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ORIGINAL RESEARCH ARTICLE

A comprehensive review of the impact of microplastics on aquatic organisms: From ingestion to ecological consequences

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ABSTRACT

The presence of microplastics (MPs) in aquatic environments has become a major environmental concern due to their adverse effects on a wide range of aquatic organisms, including vertebrates (e.g., fish and marine mammals), invertebrates (e.g., mollusks and arthropods), and microorganisms such as bacteria and algae. Owing to their small size (<5 mm), MPs can penetrate biological membranes, interfere with cellular metabolic pathways, and induce various toxic effects. This review discusses the major sources of MPs, their pathways of distribution within aquatic systems, and their biological impacts. The objective of this work is to provide a comprehensive synthesis of the scientific literature addressing the ecological consequences of MP exposure across different aquatic taxa.

Keywords: microplastic; sources; toxicity; aquatic biota

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1. Introduction

Plastic pollution is rapidly emerging as a critical environmental threat, contributing to profound ecological disturbances in both terrestrial and aquatic systems (Turner *et al*., 2014). Due to various environmental processes such as photodegradation, mechanical abrasion, and chemical weathering, large plastic debris progressively fragments into smaller particles known as microplastics (MPs) [1], MPs are commonly defined as plastic particles smaller than 5 mm, originating from a wide range of polymer types including polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polyethylene terephthalate (PET), nylon (PA), and cellulose acetate (CA) (**Figure 1**) [2], These particles are persistent, non-biodegradable, and insoluble in water, allowing them to accumulate and disperse widely across aquatic environments. MPs can originate from multiple sources, including agricultural runoff, construction activities, maritime transportation, industrial discharges, and personal care products such as facial cleansers, toothpaste, exfoliating scrubs, cosmetics, and bath foams. Once released, MPs are transported into rivers, lakes, and marine systems through direct disposal, wastewater effluents, and the degradation of plastic materials on ships and coastal zones [3]. The ocean may be the largest store for plastic in the future (**Figure 2**), Studies have demonstrated that MPs exert significant impacts on aquatic biota, affecting digestive processes, metabolic pathways, energy balance, and physiological functions in various organisms. Several analytical methods have been developed to detect and quantify

MPs in environmental samples, including density separation, chemical digestion, microscopic examination, and spectroscopic identification techniques.

Microplastics also vary widely in color (e.g., red, green, purple, transparent, white, yellow, brown) and morphology (e.g., fibers, fragments, pellets, films), as well as dimensional structure (one-, two-, and three-dimensional forms) [4]. Their extensive occurrence has been documented across numerous aquatic organisms including annelids, mollusks, arthropods, fish, reptiles, amphibians, birds, mammals, and a wide range of microorganisms such as bacteria and algae [1].

Wastewater treatment plants have been identified as one of the major pathways for MP release into aquatic environments. For example, [3] reported concentrations of approximately 0.05 ± 0.024 MPs per liter in effluent discharge, contributing billions of MPs particles annually to surrounding water bodies. MPs also serve as vectors for persistent organic pollutants (POPs) such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), dichlorodiphenyltrichloroethane (DDT), and heavy metals including Ag, Al, Pb, Cu, and Zn, through sorption–desorption processes [5,6]

Due to their small size and high surface area, MPs can interact with cellular structures, alter microbial communities, and interfere with metabolic processes in [1][7,8]microorganisms such as bacteria.

Given their widespread distribution and ecological impacts, this review aims to synthesize current scientific knowledge regarding the environmental pathways, biological interactions, and toxicological effects of MPs on aquatic organisms including fish, invertebrates, and marine mammals.

