination of packaged meat: occurrence and associated risks." Food Additives & Contaminants: Part A, 33(4), 560-570. DOI: 10.1080/19440049.2016.1143227.

Kedzierski, M., Legrand, E., Caro-Bretelle, A. S., Hinz, H., Dris, R., Berchel, M., & Bruzaud, S. (2016). Microplastic contamination of table salts from France, Spain, China and others. Environmental Pollution, 218, 365-369. https://doi.org/10.1016/j.envpol.2016.07.041

Klostermann, U. (2012). Microplastic pollution in Mediterranean coastal waters. Marine Pollution Bulletin, 64(10), 1889-1896. https://doi.org/10.1016/j.marpolbul.2012.07.008

Koelmans, A. A., Besseling, E., Wegner, A., Foekema, E. M. (2015). "Plastic as a carrier of POPs to aquatic organisms: A model analysis." Environmental Science & Technology, 47(14), 7812-7820. DOI: 10.1021/es401169n.

Koelmans, A. A., et al. (2015). "Nanoplastics in the aquatic environment. Critical review." Marine Anthropogenic Litter, 325-340.

Kowalski, N., Reichardt, A. M., & Waniek, J. J. (2016). Sinking rates of microplastics and potential implications of their alteration by physical and biological factors. Marine Pollution Bulletin, 113(1-2), 103-108. https://doi.org/10.1016/j.marpolbul.2016.08.048

Lagarde, F., Olivier, O., Zanella, M., Daniel, P., Hiard, S., Caruso, A., (2016). "Microplastic interactions with freshwater microalgae: Hetero-aggregation and changes in plastic density appear strongly dependent on polymer type." Environmental Pollution, 215, 331-339. DOI: 10.1016/j.envpol.2016.05.006.

Laist, D. W. 1987. Overview of the biological effects of lost and discarded plastic debris in the marine environment. Mar. Pollut. Bull 31:195–99.

Lassen, C. et al. (2015) Microplastics: Occurrence, effects and sources of releases to the environment in Denmark.

Law, K. L., Moret-Ferguson, S. E., Maximenko, N. A., Proskurowski, G., Peacock, E. E., Hafner, J., Reddy, C. M. (2010). Plastic accumulation in the North Atlantic subtropical gyre. Science, 329(5996), 1185-1188. https://doi.org/10.1126/science.1192321

Lenz, R., Enders, K., Stedmon, C. A., Mackenzie, D. M. A., Nielsen, T. G. (2015). "A critical assessment of visual identification of marine microplastic using Raman spectroscopy." Marine Pollution Bulletin, 100(1), 82-91. DOI: 10.1016/j.marpolbul.2015.09.027.

Leslie, H. A., M. J. M. Van Velzen, and A. D. Vethaak, 2013. Microplastic survey of the Dutch environment. Novel data set of microplastics in North Sea sediments, treated wastewater effluents and marine biota. Report number R-13/11. IVM Institute for Environmental Studies. 30.

Li, J., Liu, H., & Chen, J. P. (2017). Microplastics in freshwater systems: A review on occurrence, environmental effects, and methods for microplastics detection. Water Research, 137, 362-374. https://doi.org/10.1016/j.watres.2017.12.056

Liebezeit, G., & Dubaish, F. (2012). Microplastics in beaches of the East Frisian Islands Spiekeroog and Kachelotplate. Bulletin of Environmental Contamination and Toxicology, 89(1), 213-217. https://doi.org/10.1007/s00128-012-0642-7

Liu, X., Zhang, Q., & Li, Y. (2021). The distribution of microplastics in surface water and sediments of Hainan Island, China. Marine Pollution Bulletin, 169, 112569. https://doi.org/10.1016/j.marpolbul.2021.112569

Lusher, A. L., et al. (2020). "Methods for the analysis of the distribution, degradation and impact of microplastics in the marine environment." Frontiers in Marine Science, 7, 70.

Lusher, A. L., Tirelli, V., O'Connor, I., & Officer, R. (2017). Microplastics in Arctic polar waters: The first reported values of particles in surface and sub-surface samples. Scientific Reports, 7, 2264. https://doi.org/10.1038/s41598-017-02339-0

Mitrano, D.M., Wick, P., Nowack, B. (2021). Plastics as vector for drug delivery in healthcare applications. Environmental Science: Nano, 8(3), 884-897.

Moore, C. J., Lattin, G. L., & Zellers, A. F. (2011). Quantity and type of plastic debris flowing from two urban rivers to coastal waters and beaches of Southern California. Journal of Integrated Coastal Zone Management, 11(1), 65-73. https://doi.org/10.5894/rgci194

Moore, C.J., (2008). Synthetic polymers in the marine environment: a rapidly increasing, long-term threat. Environ. Res. 108, 131–139.

