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Micro\Nanoplastics in the Aquatic Environment: A Hidden Threat that Pollutes the Future

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Abstract: Recent decades have witnessed a significant increase in the use of plastics across various life domains, resulting in a giant accumulation of plastic waste in the environment, especially in aquatic systems. In this context, microplastics and nanoparticles stand out as one of the most prominent contemporary environmental challenges due to their superior wide-scale environmental dispersal ability and bioaccumulation. This study looks at the main ways these particles are created, which come from both direct use in industries and the slow breakdown of regular plastics, as well as how they move and interact in water environments. These particles spread through waterways and coastal ecosystems, eventually settling in the oceans where they interfere with environmental components and adversely affect marine organisms across various levels of the food chain. Scientific research has revealed that these microparticles may cause blockage of the gut of marine organisms, and may also lead to serious functional disorders such as oxidative stress and impaired immune response. Worse yet, these particles can carry harmful chemical pollutants because they stick to heavy metals and long-lasting organic compounds, passing them on to living creatures. Due to the non-biodegradable, non-rapidly biodegradable nature of these substances, they pose a long-term environmental threat, the impact of which is not limited to individual organisms but extends to entire ecosystems and aquatic food webs. Human exposure to these particles —either via the food chain, inhalation, or contaminated water - has also raised serious health concerns, including intestinal disorders, immune system dysfunction, and the potential to cause endocrine disruption. Research in this field faces serious challenges, most notably the technical difficulties in monitoring nanoparticles due to their small sizes, as well as the lack of standardized and approved analytical methodologies. This study emphasizes the urgent need to intensify research and legislative efforts in this regard, and it also calls for a comprehensive review of environmental and industrial policies related to plastic production and waste management.

Key points: Algae, Nanoplastic, Micro, bioaccumulation, blue.

1. Introduction:

Plastics have diversified to include all human activities and facilities, replacing wood and metal due to their cheap price and versatility. Leo Baekeland produced the world's first synthetic plastic in the year 1907. The production and utilization of plastics have witnessed tremendous growth between the years 1950 and 2015, as plastics, thanks to their lightness, versatility, durability, formability, and corrosion resistance, enhance the quality of life for millions globally by making it easier, safer, and more enjoyable (Plastics Europe 2020). Conversely, we are currently confronting global challenges related to the access of plastics to the environment and food supply. Terrestrial emissions constituted 80% of global plastic garbage (Geyer et al., 2017). Plastic pollution has emerged as a significant transboundary and pervasive threat to natural ecosystems (Thompson, 2015). According to Plastics Europe (2020), global plastic production in 2019 amounted to as much as 368 million tons (Plastics Europe 2020). A significant quantity of this waste ends up dispersing into the environment, resulting in a worldwide pollution crisis that is regarded as one of the main environmental issues linked with human activities (Baztan et al., 2017; GESAMP 2020; Koelmans et al., 2017; UNEP, 2016). While the majority of plastics originate from terrestrial sources, their final destination is the oceans (Beaumont et al., 2019). Upon arrival, they are aggregated in certain regions due to the global circulation of currents, posing considerable risks to marine animals (Kuhn et al., 2015; Lebreton et al., 2018; Thiel et al., 2018).

The recent COVID-19 pandemic has also led to an additional 3.5% increase in the proportion of Global Solid Waste (Patricio Silva et al., 2021). The increased consumption of single-use plastics, particularly personal protective equipment such as face masks and gloves, has contributed to the production of 4.90 trillion tons of plastic that was thrown into the oceans alone (O'Neill and Lawler, 2021).

Microplastics and nanoplastics (M\NPls) are small pieces of man-made materials that can be found in many places like oceans, rivers, soil, living things, air, and even in our food and drinking water; they are considered new types of pollution caused by humans. Thompson et al. used the term "microplastics" (MPls) in 2004 to refer to small plastic particles in the marine ecosystem. In 2009, Arthur et al. established a maximum size threshold of 5 mm for MPls (Arthur et al., 2010). Currently, plastic particles and fibers smaller than 1 µm are classified as nanoplastics (NPls), while those ranging from 1 µm to 1 mm are categorized as MPls. Particles ranging between 1 and 5 mm are classified as macroplastics. GESAMP defines micropolymers as fragments with a maximum diameter of under 5 mm (GESAMP, 2019). Frias and Nash recently characterised them as "synthetic solid particles" or "polymeric matrices", either regular or irregular in shape, ranging from 1 µm to 5 mm in size, of primary or secondary synthetic origin, and insoluble in water (Frias and Nash, 2019). The definition must be broad enough to encompass natural polymers that, with processing, would become anthropogenic waste if discharged into the environment (Hartmann et al., 2019). Concerning plastic NPs, the scientific literature has used two separate definitions: The first categorizes them as plastic nanoparticles measuring less than 1000 nm (Andrady, 2011; Cole et al., 2011); the second defines NPs as particles smaller than 100 nm in at least one dimension, consistent with the definition for manufactured nanoparticles (Bergami et al., 2016; Koelmans et al., 2016). Recently, the first viewpoint, which sees nanoparticles as unintentional plastic particles that have colloidal properties and are between 1 and 1000 nm in size, has become more popular (Gigault et al., 2018). GESAMP has likewise endorsed this limit (GESAMP 2019).

