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Review paper

Environmental Fate, Plastisphere Microbial Dynamics, and Human Health Implications of Marine Micro- and Nanoplastics

Majed A. Al-Shaeri[1,2]

[1] *Department of Biological Sciences, Faculty of Science, King Abdulaziz University, Jeddah, Saudi Arabia.*
[2] *Environmental Protection & Sustainability Research Group, Faculty of Science, King Abdulaziz University, Jeddah, Saudi Arabia.*

*Corresponding author Email:malshaere@kau.edu.sa

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Abstract

Micro- and nanoplastics are now widely recognized as contaminants of marine environments, with increasing concern about their potential effects on ecological and human health. Due to their small size, persistence, and high surface-area-to-volume ratio, these particles can interact with a large number of matrices in the environment and biological systems. Plastic particles quickly get covered by various microbial communities in water bodies to form complex structures known collectively as the plastisphere. These assemblages of microbes may influence how plastics behave in the environment and could help transport microorganisms and chemical contaminants across marine ecosystems. This review summarizes what is known about where micro- and nanoplastics are found in the environment, how they interact with microbial communities, and what their ecological and toxicological effects are. More detail is provided about the formation of plastispheres, the succession of microbes on plastic surfaces, plastic particles as vectors for pathogens and toxic substances. The review also looks at new evidence that links exposure to microplastics with oxidative stress, inflammatory responses, endocrine disruption, and changes in gut microbial communities in aquatic organisms—and perhaps even in humans. Finally, it discusses new developments and analytical challenges related to the detection and characterization of micro- and nanoplastics from environmental samples. Though substantial progress has been made, there are still significant knowledge gaps regarding standardized analytical methods for chronic exposure thresholds as well as mechanistic toxicology for nanoplastics. Overcoming these challenges through interdisciplinary research and enhanced environmental monitoring will be critical for improving risk assessment efforts aimed at reducing plastic pollution in marine ecosystems.

Keywords: Microplastics, Nanoplastics, Plastisphere, Marine microbiome, Ecotoxicology, Human exposure.

Introduction

Plastic materials are essential in modern society because of their long life, easy use, and low cost of production (1, 2). Since the middle of the 20th century, when plastics started to be produced on a large scale industrially, there has been an exponential increase in global plastic production; thus, contamination at the global level has reached alarming proportions (1). A large share of plastic waste finally ends up in aquatic ecosystems, where it gets fragmented and degraded into smaller particles known as microplastics and nanoplastics (1-3). Microplastics refer to plastic particles that generally have diameters less than 5 mm; nanoplastics usually mean particles that have sizes less than 1 µm (1, 2, 4). They can be primary microplastics that were originally manufactured for industrial or consumer use applications or secondary microplastics formed from larger plastic debris through physical, chemical, and biological degradation processes (2, 3, 5). Because of their small size and low density, micro- and nanoplastics can remain suspended in aquatic environments over long distances via ocean currents and atmospheric processes (1-3). Marine ecosystems are increasingly being regarded as the major sinks for plastic debris (1, 4, 6). Microplastics have now been found virtually in all marine compartments, including surface waters, deep-sea sediments, coastal environments poles (2, 4, 6). This wide distribution raises increasing concern about possible interactions with marine organisms and ecological processes. Different from larger plastic debris, micro- and nano-plastics can be ingested readily by a wide range of organisms across different trophic levels that include plankton, invertebrates, fish, seabirds, and marine mammals (2).

The formation of microbial biofilms on plastic surfaces is an important emerging concept in microplastic research. Plastic particles rapidly become colonized by microorganisms such as bacteria, fungi, and microalgae once they are introduced into aquatic environments (1, 7). These microbial communities associated with plastics, develop structured biofilms called the plastisphere, which is considered a unique ecological niche different from surrounding microbial communities (7). The plastisphere may play a role in influencing he microbial succession of horizontal gene transfer as well as may become a reservoir for opportunistic pathogens (1, 7).

In addition to their biological interactions, micro- and nanoplastics can adsorb and concentrate chemical contaminants such as heavy metals, persistent organic pollutants, and plastic additives (8, 9). As a result, plastic particles could serve as carriers for both microorganisms and toxic chemicals and help transport them through marine food webs (8, 10). The uptake of plastic particles by marine organisms may therefore lead to the bioaccumulation and trophic transfer of contaminants that pose potential risks to ecosystem health and human exposure via seafood consumption (11, 12). Despite an increasing amount of literature on plastic pollution in the environment, there are still some important gaps in knowledge. Most previous studies have largely focused on the distribution and ecological impacts of plastic debris (13). However, relatively few have attempted to integrate aspects of plastisphere microbial ecology, toxicological mechanisms, trophic transfer processes, and analytical detection challenges into one unified conceptual framework (14). Also, the mechanisms by which biological effects happen with nanoplastics are not well understood; since analytical limitations still prevail for accurate detection and quantification of these particles from environmental matrices (15). Fig. 1 represents a conceptual illustration of the main sources, environmental routes, and biological effects of micro- and nanoplastics. Primary plastics from industrial and urban wastes transform into micro- and nanoplastics and circulate through aquatic ecosystems via the food web, finally affecting the biological world and the health of humans through the process.