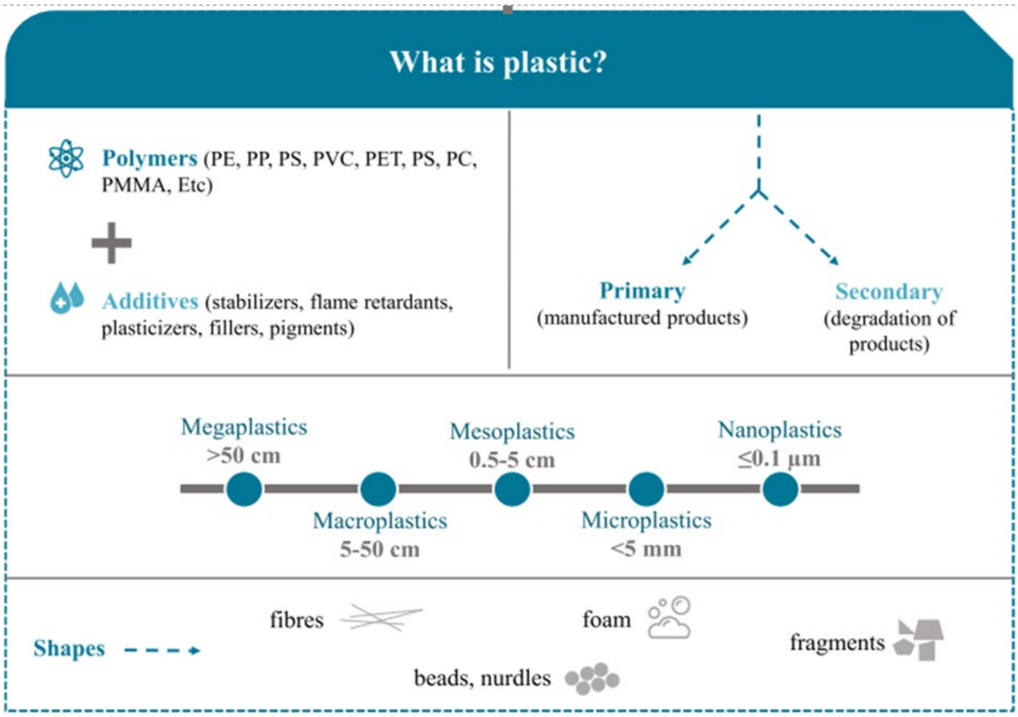

Figure 1. Definitions of plastics. PE: polyethylene, PP: polypropylene, PS: polystyrene, PVC: polyvinyl-chloride, PET: polyethylene Terephthalate, PC: polycarbonate, PMMA: poly methyl methacrylate, PU: polyurethane