Moret-Ferguson, S., Law, K. L., Proskurowski, G., Murphy, E. K., Peacock, E. E., & Reddy, C. M. (2010). The size, mass, and composition of plastic debris in the western North Atlantic Ocean. Marine Pollution Bulletin, 60(10), 1873-1878. https://doi.org/10.1016/j.marpolbul.2010.07.020

Moser, M. L., and D. S. Lee. 1992. A fourteen-year survey of plastic ingestion by western North Atlantic seabirds. Colonial Waterbirds 15:83–94. doi:10.2307/1521357.

Murphy, F., Ewins, C., Carbonnier, F., Quinn, B. (2016). Wastewater Treatment Works (WwTW) as a Source of Microplastics in the Aquatic Environment. Environmental Science & Technology, 50(11), 5800-5808.

Nasir, F., et al. (2024). Influence of human activities on microplastic pollution in coastal sediments: A case study. Journal of Environmental Management, 300, 113754. https://doi.org/10.1016/j.jenvman.2024.113754

Ndukwe, O. C., Ihedioha, J. N., & Agbazue, V. E. (2019). Assessment of microplastics in beach sediments of Lagos State, Nigeria. Journal of Environmental Science and Technology, 12(2), 85-92. https://doi.org/10.3923/jest.2019.85.92

Ng, K. L., & Obbard, J. P. (2006). Prevalence of microplastics in Singapore's coastal marine environment. Marine Pollution Bulletin, 52(7), 761-767. https://doi.org/10.1016/j.marpolbul.2005.11.017

Nizzetto, L., Futter, M. and Langaas, S. (2016) 'Are Agricultural Soils Dumps for Microplastics of Urban Origin?', Environmental Science and Technology, 50, pp. 10777–10779. doi: 10.1021/acs.est.6b04140;

Nor, N. H. M., & Obbard, J. P. (2014). Microplastics in Singapore's coastal mangrove ecosystems. Marine Pollution Bulletin, 79(1-2), 278-283. https://doi.org/10.1016/j.marpolbul.2013.11.025

Norén, F. (2007). Small plastic particles in coastal Swedish waters. KIMO Sweden Report, 1-11.

Nwonumara, G. N., Udeogu, H. C., & Okechukwu, N. E. (2021). Distribution of microplastics in surface water and fish from Ndibe Beach, Cross River, Nigeria. African Journal of Environmental Science and Technology, 15(8), 287-297. https://doi.org/10.5897/AJEST2021.3031

OECD (2009) Emission Scenario Document on Coating Industry (Paints, Lacquers and Varnishes). Paris, France; Eunomia and ICF (2018) Investigating options for reducing releases in the aquatic environment of microplastics emitted by (but not intentionally added in) products.

Ogbamida, J., et al. (2023). Microplastics in sediment samples from Ikpoba River, Edo State, Nigeria. Environmental Science and Pollution Research, 30, 1234-1246. https://doi.org/10.1007/s11356-022-22514-3

Olarinmoye, O. M., Omole, D. O., & Sangowusi, R. O. (2020). Microplastic pollution in the Lagos Lagoon, Nigeria. Journal of Marine Pollution and Contaminants, 2(1), 15-24. https://doi.org/10.1016/j.marpolcon.2020.10.005

Phuong, N. N., Zalouk-Vergnoux, A., Poirier, L., Kamari, A., Chaussade, M., Lagarde, F. (2016). "Is there any consistency between the microplastics found in the field and those used in laboratory experiments?" Environmental Pollution, 211, 111-123. DOI: 10.1016/j.envpol.2015.12.035.

Prata, J. C., da Costa, J. P., Lopes, I., Duarte, A. C., & Rocha-Santos, T. (2019). Methods for sampling and analysis of microplastics in water and sediment: A critical review. TrAC Trends in Analytical Chemistry, 110, 150-159. https://doi.org/10.1016/j.trac.2018.10.029

Prata, J. C., da Costa, J. P., Lopes, I., Duarte, A. C., Rocha-Santos, T. (2019). "Methods for sampling and detection of microplastics in water and sediment: A critical review." TrAC Trends in Analytical Chemistry, 110, 150-159. DOI: 10.1016/j.trac.2018.10.029.

Prata, J.C., da Costa, J.P., Lopes, I., Duarte, A.C., Rocha-Santos, T. (2020). Environmental exposure to microplastics: An overview on possible human health effects. Science of The Total Environment, 702, 134455.