Fishing ships, municipal wastes, and industries including pharmaceutical and bevary remain the main primary sources of the microplastics found in salt waters. Their small size increases environmental persistence. These microplastics disintegrate into nanoplastics over time: a secondary source of plastic debris in the marine ecosystems. The nanoplastics have the ability to get into biological barriers such as cell membranes to cause cellular damage that potentially leads to systemic toxicity in the food chain. Micro- and nanoplastics usually contain toxic additives known as flame retardants and plasticizers.

Thus, this review aims to summarize what is known about micro- and nanoplastics environmental fate, their interactions with microbial communities in marine ecosystems, as well as possible ecological and human health implications, while discussing new emerging analytical approaches plus priority areas needing future research.

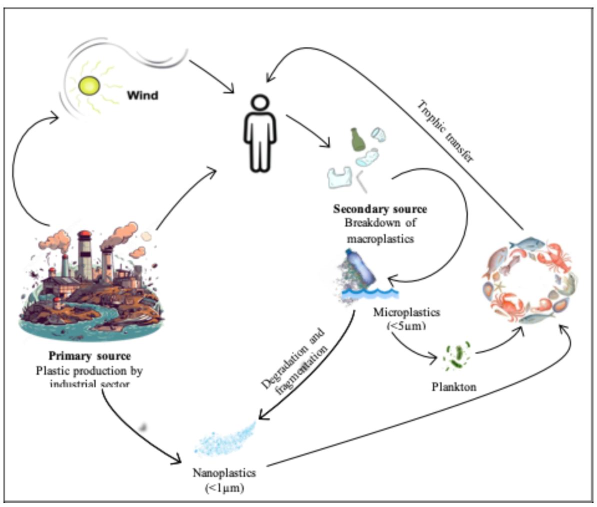

Figure 1. **Sources, pathways, and impacts of micro- and nanoplastics on the environment and human health**

Methodology of Literature Review

This review was performed through an extensive survey of the scientific literature in order to synthesize current knowledge on micro- and nanoplastics in marine environments. Relevant publications were identified through systematic searches in major scientific databases, including Web of Science, Scopus, PubMed, and ScienceDirect. The literature search was primarily focused on publications from 2010 until early 2026, with particular emphasis placed on studies published over the last five years so as to capture recent advances within this field (13). Search queries comprised combinations of keywords such as microplastics, nanoplastics, marine plastic pollution, plastisphere, plastic-associated microbial communities, ecotoxicology, trophic transfer, human exposure, and analytical detection methods (16). Only peer-reviewed research articles and high-quality review papers published in reputable international journals were considered for inclusion.

The articles were relevant if they dealt with the environmental distribution, microbial interactions, toxicological mechanisms, or analytical characterization of micro- and nanoplastics (15). Where appropriate, studies were excluded due to insufficient methodological detail and scientific validation. The literature was reviewed critically and synthesized so that key research themes and emerging mechanisms, as well as existing knowledge gaps, could be identified about micro- and nanoplastic pollution in marine ecosystems.

Overview of Micro- and Nanoplastics

Micro- and nanoplastics are a growing class of environmental contaminants from the widespread use and disposal of plastic materials (17). Their discovery in marine ecosystems has raised much interest because they are persistent, mobile, and possibly ecologically consequential (18).

Microplastics can be divided into two broad categories: primary and secondary types (19). Primary microplastics are those that are intentionally manufactured to be small in size. These include cosmetic microbeads, industrial abrasives, and plastic pellets used for pre-production (20).

Table 1. **Sources of micro/nanoplastics into aquatic systems.**

Primary sources	Secondary sources	Reference
	Microplastics	
3D printing materials	Automotive tire dust	(20)
Agricultural films	Broken-down children's toys	(23)
Industrial abrasives Primary	Broken-down plastic bags	(24)
Personal care products	Degraded plastic bottles and containers	(22)
Plastic packaging materials	Deteriorated plastic furniture	(25)
Pre-production plastic pellets	Fragmented fishing gear	(26)
Single-use plastics	Fragmented styrofoam products	(21)
Synthetic rubber products	Microfibers from washed clothing	(27)
Synthetic textiles	Photodegraded plastic film remnants	(28)
Tire wear particles	Weathered synthetic textiles	(29, 30)
	Nanoplastics	
Nanopolymer fillers (used in 3D printing & reinforced composites)	Automotive tire wear (mechanical abrasion into nano-sized dust)	(31)
Nano-encapsulated pesticides (used in precision agriculture)	Agricultural mulch films (UV degradation and soil fragmentation)	(32)
Industrial nano-abrasives (used in high-precision metal cleaning)	Degraded single-use packaging (mechanical and chemical weathering)	(8)
Nano-additives in paints and coatings(for UV resistance/hardness)	Fragmented expanded polystyrene (styrofoam weathering in marine environments)	(33)

Secondary microplastics come from the breakdown of larger plastic debris by processes such as ultraviolet radiation, mechanical abrasion, and biological degradation into smaller pieces over time (21, 22). Table 1 summarizes the primary and secondary micro/nanoplastics types found in aquatic systems.