The term "plastic" broadly refers to many polymers, with the predominant classes found in aquatic environments being polypropylene (PP), polyethene (PE), polystyrene (PS), polyamide (PA), polyester (PEST), and acrylic. This is not unexpected, as these materials represent a substantial share of worldwide plastic production and are extensively used in goods with brief lifespans (Erni-Cassola et al., 2019). They are also among the most prevalent categories of plastics present in marine contamination (Birch et al., 2020; Annenkov et al., 2021). Microparticles and nanoparticles enter water environments from household trash, wastewater treatment plants, industrial waste, stormwater, rivers, air currents, surface runoff, estuaries, and waste management practices. Microparticles and nanoparticles manifest as fragments, granules, fibres, films, beads, and polystyrene foam with diverse surface area to mass ratios (Koelmans et al., 2019).

Plastic contamination is an escalating global issue in aquatic ecosystems. Microplastics have been found in nearly all ocean environments, including both open waters and enclosed areas, from the surface to the deep sea, and from the equator to the poles. Current estimations indicate that 4.85 trillion microplastic particles are dispersed across the world's oceans (Eriksen et al. 2014). Most research on MPls has focused on maritime areas, where marine debris poses a considerable environmental and economic challenge globally. Plastic garbage infiltrates the oceans at an annual rate of 4.8–12.7 million tons, with 80% originating from terrestrial sources globally (Raju et al. 2018; Mofijor et al. 2021). Freshwater systems have recently garnered attention comparable to seas about the invasion of M\NPls through home and industrial wastewater and disposal sites (Hu et al. 2019; Wong et al.; Meng et al. 2020). Nonetheless, this restricted data has indicated that the occurrence of MPls in freshwater is analogous to that in marine ecosystems (Peng et al. 2017; Li et al. 2018).

Rivers, lakes, wastewater (Carr et al., 2016), and anthropogenic activities are significant conduits for the transmission of plastic trash to the oceans. The Marine Strategy Framework Directive (MSFD) of the European Union, the OSPAR Commission, the Stockholm Convention, and the International Marine Particle Control Board (IPP) have focused on marine litter issues to protect and conserve their resources (OSPAR 2014; UNEP 2018).

Upon entering the marine ecosystem, plastic trash interacts with several marine organisms across multiple trophic levels (Guzzetti et al., 2018; Wang et al., 2020a). M\NPs have been identified in various marine species, such as cetaceans, crustaceans, molluscs, shrimp, echinoderms, fish, zooplankton, turtles, corals, seabirds, and mammals, leading to cascading impacts within the marine food web due to their diminutive size (Botterell et al., 2019). Eating these particles harms marine animals, leading to problems like reduced performance, poor feeding habits, slowed growth, less effective nutrient absorption, weaker immune systems, stress at the cellular level, feeling falsely full, issues with growth and reproduction, malnutrition, and eventually death (Guzzetti et al., 2018; Wong et al., 2020; Gonçalves & Bebianno, 2021; Rasham, 2024). M/NPls help absorb harmful substances like persistent organic pollutants, trace metals, and dangerous additives, showing much higher levels than natural sediments (Jiang et al. 2020).

Even though there has been a lot of research on pollution in water caused by M/NPls, there are still important things we don't know that make it hard to properly understand the risks to the environment and to create good ways to reduce these problems. These knowledge gaps encompass several key aspects that require further research and study (Andrady, 2011; Gewert et al., 2015). First, we do not fully understand how polymers break down and change chemically in water, especially when they are affected by different factors like salt levels, UV light, and other pollutants. Second, current research has a big gap in long-term data that shows how these particles affect aquatic food webs, especially in how they interact with microorganisms and plankton, which are the foundation of these food chains (Wright et al., 2013; Galloway et al., 2017). Third, researchers face significant challenges due to the lack of standardized protocols for identifying and quantifying nanoplastic (NPls) particles (smaller than 100 nm) in environmental samples. This uncertainty makes it hard to compare results from different studies and reduces the accuracy of understanding how widespread these pollutants are globally. Fourth, we don't fully understand how NPls particles pass through different biological barriers like the intestinal wall or placental barrier and affect human health, mainly because current experimental models don't accurately mimic the real conditions where these processes happen.

To overcome these cognitive challenges, it has become necessary to enhance collaboration between various scientific disciplines, including environmental chemistry, microbiology, and materials science, along with investing in the development of advanced analytical techniques and adopting long-term research methodologies that combine field and laboratory studies to monitor dynamic Change systems and their potential impacts on public health (Rochman et al., 2019; SAPEA, 2019).

2. Sources and formation of Nano plastics in the aquatic environment:

2-1 Primary sources: Industrial products (cosmetics, pharmaceuticals, textiles).