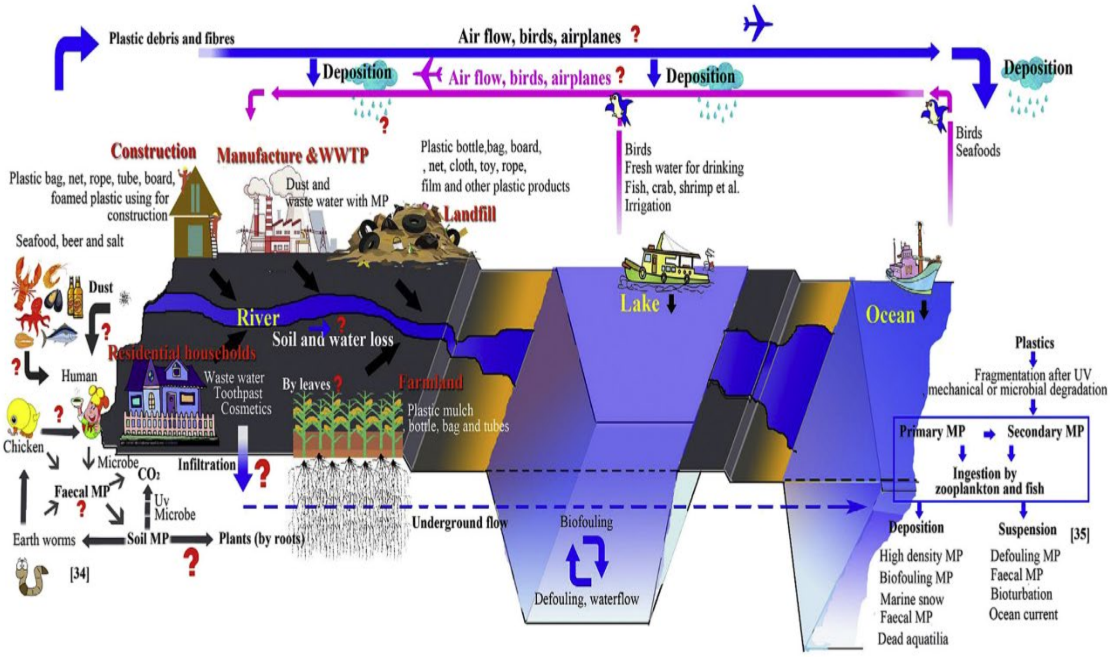

Figure 2. MP cycling in the ecosystems (Part of terrestrial ecosystem refers to Ref. [9], and part of marine ecosystem refers (Wright *et al*. 2013).

2. Sources of microplastic

The need for industrial development and the diversity of technologies after World War I led to the manufacture of many materials, including plastic materials, which are high molecular weight polymers to which other materials are added when manufacturing [11]. Bakelite was the first plastic that was manufactured by Leo Baekeland, a chemist who used as an electrical insulator for the first time in (1907), this development stimulated the rapid expansion of plastic manufacturing, owing to the material's high durability, low electrical conductivity, and ease of processing. As a result, global plastic production reached approximately 368 million tons by 2019, Thus, plastic has become one of the most widely produced and utilized materials developed by humans. However, due to poor management practices and improper disposal methods, it has become a major contributor to environmental pollution [12,13].

Plastic comes from fossil fuels (natural gas and oil) and from renewable sources such as bioplastics derived from cornstarch the use of plastic has recently increased dramatically, since the fifties of the last century, as it has now reached approximately 3800 million metric tons of plastic, 45% of which are polyethylene and polypropylene. Until now, plastic recycling has not become parallel with production. [14]

Plastic materials enter the environment through several ways, as their decomposition leads to the formation of primary microplastics and secondary microplastics. Where the materials that are manufactured for the first time were considered MP such as raw industrial materials, cosmetics, while the secondary ones are produced as a result of the division of raw materials due to several factors, including sunlight [15], MP/NPs also originate from domestic waste, sewage sludge/biosolids, land fillings, irrigation, greenhouse materials, fertilization, atmospheric deposition, plastic film mulch, garden organic waste and tire abrasion [16], personal care products (including scrub, toothpaste, facial cleanser, and detergent [17] [6].

Microplastics have also been observed in large quantities in the United States due to sewage [18], MP particles have been found distributed in large numbers in Southeast Asia, Asia, Africa, Europe, North America, South Africa, and in India [19]

3. Impact of MP on microorganisms

Many microorganisms can colonize the surfaces of macroplastics and disperse widely throughout aquatic ecosystems. This process facilitates the horizontal transfer of genetic material among the microbial strains attached to these pollutants, potentially enhancing their antibiotic resistance. Such interactions pose significant risks to environmental integrity and the health of other organisms within the ecosystem [17], Certain chemicals can adsorb onto the surfaces of MPs, and the resulting toxic effects may inhibit the growth and reproduction of microorganisms such as microalgae, bacteria, and viruses. When these contaminated MPs are ingested by other organisms, they can contribute to the development of infections and further disrupt biological processes within the aquatic ecosystem [1], The availability of MPs in aquatic environments leads to their transmission to herbivores and then to larger animals (predators). This indicates their transmission through the food chains in the water column over time, and this results from their accumulation, which increases their negative impact on the entire system [1], It was mentioned in a study to Frère et al [20] who focused on three bacterial communities associated with MPs in in the Bay of Brest, where they proved that they promote microbial colonization. The study focused on polymers (polystyrene, polypropylene and polyethylene) within ranges. The results showed that there are large gatherings of microbes on polymers, especially polystyrene. The disease-causing strains were detected for both (namely *V. aestuarianus and the V. splendidus polyphyletic* group) by PCR.