Nanoplastics are an even smaller fraction of plastic particles created by advanced degradation processes (34). Because they are so small in size, nanoplastics may have different physicochemical properties than larger microplastics—such as having more reactive surfaces or being taken up more easily into cells (35, 36). The micro- and nanoplastics are generally derived from the disintegration of macroplastics. Fig. 2 below shows a Petri plate with diverse plastic types (size and color) that was published in 2018 by the Australian Institute of Marine Sciences (AIMS).

Figure 2. **Illustrative representation of the morphology of plastic debris isolated from aquatic environments**

Microbial Interactions and the Plastisphere

The most important biological phenomenon associated with micro- and nanoplastics in aquatic environments is the formation of microbial biofilms on plastic surfaces (37, 38). Plastic particles introduced into marine systems rapidly become colonized by diverse microbial communities, including bacteria, archaea, fungi, microalgae, and protozoa (39). Colonized plastic surfaces form structured biofilms that are collectively referred to as the plastisphere. The plastisphere represents a unique ecological niche that is separate from surrounding planktonic microbial communities (14, 38). Physicochemical properties of plastic particles, such as polymer composition, surface hydrophobicity, particle size, and surface roughness, are very important in determining patterns of microbial colonization (39). Hydrophobic surfaces of plastics usually enhance microbial attachment because they facilitate interactions with extracellular polymeric substances produced by microorganisms during biofilm formation on these surfaces (37). Environmental conditions such as salinity, temperature, nutrient availability, and ultraviolet radiation also influence microbial succession within plastisphere communities (40). Fig. 3 indicates the formation and succession of biofilms found on the surface of micro- and nanoplastics in the aquatic environment. After exposure to the aquatic environment, these plastic materials get colonized by microbes that produce exopolymeric substances, which allow them to attach stably. These plastisphere biofilms generate new ecological niches, improve microbial survival, and aid in the transport of pathogens and functional microbes along the aquatic food web.