Microplastics and nanoplastics have become a major problem (Mariano et al., 2021), found in many everyday products (primary) or created when larger pieces of plastic break down (secondary) (Kokalj et al., 2021). Primary plastics are produced in large amounts through various industrial and household uses, including toothpaste, facial scrubs, detergents, cleaning products, plastic moulding powder, synthetic fabrics like nylon and polyester, and personal care products. Adhesives, paints, and electronics, among other materials, contribute to nanoparticle emissions (Kihara et al., 2020), which constitute 70–80% of the total plastic released into the environment, whereas primary NPls comprise about 15–30% (Mariano et al., 2021). Secondary M/NPls particles and fibers, like nylon, PES, and PA, are created when leftover plastic breaks down in the environment due to wear and tear, bacteria, sunlight, or the breakdown of materials that contain plastic. Nanoparticles may be released as primary (deliberately made) or secondary (unintentionally produced) particles. Primary NPls can be synthesized at the nanoscale by established methods and utilized in various applications (Rao & Geckeler, 2011; Stephens et al., 2013). Certain techniques, such as the thermal degradation of polystyrene foam, can produce secondary NPls (Zhang et al., 2012). A further potential cause is the fragmentation of tiny particles into smaller entities that ultimately attain the nanoscale (Andrade, 2011). Micro-- and nanoparticles are spread across land, freshwater, and ocean environments, from the equator to the poles, and from the top layers of water to the deep-sea sediments.

The terrestrial environment is especially vulnerable to M/NPls, with annual land-based contributions surpassing the total floating M/NPLls in the oceans worldwide (Hu et al., 2019; Yee et al., 2021). M/NPls found in soil come from many different places, such as sewage sludge, household waste, irrigation, landfills, compost, plastic coverings, greenhouse materials, air pollution, tire wear, and organic garden waste. M\NPs penetrate vertically through water, facilitated by soil tillage and the activities of soil microorganisms (O'Connor et al., 2019). Furthermore, a disposable facial cleanser may release as much as 10% of elemental NPls into the municipal sewage system (Shen et al., 2019). Annually, about 306.9 tons of MPls are discharged into the environment, with 80% emanating from wastewater treatment facilities (Cheung & Fok, 2017). Bits and other secondary plastic debris are prevalent in effluent from wastewater treatment plants, facilitating their entry into freshwater and marine habitats (Bayo et al., 2020). Textiles account for 35% of M/NPls in the oceans, primarily as synthetic microfibers (Xu et al. 2020). Stormwater runoff from agricultural soils and urban areas significantly contributes to stormwater contamination. Commercial and industrial areas play a big role, and synthetic rubber particles from worn-out car tires often end up in sediments created by rainwater runoff from roads (Liu et al., 2019; Ziagahromi et al., 2020). Moreover, plastic debris from materials employed in wetland construction, agricultural plastic remnants, and several other secondary organic substances are transported to natural habitats by wind (Zhang et al., 2019).

2-2 Methods of spread: rivers, rain, wastewater:

The inaugural report on the presence of plastics in marine ecosystems was published in the early 1970s (Carpenter & Smith, 1972). Plastics infiltrate freshwater and marine ecosystems chiefly by natural erosion and anthropogenic activities, including tourism, residential and industrial wastewater, and aquaculture (Guo et al.; Birch et al., 2020;; Eslami et al., 2025). River to ocean transportation constitutes a primary conduit for plastic accumulation (Wu et al., 2019). Eight rivers in Asia and two rivers in Africa contribute to 90% of the plastic entering the sea annually (Sadeghi et al., 2021). Approximately 1.15 and 2.41 million tons of plastic debris are released into the ocean each year from river estuaries (Lebreton et al., 2018). The Arabian Gulf and the northwest ocean of the Pacific are markedly polluted with M/NPls, displaying concentrations ranging from 640 to 42,000 particles/km² to 4.38×10^4 particles/km² (Xu et al., 2019). The estimated quantity of M\NPLs in the oceans ranges from 15 to 51 trillion particles, equivalent to (93 to 236) thousand metric tons (Naik et al., 2019). Plastic pollution, littering, and waste ultimately accumulate in estuaries and coastal waters. Fluctuations in precipitation, wind velocity, oceanic currents, and wave dynamics enable the transport of pollutants into seawater (Cózar et al., 2014). Soil erosion, agricultural runoff, and atmospheric sediments convey M/NPls to marine ecosystems (Hale et al., 2020). Field studies along Indonesia's Siwalingki River revealed micronanoparticles as the most common fibers. Their sizes ranged from 50 to 2000 µm, and their concentrations ranged from 5.85 particles per liter in surface water to 3.03 particles per 100 g of sediment (Alam et al., 2019). The concentration of MPls varied between 112 and 234 particles in the sediments along the coasts of Lake Bolsena in central Italy (Lake Chiusi) (Fischer et al., 2016). Microalgae can grow on M/NPls through biofouling and clumping together, which makes them heavier (Mateos-Cárdenas et al., 2021). Five million tons of plastic debris were released into the Pacific Ocean by the 2011 Japanese tsunami, which is almost equivalent to the annual influx of plastic garbage into the ocean (Murray et al. 2018).