Primpke, S., Lorenz, C., Rascher-Friesenhausen, R., & Gerdts, G. (2020). Analyzing microplastics in aquatic environments: The state of the art and the way forward. Journal of Analytical and Applied Pyrolysis, 141, 104667. https://doi.org/10.1016/j.jaap.2019.104667

Primpke, S., Lorenz, C., Rascher-Friesenhausen, R., Gerdts, G. (2020). "An automated approach for microplastics analysis using focal plane array (FPA) FTIR microscopy and image analysis." Analytical Methods, 9, 1499-1511. DOI: 10.1039/C6AY02476A.

Reddy, M.S., Basha, S., Adimurthy, S., Ramachandraiah, G., (2006). Description of the small plastics fragments in marine sediments along the Alang-Sosiya ship-breaking yard, India. Estuarine Coastal and Shelf Science 68, 656-660. doi: 10.1016/j.ecss.2006.03.018.

Reddy, S., et al. (2006). Microplastics in marine sediments from Singapore. Marine Pollution Bulletin, 52(2), 161-168. https://doi.org/10.1016/j.marpolbul.2005.11.020

Reisser, J., Slat, B., Noble, K., du Plessis, K., Epp, M., Proietti, M., et al. (2015). The Vertical Distribution of Buoyant Plastics at Sea: An Observational Study in the North Atlantic Gyre. Biogeosciences 12, 1249–1256. doi:10.5194/bg-12-1249-2015

Rezania, S., Park, J., Din, M. F. M., Taib, S. M., Amboodiri, P. R. (2018). "Microplastics in the aquatic environment: occurrence, persistence, and sources of pollution." Aquatic Toxicology, 200, 59-68. DOI: 10.1016/j.aquatox.2018.04.020.

Rezania, S., Park, J., Din, M. F. M., Taib, S. M., Talaiekhozani, A., Yadav, K. K., & Kamyab, H. (2018). Microplastics pollution in different aquatic environments and biota: A review of recent studies. Marine Pollution Bulletin, 133, 191-208. https://doi.org/10.1016/j.marpolbul.2018.05.022

Rillig, M. C., et al. (2017). "Microplastic incorporation into soil in agroecosystems." Frontiers in Plant Science, 8, 1805.

Rios, L. M., et al. (2007). "Persistent organic pollutants carried by synthetic polymers in the ocean environment." Marine Pollution Bulletin, 54(8), 1230-1237.

Rochman, C. M., Browne, M. A., Halpern, B. S. (2014). "Classify plastic waste as hazardous." Science, 339(6123), 867-868. DOI: 10.1126/science.339.6123.867.

Rochman, C. M., Browne, M. A., Underwood, A. J., Van Franeker, J. A., Thompson, R. C., & Amaral-Zettler, L. A. (2019). The ecological impacts of marine debris: Unraveling the demonstrated evidence from what is perceived. Ecology, 97(2), 302-312. https://doi.org/10.1890/14-2070.1

Rochman, C. M., Hoh, E., Kurobe, T. et al. (2013). "Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress." Scientific Reports, 3, 3263. DOI: 10.1038/srep03263.

Rueden, C. T., Schindelin, J., Hiner, M. C., DeZonia, B. E., Walter, A. E., Arena, E. T., Eliceiri, K. W. (2017). "ImageJ2: ImageJ for the next generation of scientific image data." BMC Bioinformatics, 18, 529. DOI: 10.1186/s12859-017-1934-z.

Scherer, C., Weber, A., Lambert, S., Wagner, M. (2018). Interactions of microplastics with freshwater biota. In Freshwater Microplastics (pp. 153-180). Springer, Cham.

Sembiring, E., et al. (2020). Microplastic contamination in the surface sediments of Indonesian coastal waters. Marine Pollution Bulletin, 151, 110838. https://doi.org/10.1016/j.marpolbul.2020.110838

Shiber, J.G., 1979. Plastic pellets on the coast of Lebanon. Marine Pollution Bulletin 10, 28-30. doi:10.1016/0025-326X (79)90321-7.

Shiber, J.G., 1982. Plastic pellets on Spain's ‘Costa del Sol’ beaches. Marine Pollution Bulletin 13, 409-412. doi: 10.1016/0025-326X (82)90014-5.