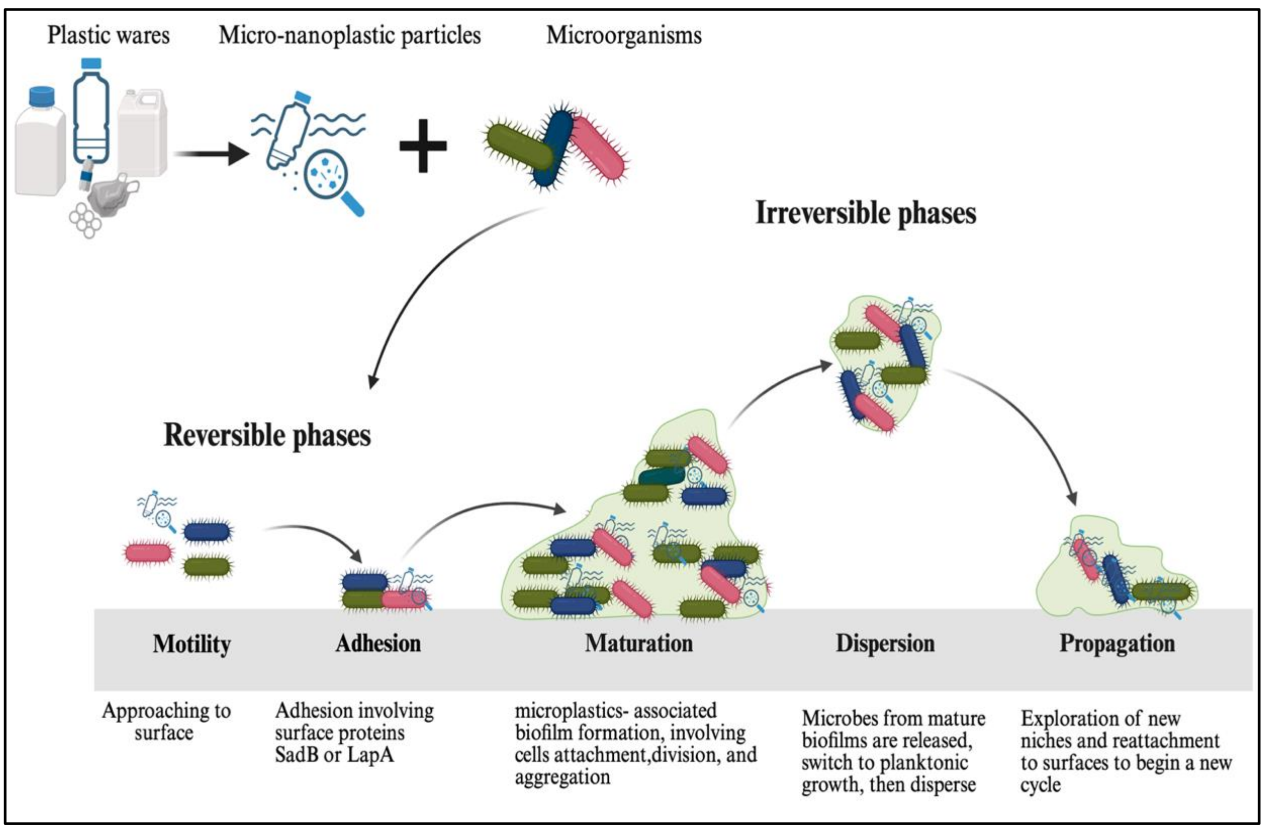

Figure 3. **Formation and development of micro-nanoplastic associated biofilm**

Studies have shown that plastisphere biofilms may contain microbial taxa that differ significantly from those found in surrounding seawater (40). In some cases, plastic-associated biofilms have been found to harbor opportunistic or pathogenic microorganisms, including species belonging to genera such as *Vibrio*, *Pseudomonas*, and *Aeromonas* (41). These findings have raised concerns about the potential role of plastic particles in acting as vectors for the transport of these microorganisms across marine ecosystems (41). Beyond facilitating microbial colonization, plastic particles can also adsorb various chemical contaminants present in the environment around them. This includes heavy metals, persistent organic pollutants, and additives used in plastics themselves (42). These contaminants could get trapped inside plastisphere biofilms, forming intricate microenvironments that would then have an effect on both metabolism and structure within a community of microbes (39). As a result, development into a plastisphere can be seen as an interface of great ecological importance connecting pollution through plastics with both microbial ecology and biogeochemical processes found within marine ecosystems.

Ecological Impacts on Marine Organisms

The vast distribution of micro- and nanoplastics within marine environments has raised substantial concerns over their ecological impacts on aquatic organisms (18). These particles are small enough to be easily ingested due to their buoyant properties by organisms at all trophic levels, from planktonic microorganisms up through large marine vertebrates (43, 44).

Primary producers such as phytoplankton might have some interaction with microplastics that are suspended in the water column (18). Experimental studies have shown that plastic particles can influence photosynthetic efficiency, nutrient uptake, and cell growth of certain phytoplankton species (45-49).

Zooplankton and filter feeders are very important as they are the first points where microplastics enter marine food webs (43). Copepods, krill, and bivalves can take in microplastic particles because these plastics look like real food items when it comes to size and shape (50).

Fish and other higher trophic organisms can get microplastics through diet exposure and trophic transfer (11, 51). Many studies reported plastic particles inside the gastrointestinal tracts of marine fish species (52, 53). Long-term exposure could bring about physiological stress responses like oxidative stress, inflammation, and tissue damage (54).

Besides physical impacts, micro- and nanoplastics can be carriers for toxic substances as well as microorganisms (42). Pollutants that are adsorbed plus microbes associated with the plastisphere could be transferred to organisms when ingested; this may increase ecological risks (10).

Gut Microbiome Changes and Immune Reactions

Recent studies have focused more on the possible interactions between microplastics and the gastrointestinal microbiome of exposed organisms (55). The gut microbiome is important in keeping host metabolic functions, immune regulation, and nutrient absorption (56). Changes to microbial community composition could have big implications for organismal health. Experimental studies in aquatic organisms such as zebrafish and invertebrates have shown that exposure to micro- and nanoplastics can alter gut microbial diversity and abundance (54). These changes might happen through direct contact between plastic particles and intestinal tissues or indirect effects mediated by associated chemical contaminants and microbial communities.

Microplastic exposure has been linked to increased production of reactive oxygen species and inflammatory signaling pathways in the intestinal tract (57). Such responses may disrupt epithelial barrier integrity and promote immune activation (58). Changes in microbial community composition have also been associated with increased abundance of opportunistic bacteria and reduced populations of beneficial microbial taxa (59, 60). The possible effect from gut microbiome disruption induced by micro- and nanoplastics goes beyond the localized gastrointestinal impacts. In fact, the changes within microbial metabolic activity can impact nutrient absorption, immune response, as well as general physiological homeostasis (61-63). Most current evidence comes from experimental models, but exposure to microplastics might cause larger biological implications due to interactions with host-associated microbial communities.

Human Exposure Routes and Health Effects

Human exposure to micro- and nanoplastics can occur through multiple environmental pathways, including ingestion, inhalation, and dermal contact (64). Among these pathways, dietary intake—particularly through seafood consumption—has received considerable attention as a potential route of exposure (10).

Marine organisms that accumulate microplastics through trophic transfer may serve as vectors for introducing plastic particles into human food chains. Studies have detected microplastic particles in a variety of seafood products, including fish, shellfish, and crustaceans. Drinking water, both bottled and tap water, has also been identified as a potential source of human exposure (65).