3. Reactions of plastic in the aquatic environment:

Plastic waste in water goes through complicated changes, starting with big pieces breaking down into microplastics (MPls) and then into nanoplastics (NPls) through various methods, including natural breakdown and non-biological processes (Yee et al., 2021). These processes depend mainly on the structural properties of long-chain organic polymers, where physical factors such as morphology, dimension, porosity, surface area and degree of crystallization play a pivotal role in determining the course of decomposition and the ability of these substances to interact with other contaminants (Cai et al., 2017; Campanale et al., 2020). The ways plastic breaks down involve several connected processes, such as thermolysis, physical degradation, photolysis, thermal oxidative decomposition, biodegradation, sand erosion, and hydrolysis; these processes work together to turn large plastic items into tiny particles. Nanoparticles become especially noticeable when plastics are exposed to visible and ultraviolet light at around 30 degrees Celsius, where hydrolysis and photolysis are the main ways that water and UV light break down the plastic into smaller parts called monomers. Heterogeneous atoms in the polymer structure, like oxygen, nitrogen, and sulfur, speed up the breakdown of polymers by creating active spots for hydrolysis and enzyme reactions, which help break down polymers into smaller pieces that microbes can absorb. These processes lead to radical modifications of the molecular structure that include the cleavage of polymer chains, the formation of new cross-links, and the addition of oxygen-containing functional groups such as esters, ketones, and alcohols, which reduce the hydrophobic nature of plastic particles (Yee et al., 2021). Microorganisms, including bacteria, fungi, and other eukaryotic organisms, promote the biodegradation process by secreting extracellular enzymes that break down polymeric structures (Nike et al., 2019; Enfrin et al.). The creation of biofilms is also important in this process because the extracellular polymeric matrix helps form mixed groups that NPls stick to. Marine environments are characterized by special conditions that accelerate plastic degradation processes compared to terrestrial environments, where increased salinity combined with the presence of specialized microbial communities enhances these processes (Ng et al., 2018). Environmental factors such as wind, waves, exposure to solar ultraviolet radiation, temperature fluctuations, additives, and abrasive processes (such as peeling) also affect the integrity of plastic structures and accelerate their decomposition (Jiang et al., 2020).

3-1 Physical reactions:

The harm that plastic waste causes to living things is more related to the shape and size of the debris than to the chemicals in the plastics or how toxic they might be, because the damage mainly depends on how big and what shape the plastic waste is (Mateus-Cardenas et al., 2020). The biggest environmental problems happen when microplastics get into the stomachs of small creatures or move up the food chain to important body parts, and how bad these problems are can be affected by things like the amount of other pollutants, temperature, salt levels, and the presence of certain microbes (Mateus-Cardenas et al., 2020). Scientific concerns are emerging about plastic waste's ability to disrupt basic environmental functions, as studies indicate its possible negative impact on the primary productivity of marine waters and disruption of nutrient and carbon cycles (Troost et al., 2018). Despite the relative chemical inertness of the original polymeric compounds, their decomposition products exhibit entirely different properties, since the constant fragmentation of particles increases the surface-volume ratio and thereby enhances the likelihood of leakage of chemical components (Andrade, 2011; Eriksen et al., 2014). It is estimated that there are well over 250 thousand tons of plastic residues floating in the oceans, which are constantly subjected to photodegradation and oxidation as the two main mechanisms of environmental degradation (Andrade, 2011; Eriksen et al., 2014). Recent studies show that the breakdown of plastics in the ocean can release about 23,600 tons of dissolved organic carbon each year, and up to 7% of the plastic's weight can turn into small carbon compounds due to ultraviolet radiation.

Plastic decomposers have a remarkable ability to modify aquatic food webs, as their stimulating effect on the growth of marine bacteria has been proven on the one hand and their inhibitory effect on the activity of cyanobacteria and photosynthesis on the other (Romera-Castillo et al., 2018; Teto et al., 2019; Zhu et al., 2020). The rates at which chemical components are released from polymers vary depending on environmental conditions, and salinity plays an important role in this process based on the chemical properties of additives (Suhrhoff & Schulz-Butcher, 2016). Research confirms that the abiotic aging processes of polymers inevitably lead to the formation of fine fragments, emphasizing the role of mechanical factors in the manufacturing process in the development of surface cracks that, in turn, determine the quantity and dimensions of particles resulting from fragmentation (Gewert et al., 2015; Kalogirakis et al., 2017; Julienne et al., 2019). Taken together, these results indicate the urgent need for more comprehensive studies to understand the exact mechanisms and their long-term environmental implications.

3-2 Chemical interactions:

The chemical composition of commercial plastics is of considerable complexity, since it includes not only basic polymers, but also a wide range of additives aimed at improving their manufacturing and performance characteristics. These additives include fillers, plasticizers, colorants, stabilizers, flame retardants, compatibility substances, and other chemical compounds whose ratios vary in the final composition (Ambrogi et al., 2017). While some of these substances are present in trace concentrations not exceeding a few per cent, others, such as flame retardants and plasticizers may reach percentages as high as 50% of the total weight (Hahladakis et al., 2018). These additives are of significant environmental concern due to their transportability to the aqueous medium, as the mechanisms of this transition vary depending on the nature of the chemical. While inorganic materials such as metals diffuse easily, organic materials require photochemical reactions to free them from the plastic Matrix (Bandow et al., 2017). Studies have proven the transfer of these substances to water upon direct contact (Mato et al., 2001; Koelmans et al., 2014; Romera-Castillo et al., 2018), raising particular concerns regarding plastic packaging in contact with food and its impact on food safety and human health (Bhunia et al., 2013).