4. Toxicity of microplastic

Unlike macroplastics, the microplastics are not readily visible to the naked eye [21]. The smaller fraction of MPs is considered bioavailable to zooplankton and phytoplankton [22]. With their relatively large surface area, 85 MP tend to adhere to waterborne pollutants and leach toxic plasticizers [23]. By the ingestion of MP, there is a large potential for bioaccumulation and biomagnification of toxins that are introduced to the bottom of the food chain, Paul-Pont et al [24] was proved that the feeding of mussels Mytilus spp. in the seas is affected by the presence of polystyrene. The mussels' diet depended on algae that were associated with fluoranthene. The results showed that there is a high affinity of polystyrene with fluoranthene, and that the concentrations of fluoranthene in mussels were higher in the presence of polystyrene than the concentrations of fluoranthene without the presence of polystyrene. It led to increased death rates of blood cells and caused toxicity to tissues.

The following strains (*V. aestuarianus* and the *V. splendidus polyphyletic* group) came by PCR, Which are known to be pathogens have been seen accumulated on MPs, especially polystyrene [20], On the other hand, microplastics can reactive oxygen species generation for the marine bacteria Halomonas alkaliphila, and the effect was greater for positively charged macroplastics [6], As a result of its high molecular weight, it may limit enzymatic reactions within the bodies of microorganisms (Ho *et al.* 2018), It may lead to effect on the absorption of carbon as an energy source, and this in turn affects the metabolic activity of microorganisms [26], clearer the effect of polystyrene nanoparticles (159 ± 0.9 nm) that were combined with palladium (pd), polyethylene thin films, and colloidal TiO2 nanoparticles on the secretion of riboflavin from bacteria (*Shewanella oneidensis*), the results showed that bacteria (*S. oneidensis*) are affected by the secretion of riboflavin when treated with polystyrene nanoparticles, This may lead to a change in its cellular function, which affects the entire ecosystem [27]. Also effects on the epithelial permeability of the intestine, changes in the gut microbiota, and chronic immune disorders [28], Some microbes show a decrease in sugar production as a result of exposure to concentrations ranging from (1-100) µm of MPs, The effect of MP on microorganisms increases by increasing the concentration of the substance, as polypropylene, polyethylene, polystyrene, and polyethylene terephthalate and their effects on growth inhibition for each of (Saccharomyces cerevisiae, Scenedesmus sp, Pseudomonas putida) [29]

5. Methods for measuring the sizes, shapes, and concentrations of microplastics

Reliable quantification of microplastics (MPs) in aquatic environments requires standardized analytical procedures that ensure high accuracy and reproducibility. Water sampling is typically conducted through bulk water collection or in-situ filtration using mesh sizes between 20–300 µm, depending on the targeted particle size range [30]. Following collection, samples often require pre-treatment to remove dissolved and particulate organic matter; this is commonly achieved through oxidative digestion using hydrogen peroxide (H_2O_2) or Fenton's reagent, which effectively eliminates organic material without altering polymer structure [31]. Density separation represents a fundamental step in MP analysis, where solutions such as sodium chloride (NaCl), zinc chloride ($ZnCl_2$), or sodium iodide (NaI) are employed to isolate plastic particles based on their lower densities relative to inorganic debris [32]. After separation, preliminary identification is performed visually under a stereomicroscope to document MPs morphology, including size, color, and shape. Studies consistently show that fibers and fragments are the most dominant shapes in aquatic systems, while beads and films occur at lower frequencies; typical MPs sizes in freshwater and marine samples range from <100 µm to 5 mm, with the majority falling within the smaller fractions due to progressive fragmentation [32]. Concentrations reported across global waterways vary widely—from a few particles per liter in drinking water and groundwater to thousands of particles per liter in wastewater effluents and coastal zones—reflecting differences in anthropogenic impact and methodological variability [33] . However, accurate confirmation of polymer type requires spectroscopic analysis. Fourier-transform infrared (FTIR) spectroscopy and Raman spectroscopy are considered the most robust techniques for MP identification in water samples, capable of distinguishing polymer composition even for particles smaller than 20 µm [34,35]. For mass-based quantification, thermoanalytical techniques such as pyrolysis–gas chromatography–mass spectrometry (Py-GC-MS) provide sensitive detection of polymer-specific thermal degradation products, enabling precise measurement of MP concentrations within complex aqueous matrices [33]. Together, these methods constitute the core foundation for standardized and reproducible assessment of MP levels in water environments.