Inhalation of airborne microplastic fibers represents another emerging exposure pathway, particularly in indoor environments where synthetic textiles and plastic materials are common (66, 67). Airborne particles can be inhaled and deposited within the respiratory tract, potentially contributing to pulmonary exposure (68). Fig. 4 below conceptual representation for a general overview of the main routes of exposure to micro and nanoplastics by humans. Humans tend to be exposed to micro and nanoplastics mainly through the ingestion of contaminated seafood, exposure to airborne particles, and uptake of contaminated drinking water (69). These exposure routes allow micro and nanoplastics to deliver associated chemicals and microorganisms to the human body.

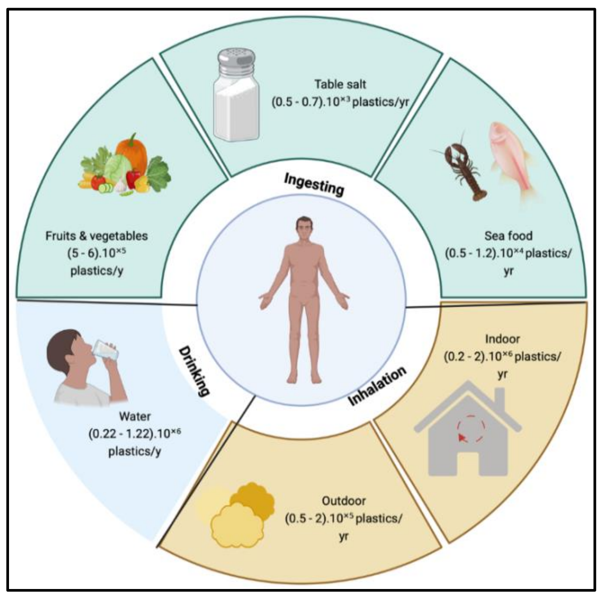

Figure 4. **Sources of plastics pollutants in human systems. 50% of the plastics contaminants are ingested, 33% are inhaled while 17% get into the human body via drinking of exposed water samples**

Although research on the human health effects of microplastics is still evolving, several potential mechanisms have been proposed. These include oxidative stress, inflammatory responses, endocrine disruption caused by plastic additives, and interactions with the human gut microbiome (36, 70). Nanoplastics, due to their extremely small size, may have the ability to cross biological barriers and enter systemic circulation, although further research is required to clarify these processes.

Current evidence does not yet provide definitive conclusions regarding the long-term health risks associated with microplastic exposure in humans. However, the widespread presence of plastic particles in environmental and food systems underscores the importance of continued investigation into their potential toxicological effects. Tables 2A and 2B summarize micro- and nanoplastics found in the animal systems, from studies across the globe.

Table 2A. **Summary of recent ecotoxicological studies and environmental detection of nanoplastics (NPs) in aquatic and terrestrial systems (2024–2025).**

Nanoplastics (Polymer/Type)	Effect	Affected animal (species)	Country/region (study location)	Reference
Polystyrene (PS) (88 ± 11 nm), gold-doped	Uptake confirmed. Filter feeders (D. magna) accumulated 5x more NPs than detritivores (A. aquaticus). 97% of NPs retained in the sediment.	Water flea (*Daphnia magna*), aquatic sowbug (*Asellus aquaticus*)	Sweden (Lund University, Wetland Mesocosms)	(71)
Polystyrene (PS) (Unspecified size)	Grazing severely impacted. Collapse of zooplankton (Daphnia) populations; phytoplankton diatoms severely impacted. Cyanobacteria unaffected (resistant).	Zooplankton (Daphnia), Phytoplankton (Diatoms)	Sweden (Lund University, Artificial Wetlands)	(72)
BiosourcedNanoplastics (Type unspecified)	Ecotoxicological impact on commercially exploited oysters. (Specific pathology data not detailed in abstract - Thesis document).	Oysters (*Crassostrea gigas/edulis*)	France (Arcachon Bay)	(73)
Unspecified Nanoplastics (Environmental detection)	Detected in environment. Particles found in agricultural soils, air, water bodies, and aquatic organisms. Potential entry into livestock identified as a risk.	Aquatic organisms (unspecified), poultry, livestock	Bangladesh (Environmental detection - Risk assessment)	(74)

Table 2B. **Summary of recent ecotoxicological studies and environmental detection of microplastics (MPs) in aquatic and terrestrial systems (2024–2025).**