On the other hand, some additives such as antioxidants and UV absorbers play a dual role, contributing to the stability of the plastic and prolonging its shelf life (Hahladakis et al., 2018), while they may turn into environmental pollutants when decomposed. The leftover unreacted monomers and oligomers in the plastic can also be harmful to the environment. Free styrene has been found in polystyrene products and PET oligomers in drinking water, leading to extensive research on their health and environmental impacts.

The rates at which these chemicals move are affected by various environmental factors, as physical disturbances make additives, especially those that don't dissolve well in water like phthalates, escape more easily than other substances like bisphenol A. However, we still don't know much about how these substances break down in the environment because it's hard to track their changes when they oxidize, break down from light, or transform through biological processes. Plastics have a tremendous ability to absorb organic pollutants from the surrounding environment, as the concentrations of persistent organic pollutants on their surfaces can reach much higher levels than those in the aqueous medium (Mato et al., 2001). Field studies have revealed the presence of a wide range of pollutants associated with plastics in marine ecosystems, such as aromatic hydrocarbons, polychlorinated biphenyls, and organochlorine pesticides (Camacho et al., 2019). However, the actual role of plastics in the global distribution of these pollutants remains controversial, as some studies suggest that their impact may be limited compared to other diffusion pathways (Lohmann, 2017).

The importance of plastic as a pollutant carrier depends on multiple factors, including polymer properties, material ages, and environmental conditions (Koelmans et al., 2016). Although laboratory studies suggest that the role of plastics in the transfer of pollutants to living organisms may be limited, more research is urgently needed to assess this effect on a larger scale of biotic species (Bakir et al., 2016). It is worth mentioning that the ability of plastics to concentrate pollutants may lead to the exposure of marine organisms to high doses of these substances, with the possibility of their transmission through the food chain up to humans (Puteri et al., 2025).

3 -3 Stability: Resistance to biodegradation.

Plastics in the environment represent an ideal substrate for the colonization of microorganisms, including bacteria, archaea, and eukaryotes, as well as fungi, diatoms, and protists (McCormick et al., 2016; Kettner et al., 2017). This interaction has given rise to the concept of "plastisphere", which defines plastic as a new habitat for microbial communities (Zettler et al., 2013; Amaral-Zettler et al., 2020), since it has been observed that biodegradable plastics are experiencing intensive colonization compared to non-biodegradable species (Dussud et al., 2018). Although most studies indicate that the local environment and not the type of polymer is the decisive factor in the formation of microbial communities on plastic surfaces, the available data are still insufficient to identify clear patterns in this regard.

The formation of biofilms on plastic surfaces goes through successive stages starting with initial colonization and ending with maturation, in which the physical properties of plastics such as surface roughness, electric charge, density, mechanical stability and degree of hydrophobicity play a pivotal role in determining the intensity of initial microbial adhesion (Flemming et al., 2007). The release of polymeric molecules from the cell is an important step in biofilm development, allowing them to create protective bonds as a way to adapt to harsh environmental conditions.

One major worry is that certain microbes might start to break down plastic polymers, as some blue algae are known to decompose polyethylene (PE), polypropylene (PP), and PVC. Other research has found that certain bacteria, especially Rhodococcus ruber from the Rhodobacteraceae family, can break down polyethylene. In a related context, a study conducted on microbes in wastewater treatment plants revealed the dominance of the Pseudomonas aeruginosa, variovorax, aquabacterium and Acidovorax genera, known for their ability to metabolize resistant materials,, including plastics (Martinez-Campos et al., 2021). The analysis can also include certain fungi that create special enzymes, like oxidases, lacases, and peroxidases, which are useful for studying complicated materials like polyurethane. However, scientists still debate whether fungi can break down polyethylene, even though they are better at analyzing materials like Polyhydroxybutyrate (PHB) compared to biodegradable plastics.

These natural processes conflict with how regular plastic is made to be very stable, as it includes stabilizers that stop it from breaking down through oxidation or light, making it a long-lasting pollutant. European legislation has responded to this problem by banning oxidatively degradable polymers (Directive 2019/904). Many aspects related to the colonization of plastics remain unknown, especially about the impact of the transition of microbes from processing plants to natural water bodies, as studies indicate that geographical and seasonal factors are the most influential on the formation of microbial communities on plastic surfaces (Lee et al.2014; oberbekman et al., 2014).

4. Effects on the aquatic environment.

4-1 On living things:

The environmental effects of plastic waste in aquatic systems are represented by a tangle of negative effects on living organisms. The accumulation of these substances leads to changes in light permeability and disruption of biogeochemical processes in the water column (Chen et al., 2020). Studies show that the adhesion of NPls to the surfaces of microalgae causes ghosting effects and leads to a decrease in the fluidity of cell membranes, and these particles, when absorbed, also inhibit the processes of carbohydrate metabolism, cellular esterase activity, electron transfer rates and fat stores, which negatively affects the energy metabolism of algae (Zhu et al., 2021).