6. Challenge and limitation in measuring microplastics in water

Measuring microplastics in aquatic environments remains challenging due to substantial variability across sampling strategies, extraction procedures, and analytical techniques. Studies have shown that the absence of harmonized protocols leads to discrepancies in reported concentrations and particle characteristics, as laboratories often rely on different mesh sizes, filtration methods, and digestion procedures, ultimately influencing detection efficiency [36,37]. The recovery of particles is also strongly dependent on the type of water matrix—wastewater, drinking water, or freshwater—each requiring customized extraction steps that can introduce bias or particle loss during density separation, chemical digestion, or filtration [38,39]. Analytical identification using FTIR and Raman spectroscopy, although widely employed, faces limitations such as overlapping polymer spectra, interference from organic residues, and the lower detection limit for particles below 20–50 µm. These constraints reduce the accuracy of polymer identification and quantification [40]. Furthermore, even advanced tools such as machine learning–assisted spectral processing can misclassify particles if training datasets are incomplete or if environmental samples contain weathered or biofouled plastics with altered spectral signatures [41]. Collectively, these challenges highlight the urgent need for standardized, cost-effective, and validated analytical workflows to ensure comparable and reliable measurements of microplastics across water environments.

7. MP can effect on biota

Interest about interactions between MP and organisms is on the rise. Accessing organisms' responses to these chemically "inert" compounds plays an important role in determining their potential toxicity.

Microplastics from the environment tend to accumulate and move through living organisms, inducing a variety of biological effects, such as disturbances in energy metabolism, oxidative balance, antioxidative capacity, DNA, immunological, neurological and histological damage, The following is an outline of some previous studies of the types of MP and their effect on different types of aquatic organisms (**Table 1**), Also, a group of researches that summarized their studies on MP (**Table 1**).

Table 1. Some examples about MP studies on a biota

organism	Size of MP	Type of MP	references
Mytilus galloprovincialis	<100	Polyethylene	[42]
Scrobicularia plana	20 µm	polystyrene	[43]
Marine muscle	2µm	polystyrene	[44]
male mice	5µm	polystyrene	[45]
Spirulina platensis	(12.5, 25, 50, 75, 100,125, and 250) mg/L	(Polyethylene, Polystyrene, Polystyrene Blue, and polyvinyl chloride)	[8]
marine medaka (Oryzias melastigmas)	(10- and 200) µm	PL	[46]
(Spirullina platensis, Asterarcys quadricellulare, Cyanobacterium aponinum,and Desertifilum tharense)	(12.5, 25, 50, 75, 100, 125, 250) mg / liter	(Polyethylene, Polystyrene, Polystyrene Blue, Polyvinyl Chloride	[18]
Scenedesmus sp., Pseudomonas putida, and Saccharomyces cerevisiae	200–600 µm	polyethylene, polypropylene, polystyrene, polyvinyl chloride	[29]
mitten crab (Eriocheir sinensis)	5 µm	polystyrene	[47]
marine mussels Mytilus spp	32 mg/L	Polystyrene, fluoranthene	[24]
Halomonas alkaliphila	(50 nm-NH2, 55 nm and 1 µm-NH2)	polystyrene	[6]
Shewanella oneidensis	159 nm	polystyrene	
Rainbow fis (Melanotaenia fluviatilis)	<5 µm	plastics	[22]
Tribolium castaneum		Polystyrene	[48]
freshwater biofilm	100 nm	Nanoplastics	[26]
V. aestuarianus and the V.splendidus	2-5 µm	polyethylene, polypropylene and polystyrene	[20]
Pomatoschistus microps juveniles	0.184 mg/L	polyethylene	[49]
spirulina platensis	s200– 500 nm	Polyethylene, polystyrene, polyvi-nyl chloride	[50]