Microplastics (Polymer/Type)	Effect	Affected animal (species)	Country/region	Reference
Polyethylene, Polypropylene, Polyester (Fibers/Fragments)	Ingestion present; higher concentrations in non-selective grazers (e.g., buffalo: 17.7 MPs/g).	Feral Cattle, Water Buffalo, Wild Boar, Rhesus Macaque, Porcupine	Hong Kong (China)	(75)
High/Low-Density Polyethylene (Fiber 72%, Fragment 22%, Pellet 4%)	Ingestion in 100% of individuals; found in intestine > gill > muscle; intestinal blockage risk noted.	Indigenous Fish (Ompokpabda, *Mystus tengara*, Labeobata, etc.)	Bangladesh (Padma River)	(50)
Filament-type (Predominant)	100% contamination of mollusks; *Crassostrea rhizophorae* accumulated more than *Mytellastrigata.*	Oyster (*Crassostrea rhizophorae*), Mussel (*Mytellastrigata*)	Brazil (Aracruz mangrove)	(44)
Textile fibers, Cosmetic microbeads, Industrial pellets	Universal ingestion in digestive tracts; species-specific accumulation patterns observed.	Freshwater Snails (*Pomaceacanaliculata, Filopaludinajavanica, Sulcospiratestudinaria*)	Indonesia (Brantas River)	(52)
Unspecified Microplastics	First evidence of animal death caused by MP pollution (suffocation by plastic bag); widespread contamination.	*Manatee*, Turtles, Birds, Fish	Amazon Basin (Brazil/Region)	(53)

Reliable detection and characterization of micro- and nanoplastics in environmental samples represent critical challenges in plastic pollution research. The small size, diverse polymer composition, and heterogeneous distribution of plastic particles complicate analytical identification and quantification (15). Several spectroscopic and microscopic techniques have been developed to address these challenges. Fourier-transform infrared spectroscopy (FTIR) and Raman spectroscopy are among the most widely used analytical tools for identifying polymer types in environmental samples (15). These methods enable the detection of characteristic molecular vibrations associated with different plastic polymers.

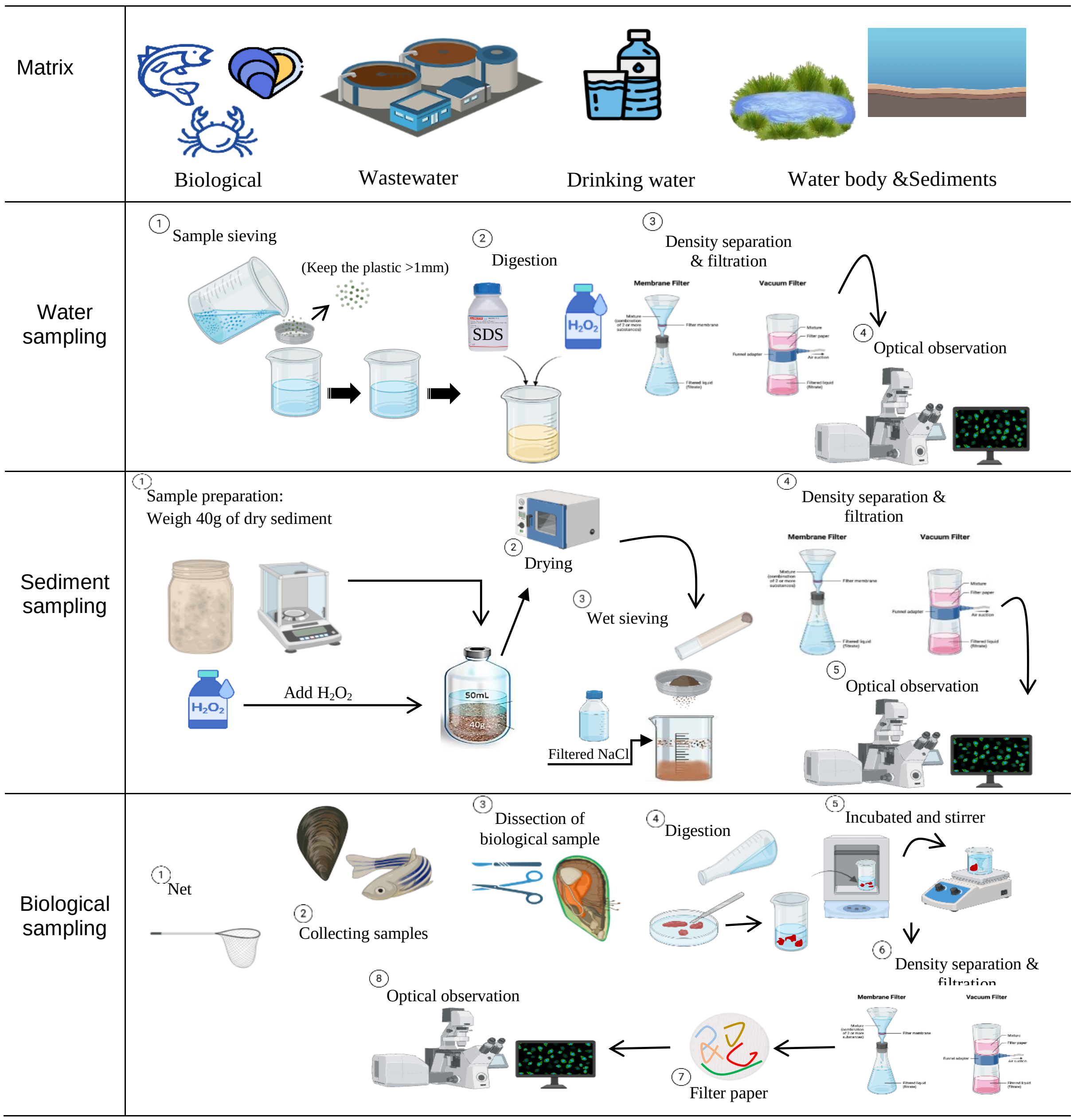

Figure 5. **Stages and techniques for micro- and nanoplastics detection from water, sediment, and biological organisms**

Microscopic techniques such as scanning electron microscopy (SEM) and transmission electron microscopy (TEM) are often used to visualize particle morphology and surface characteristics (77). When combined with spectroscopic methods, these approaches provide detailed information regarding particle size, shape, and chemical composition.