The ways that marine organisms are affected range from large plastic pieces like fishing lines and nets sticking to turtles, birds, and marine mammals, to smaller particles being eaten, which can cause blockages in their intestines. Microplastics and nanoparticles in freshwater systems are particularly important because they can potentially pollute drinking water and human food chains (Senathirajah et al., 2021; Eslami et al., 2025). The presence of these particles accumulates in the body for long periods before their transfer to the digestive glands, since research on the food transport of microplastic particles suggests that they cause tissue inflammation, reduced fat reserves, impaired absorption of nutrients, and instability of the digestive cell membranes (O'Neill & Lawler, 2021).

The impact of eating MPls goes beyond just physical harm and intestinal obstruction to include a decrease in energy consumption and respiration, as well as behavioral changes such as reduced efficiency of food intake (Cole et al., 2015; De Sa et al., 2015; Besseling et al., 2017). Research in this area has used animals like Daphnia magna and zebrafish to study how plastic particles affect freshwater environments, where zebrafish embryos exposed to polystyrene nanoparticles showed buildup in their tissues and placental membranes, leading to harmful effects in future generations. Freshwater organisms like Daphnia magna, Gammarus pollex, and Lumbriculus variegatus can take in polymeric molecules, which move from their cells to droplets and fat storage areas (Imhof et al., 2013). Field studies confirm the prevalence of this phenomenon, as in the case of French watercourses, where 7 out of 11 guppies contained polymeric molecules in their tissues (Sanchez et al., 2014). The harmful effects are especially strong when it comes to polystyrene nanoparticles (20–39.4 nm), which impact growth, photosynthesis, and death rates in species like Chlorella, Daphnia magna, Rhaphidocelis capitata, and Scenedesmus obliquus, leading to serious environmental issues because these organisms are important for the health of aquatic ecosystems.

Careful field studies reveal the extent of this problem, as in the case of samples collected from the island of Giglio after the Costa Concordia ship accident, where 85% of the tested fish (especially benthic species like Scorpaena) showed obvious histological changes (Avio et al., 2017). The percentage of plastic particles in the uranoscopus scaberfish varies between 77% and 86%, while it reached 100% in the digestive system of the spondylosoma cantharus fish, with a variety of particle shapes between fragments, filaments, and plastic membranes (Avio et al., 2017).

4-2 The impact on the aquatic food web.

Scientific studies suggest that the observed effects of MPls in laboratory environments may have major implications for the performance of aquatic ecosystems, although it is difficult to accurately predict how these laboratory results will translate into natural aquatic systems (Wright et al., 2013). These effects are especially important when considering the microalgae that form the bedrock of many aquatic ecosystems, since any changes in their communities may lead to cascading effects across the entire food web.

The effects of plastic pollution extend not only to individual organisms or isolated populations but may also cause a series of secondary effects on the functions and services of entire aquatic ecosystems (Leon et al., 2018; Kong & Kollmans, 2019). One of the most important environmental processes is the potential impact of the interaction between MPls and algae on the aquatic food web, where scientific concerns are raised about the impact of these substances on both quantity and quality in algal production, and the possibility of transmission of these effects across the levels of the food web.

Research suggests that microalgae mixed with plastic particles may undergo morphological changes that affect their detectability by other organisms, their nutritional value, and their ability to resist grazing by herbivores (Yokota et al., 2017; Lacerde et al., 2019). The process of biofouling may also increase the chances of MPls particles interacting with other aquatic organisms, since complex biofilms may mask these particles and make them more attractive as food for zooplankton and other herbivorous organisms (Fromm et al., 2017). The consumption of plastic particles accompanying algae leads to the phenomenon of "food dilution", in which non-food plastics are ingested with natural food (Kong & Kollmans, 2019). The most important expected environmental effects are concentrated at the level of zooplankton, which are the natural predators of algae, where a theoretical study by Kong and kollmans (2019) showed that the decrease in feeding efficiency resulting from the consumption of algae mixed with plastic led to a decrease in the density of these plankton, which in turn affected the ecological balance sequentially.

These changes relieved grazing pressure on phytoplankton, which led to an increase in the numbers of diatoms and green algae. Meanwhile, the decrease in zooplankton numbers restricted food sources for fish that fed on them, negatively affecting large fish populations and paving the way for benthic fish supremacy. This shift subsequently impacted benthic communities through increased predation and sediment disturbance (Kong & Kollmanns, 2019).

The effects of plastic particles not only dilute the nutritional value, recent data indicate their ability to change the chemical composition of algae, especially their fat content and unsaturated fatty acids that play a crucial role in the growth and reproduction of many aquatic organisms (Leoni et al., 2014; Guschina et al., 2020) Given the importance of these compounds in the transmission of energy through the food web, any change in their quantity or quality could have far-reaching effects on the reproductive fitness and growth of many aquatic organisms across different levels of the food web.