[51-66][50]

Table 2. List of review papers covering microplastics in the environment

Topic	Title	Reference
general	• "The physical impacts of microplastics on marine organisms" • "Identification methods in microplastic analysis" • "Environmental distribution, transport and ecotoxicity of microplastics" • "Micro/nano-plastics occurrence, identification, risk analysis and mitigation challenges and perspectives" • "Research progress in sources, analytical methods, eco-environmental effects, and control measures of microplastics" • "Microplastics and Nanoplastics in Aquatic Environments: Aggregation, Deposition, and Enhanced Contaminant Transport"	[10] [67] [68] [16] [15] [69]
toxicity	• "Immunotoxicity and intestinal effects of nano- and microplastics" • "Ecotoxicological effects of microplastics: Examination of biomarkers, current state and future perspectives" • Test of polystyrene toxicity on *Aeromonas-sobria* and *staphylococcus-homini* bacteria	[28] [14] [70]
biological impacts	• "Microplastics in the environment: A review of analytical methods, distribution, and biological effects"	[1]
Interaction with biota	• "An overview on biodegradation of polystyrene and modified polystyrene: the microbial approach" • "Research and management of plastic pollution in coastal environments of China"	[71] [5]
(Bio)degradation	• *The plastic in the oceans: A review of photodegradation and biodegradation* • *A bacterium that degrades and assimilates poly(ethylene terephthalate)* • *Plastics: Environmental and biotechnological perspectives on microbial degradation.* Biodegradation of microplastics by fungi and bacteria • Degradation of plastics and plastic-degrading bacteria in cold marine habitats • Pathways for degradation of plastic polymers floating in the marine environment • *Microbial enzymes for the recycling of recalcitrant petroleum-based plastics: How far are we?* • Occurrence, degradation pathways, and potential synergistic degradation mechanism of microplastics in surface water: a review • Microbial enzymes for the recycling of recalcitrant petroleum-based plastics: how far are we? • Biodegradation of microplastic derived from poly (ethylene terephthalate) with bacterial whole-cell biocatalysts • A review of biodegradation and formation of biodegradable microplastics in soil and freshwater environments • Degradation of bio-based and biodegradable plastics in a salt marsh habitat: another potential source of microplastics in coastal waters • Plastics: environmental and biotechnological perspectives on microbial degradation	[72] [73] [74] [75] [76] [77] [78] [77] [79] [80] [81] [74]

8. Conclusion

In this review, we briefly summarized the definition, sources, transmission, and toxicity of microplastics (MPs) on various organisms, including mammals, vertebrates, microorganisms (bacteria and algae), and invertebrates. Due to the rapid increase in MP production, these pollutants have accumulated in rivers, streams, lakes, oceans, and even remote regions, leading to ingestion by marine organisms such as whales, dolphins, and seabirds, with up to 90% of seabirds reported to swallow [7] .

Most studies focus on MPs smaller than 100 µm, whose toxicity depends on concentration, exposure time, surface area, and adsorption of co-pollutants. MPs can act as carriers for pathogenic microorganisms or form synergistic complexes with other pollutants, increasing environmental risks. Once ingested, MPs can penetrate body membranes, accumulate in organs like the liver and alimentary canal, block digestive processes, and disrupt feeding, photosynthesis, and enzymatic pathways in various organisms [10].

However, measuring MPs in aquatic environments remains challenging due to the variability in sampling, extraction, and analytical procedures. Standardized protocols are often lacking, and methods such as visual identification, FTIR, Raman spectroscopy, and thermoanalytical techniques (e.g., Py-GC-MS) each have limitations in terms of detection limits, interference from organic matter, or particle misclassification [30-35][40,41]. These challenges highlight the urgent need to establish reliable, cost-effective, and validated analytical workflows for accurate quantification of MPs in water.

Therefore, in addition to monitoring their ecological and health impacts, it is essential to develop robust measurement methods and effective treatment strategies to prevent MPs from entering aquatic environments.

Conflict of interest

The authors declare no conflict of interest

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