Another powerful analytical technique is pyrolysis–gas chromatography–mass spectrometry (Py-GC/MS)**,** which enables the identification of polymer types through thermal decomposition and chemical analysis (15). This method is particularly useful for quantifying plastic polymers in complex environmental matrices.

Despite these advances, significant analytical limitations remain, particularly for detecting nanoplastics (78). Current methods often require extensive sample preparation and may have limited sensitivity for extremely small particles (79). Consequently, the development of standardized analytical protocols and improved detection technologies remains a priority for advancing microplastic research. Fig. 5 is a comprehensive procedure for micro- and nanoplastics detection from marine samples such as water, sediment, and aquatic living systems.

Regulatory and Policy Perspectives

The growing perception of plastic pollution as an environmental challenge of global dimensions has led to increasing attention from policymakers and regulatory agencies. Several international initiatives have been developed in this regard, namely, to address the environmental impacts of plastic waste and promote sustainable management of plastics (80, 81). The United Nations Environment Programme (UNEP) and the European Union introduced policy frameworks that reduce plastic waste generation, enhance recycling systems, and restrict the use of certain single-use plastic products (82, 83). Many countries have already imposed restrictions on microbeads in personal care products for their entry into aquatic environments (84). According to 2022 data (Fig. 6) presented by the Organization for Economic Co-operation and Development (OECD) (85), global plastic production reached 400 million tonnes (Mt), with China leading as the top producer, contributing 32% of the total. This was followed by Other Asian countries (23%), the United States (US; 14%), the European Union 28 (EU28; 14%), the Middle East (ME; 5%), Africa (4%) and the rest of the world (ROW; 8%) (30). The high rate of plastic production has significantly contributed to its entry into the marine environment, resulting in extensive ecological contamination and posing significant risks to human health (Fig 6).

Regulatory approaches to micro- and nanoplastics are currently limited due to uncertainties concerning their environmental concentrations, exposure pathways, and their toxicological effects. Effective policy development will require a better scientific understanding of dynamics related to plastic pollution as well as standardized monitoring methodologies (86-88). Future policies could benefit from an integration between environmental monitoring programs and improved waste management systems, along with international cooperation towards addressing this problem at its source. Mitigating long-term environmental impacts caused by plastic contamination will largely depend on the success of such strategies. As depicted in Fig. 7, plastic production globally can be visualized based on its geographical distribution in the top-producing countries along with stock build-up in specific industrial sectors. The comparison at the country level reveals the dominance of a few high-production countries, such as China, in terms of their contribution to total plastic production. Simultaneously, the comparison between industrial sectors indicates that most of the plastics are accumulated in sectors like construction, packaging, automobiles, and electronics due to varied lifespans and uses.