4-3 Interaction with microorganisms and plankton:

Recent scientific studies confirm the widespread presence of MPls particles in aquatic ecosystems, both marine and freshwater (Van Cauwenberg et al., 2014; Horton et al., 2017; Jiang, 2018), as these particles form ideal environments for the growth and reproduction of diverse microbial communities known as biofouling (Carson et al., 2013; Reisser et al., 2014). The concept of a "plastic ball" was coined by Zettler et al. (2013) to describe the miniature ecosystem formed on the surfaces of plastic waste, which includes heterotrophic and autotrophic organisms, predators and symbionts (Zettler et al., 2013). Scientists have been interested in studying how microorganisms settle on plastic since the 1970s, when early research in the Sargasso Sea found microalgae, especially diatoms, sticking to plastic surfaces, and later studies showed a variety of both bacterial and eukaryotic autotrophic organisms living in the biofilms formed there.

The groups of microorganisms living on plastic surfaces were found to be quite different from those living freely in the surrounding water, as many studies noted clear differences between the microorganisms attached to plastic and those that are free in various water environments. These findings show that the differences in the types of microorganisms are caused not just by the plastic surface itself, but also by the good conditions that help them stick and grow. Some species use plastics as a place to live, but they can also be found on other surfaces, as shown by experiments that found clear differences in the types of communities on plastic compared to surfaces like glass, which is used for comparison because it doesn't react (Vosshage et al., 2018). In a two-week laboratory experiment, Ogonowski et al. observed significant differences in symbiotic microbial communities on polyethene, polypropylene and polystyrene particles compared to glass beads exposed to the waters of a coastal bay under controlled conditions, indicating a clear preference for a plastic substrate (Ogonowski et al., 2018). A six-week field study in the North Sea of the United Kingdom using polyethene terephthalate (PET) bottles and glass slides as reference elements also showed significant variations in the microbial composition between the two substrates, since exclusively biocomponents were identified for each surface, reflecting clear substrate preferences (Oberbeichmann et al., 2014). However, subsequent studies at the same site did not show significant differences between microbial communities on glass and PET (Oberbekman et al., 2016), highlighting the controversial nature of this scientific topic.

5. Indirect risks (to humans).

The utilization of plastic in everyday human activities (such as drinking water bottles, food packaging, soft beverages, and medical devices) amplifies its prevalence and poses threats to human health (Jiang et al., 2020). The extent of human exposure to MPls through air, water, and food, along with the related impacts, is presently the subject of rigorous research (Vianello et al., 2019; Paul et al., 2020). Although MPs are present in numerous human dietary products, the greatest exposure is thought to occur through inhaled air (Prata, 2018; Cox et al., 2019). The primary pathways for fine particle penetration include inhalation, dermal blood leakage, and ingestion. Despite the limited knowledge about NPls' effects on people, we have established their ability to cross the intestinal barrier. It can infiltrate living organisms via cellular phagocytosis and somatic pores (O'Neill & Lawler, 2021; Eslami et al., 2025). The main way people are exposed to M/NPls is by eating contaminated food, which can lead to problems in the intestines, like tiny gaps in the cell lining, changes in gut bacteria, and local inflammation. Numerous European nations depend on crustaceans and shellfish for sustenance, with a projected yearly intake of 1800 grams per capita (Barboza et al., 2018). Nanoparticles have been detected in the tissues of commercially farmed bivalves (Van Cauwenberghe & Janssen 2014; Zhang et al. 2020). Breathing in NPls quickly causes tightness in the airways, widespread scarring in lung tissue, damage between air sacs, and changes and swelling in the bronchial tissues (Mariano et al. 2021). The accumulation of NPls by "primary producers" such as Daphnia magna and Chlamydomonas reinhardtii starts the transfer of NPls through the food chain (Zhu et al. 2021). Trophic transmission happens when "secondary" consumers like Oryza sinensis and "tertiary" consumers like Zaco timinki eat primary goods before they are passed on to humans (Zhu et al., 2021). Nanoparticles transmitted from "primary producers" to primary consumers trigger morphological revisions and significantly affect their metabolism and behavior (Zhu et al. 2021). Possible negative effects may be linked to the release of additives and monomers, some of which are toxic, cancer-causing, or disrupt hormones. Additionally, harmful gases like benzene, styrene, and acrolein can be created and released when plastic waste breaks down in sunlight. Moreover, MPls can absorb harmful metals and persistent organic contaminants from the environment and serve as vectors for antibiotic-resistant and pathogenic microbes (Zettler et al. 2013; Bank et al. 2020). On the other hand, MPls are unlikely to get through the skin because only very tiny polymers, less than 100 nm wide, can pass through the outer layer of skin (Gonsalves & Piano, 2021). This encompasses personal and cosmetic items, wherein facial cleansers are applied externally to the skin. Glycerol, urea, and hydroxyl acids, common ingredients in lotions, improved the ability of nanoparticles to pass through the skin barrier (Jatana et al., 2016). Taking in polymer M/NPls by mouth causes an imbalance in oxidation and reduction, toxic effects on the kidneys and gut, and problems with energy production (Deng et al. 2017). Endocytosis processes help polystyrene and polyvinyl chloride (PVC) particles pass through the intestinal wall and enter the bloodstream and lymph nodes (Xu et al., 2019). Mice given 40 nm polystyrene nanoparticles for 35 days showed a big drop in luteinizing hormone, testosterone, and follicle-stimulating hormone levels (Amereh et al., 2020). Recent research found 20 polymer compounds (50–500 µM) in every 10 grams of human feces, including 9 different kinds of plastic, mainly polypropylene and PET (Shen et al., 2019).