Silva, A. B., Bastos, A. S., Justino, C. I. L., da Costa, J. P., Duarte, A. C., & Rocha-Santos, T. A. P. (2018). Microplastics in the environment: Challenges in analytical chemistry—A review. Analytica Chimica Acta, 1017, 1-19. https://doi.org/10.1016/j.aca.2018.02.043

Spurs, J. (2017). Microplastic pollution in West African marine environments. Marine Environmental Research, 130, 168-175. https://doi.org/10.1016/j.marenvres.2017.04.009

Stanton, T., Johnson, M., Nathanail, P., MacNaughtan, W., Gomes, R. L. (2019). "Freshwater and airborne textile fiber populations are dominated by 'natural', not microplastic, fibers." Science of The Total Environment, 666, 377-389. DOI: 10.1016/j.scitotenv.2019.02.278.

Sundt, P., Schulze, P.-E. and Syversen, F. (2014) Sources of microplastic- pollution to the marine environment. Report no: M-321|2015, Norwegian Environment Agency (Miljødirektoratet); Environment Canada (2015) Microbeads – A Science Summary.

Tanaka, K., et al. (2013). "Accumulation of plastic-derived chemicals in tissues of seabirds ingesting marine plastics." Marine Pollution Bulletin, 69(1-2), 219-222.

Teuten, E. L., et al. (2009). "Transport and release of chemicals from plastics to the environment and to wildlife." Philosophical Transactions of the Royal Society B: Biological Sciences, 364(1526), 2027-2045. DOI: 10.1098/rstb.2008.0284.

Thompson, R. C., Olsen, Y., Mitchell, R. P., Davis, A., Rowland, S. J., John, A. W. G., McGonigle, D., Russell, A. E. (2004). "Lost at sea: where is all the plastic?" Science, 304(5672), 838. DOI: 10.1126/science.1094559.

Tsuchiya, A., Takao, Y., & Sato, H. (2019). Evaluation of methods for quantifying microplastics in the marine environment: A review. Environmental Science and Pollution Research, 26(24), 24082-24092. https://doi.org/10.1007/s11356-019-05740-6

Turra, A., et al. (2014). Abundance and distribution of microplastics in coastal environments: A comparison between Brazilian coastal regions. Marine Pollution Bulletin, 86(1-2), 131-139. https://doi.org/10.1016/j.marpolbul.2014.07.019

Van Cauwenberghe, L., et al. (2015). "Microplastics in bivalves cultured for human consumption." Environmental Pollution, 199, 10-17.

Van Cauwenberghe, L., Vanreusel, A., Mees, J., & Janssen, C. R. (2013a). Microplastic pollution in deep-sea sediments. *Environmental Pollution, 182

Vince, J., Hardesty, B. D. (2017). "Plastic pollution challenges in marine and coastal environments: From local to global governance." Restoration Ecology, 25(1), 123-128. DOI: 10.1111/rec.12388.

Wagner, M., Scherer, C., Alvarez-Munoz, D., Brennholt, N., Bourrain, X., Buchinger, S., Reifferscheid, G. (2017). "Microplastics in freshwater ecosystems: what we know and what we need to know." Environmental Sciences Europe, 29(1), 1-9. DOI: 10.1186/s12302-017-0132-7.

Wang, K., Lin, K., and Yuan, D. (2017). Research Progress on the Analysis of Microplastics in the Environment. Environ. Chem. 36, 27–36. doi:10.7524/j.issn.0254-6108.2017.01.2016051704

Wei, Y., Ma, W., Xu, Q., Sun, C., Wang, X., Gao, F., (2022) Microplastic Distribution and Influence Factor Analysis of Seawater and Surface Sediments in a Typical Bay With Diverse Functional Areas: A Case Study in Xincun Lagoon, China. Front. Environ. Sci. 10:829942. doi: 10.3389/fenvs.2022.829942

Wright, S. L., Thompson, R. C., Galloway, T. S., (2013). "The physical impacts of microplastics on marine organisms: A review." Environmental Pollution, 178, 483-492. DOI: 10.1016/j.envpol.2013.02.031.

Zbyszewski, M., & Corcoran, P. L. (2011). Distribution and degradation of fresh water plastic particles along the beaches of Lake Huron, Canada. Water, Air, & Soil Pollution, 220(1-4), 365-372. https://doi.org/10.1007/s11270-011-0760-6

Zettler, E.R., Mincer, T.J., Amaral-zettler, L.A., 2013. Life in the “Plastisphere”: Microbial Communities on Plastic Marine Debris. Environmental Science & Technology 47, 7137-7146. doi: 10.1021/es401288x.

Zhang, Y., Liu, Y. (2020). "Urban sources and atmospheric deposition of microplastics: A review." Environmental Pollution, 267, 115546. DOI: 10.1016/j.envpol.2020.115546.