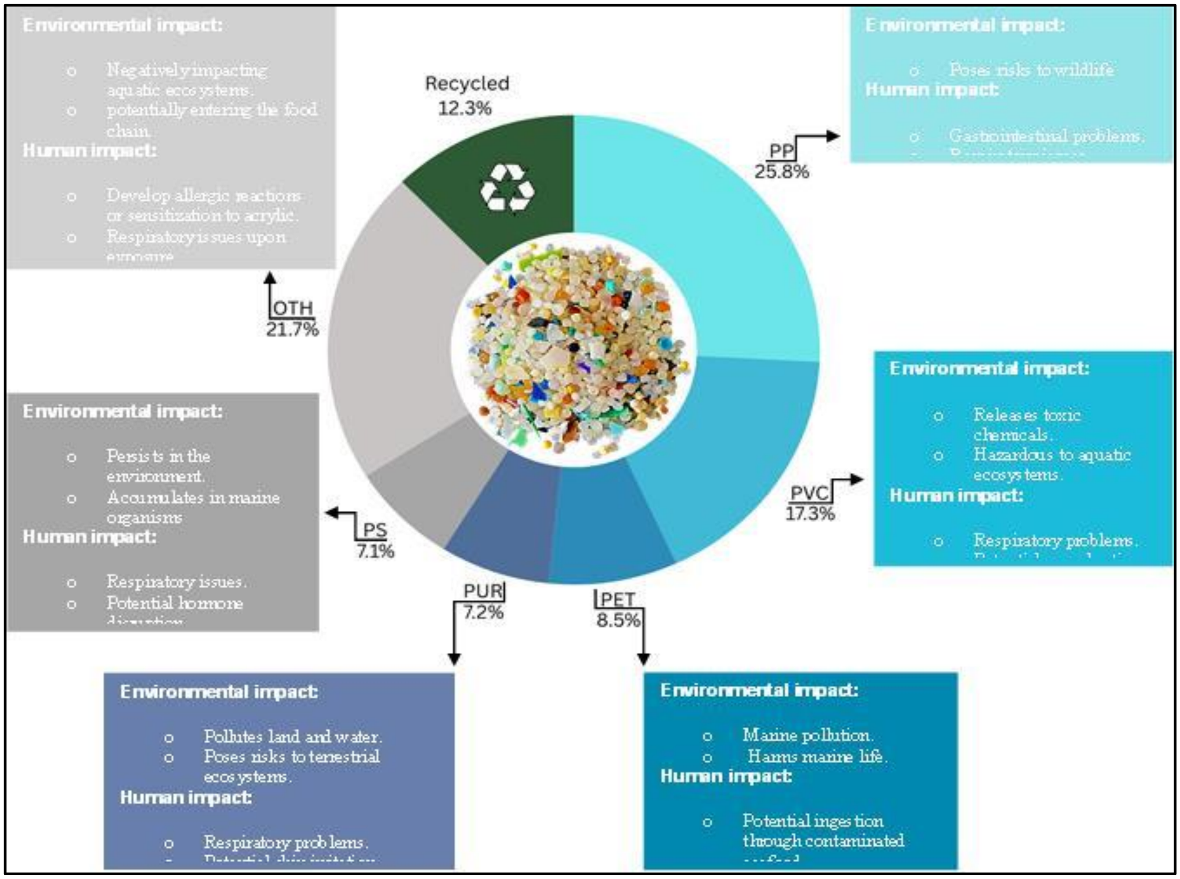

Figure 6. **The percentage of Global polymer production and environmental impacts, and potential health effects**

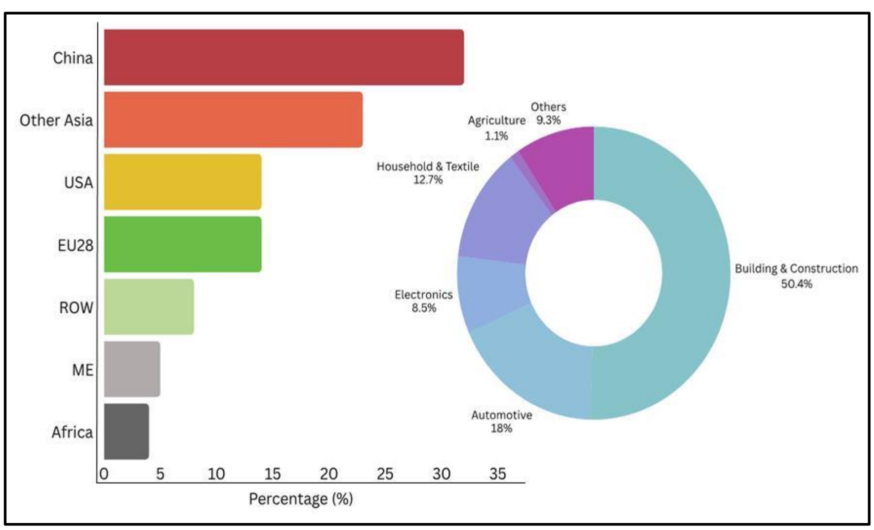

Figure 7. **Global plastic production categorized by country and plastic stocks per industrial sector**

Conclusion and Future Perspectives

Micro- and nanoplastics are now recognized as persistent contaminants that have a worldwide distribution in marine ecosystems. Their small size, persistence in the environment, and ability to interact with biological and chemical components of aquatic systems raise great concern about their ecological effects as well as human health implications. The formation of plastisphere microbial communities is an important interface between plastic particles and marine ecosystems since it controls microbial dynamics, transport of contaminants, and possible dissemination of pathogens. Microplastics can be transferred through food webs by marine organisms, creating possible exposure pathways for higher trophic organisms, including humans. There have been major advances in understanding how microplastics distribute environmentally and their biological interactions, but many knowledge gaps still exist. Areas needing more research include toxicological mechanisms related to nanoplastic exposure, long-term ecological impacts resulting from plastic accumulation, and potential health risks posed to human populations. Advances in analytical technologies will be essential for improving the detection and characterization of plastic particles in environmental matrices. In addition, interdisciplinary research integrating environmental science, microbiology, toxicology, and public health will be necessary to develop comprehensive risk assessment frameworks.

To tackle the challenges brought about by plastic pollution, it will take concerted actions that include scientific research, technological innovation, and policy development. Strengthening environmental monitoring systems, promoting sustainable materials management, and reducing plastic waste generation are key steps in mitigating the long-term impacts of micro- and nanoplastics on marine ecosystems and human health.

Ethics and Consent to Participate

Not applicable.

Availability of Data and Materials

The data supporting the findings of this study are included within the article.

Conflict of Interest

The author declare that have no conflict of interest.

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