6. Challenges in detection and surveillance.

6-1 Technical difficulties: small size, lack of standardized measurement methods:

A significant issue is the absence of appropriate and dependable techniques for sampling and evaluating NPls. Analytical and detection methodologies are in the nascent phase of development. No established procedures are available for the identification of NPls in any environment, including biological entities and food (Lehner et al. 2019; Peng et al. 2020). To distinguish large plastic particles from NPL substances, we frequently use optical microscopes or visual inspection. This method helps evaluate the color, shape, size, and number of plastic particles, which helps create guidelines for recognizing them visually (Lv et al., 2020). Dyes, such as indigo red fluorescent dye, are occasionally employed to enhance differentiation. Nonetheless, optical identification lacks the requisite precision for scientific and observational applications, necessitating the use of alternative approaches. Recent advancements in high-throughput methodologies utilize specialized equipment designed for zooplankton analysis, emphasizing the significance of plankton abundance. The amount of MPls compared to plankton is an important sign of how likely plastic is to get into the food web, using methods like filtering, flow cytometry, or detailed scanning along with automated image analysis or computer vision. This aims to quantify and categorize plastic contaminants into distinct visual classifications, hence minimizing the time and expense of the study (Lorenzo-Navarro et al., 2020). Nonetheless, despite the utilization of high-throughput methodologies, the study of plastic pollutants remains intricate, costly, and labor-intensive. Consequently, research rarely acknowledges the importance of determining the subsample size for analysis based on specific statistical criteria. Basic statistical methods can estimate the precision of outcomes within a defined margin of error (Kedzierski et al., 2019). There is an urgent necessity for data regarding the disposition of smaller fine particles, specifically those less than 100 or 200 μm, which are presently not subjected to systematic sampling. It is essential to establish standardized methodologies that facilitate comparison across various sources. All research must document the utilization of suitable sample processing and storage protocols.

6-2 Micro and Nano plastic screening: integrated techniques for understanding environmental challenges.

With increasing industrial expansion, micro (less than 5 mm) and nanoplastic particles (less than 1 micrometer) are becoming a serious environmental and health threat. The difficulty in analyzing these particles lies in the variety of their chemical sizes and the complexity of the environmental samples in which they are found, such as seawater, soil, or even the tissues of living organisms (Gambino *et al*., 2025). To overcome these challenges, scientists have developed a range of advanced technologies, each of which complements the others to provide a comprehensive picture of the presence and impact of plastic.

1. Pyrolysis with Gas Chromatography/Mass Spectrometry (Py-GC/MS): Py-GC/MS is one of the most effective methods for determining polymer type and quantity, even in complex samples. The idea is to heat the sample in an inert atmosphere to break down the polymers into simpler molecules, which are later separated by gas chromatography (GC) and identified by mass spectrometry (MS). Each polymer produces a unique pattern of peaks called a "pyrogram", representing its chemical fingerprint. For example, polyethylene (PE) produces a series of alkanes and alkenes, while polystyrene (PS) produces aromatic compounds like styrene (Brennecke *et al*., 2016). In a recent drinking water study, researchers used Py-GC/MS to detect the presence of polyethylene terephthalate (PET) at concentrations as trace as 0.01 ppm, distinguishing it from natural organics using specific chemical indicators such as dimethyl terephthalate (Kirstein *et al*., 2021). However, this method is not without challenges; Analysis of organic-rich samples (such as marine sediments) may lead to overlapping degradation signals, requiring pre-treatment to remove non-plastic components (Okoffo *et al*., 2020).

2. Infrared Spectroscopy (FTIR): FTIR provides detailed insight into the chemical composition of polymers by measuring their infrared absorption. This technology is often used in Hyperspectral Imaging mode, where thousands of particles are automatically analyzed on the surface of the filter. For example, in a study on wastewater samples, 20 μm polyethylene terephthalate (PET) fibers were identified and distinguished from natural fibers such as cotton using characteristic absorption peaks of C=O bonds at 1720 cm^{-1} (Horton *et al*., 2021). But the spatial resolution of FTIR is limited to about 10 μm due to the optical diffraction phenomenon, making it unsuitable for NPls. In addition, analysis requires careful drying of samples, as water strongly absorbs infrared radiation and hinders the acquisition of clear signals (Cabernard *et al*., 2018).

3. Raman Spectroscopy: Raman is superior to FTIR in analyzing small particles, with a spatial resolution of up to 300 nm. It is based on measuring the change in frequency of light after it interacts with the molecular vibrations of the sample. In an experiment with freshwater fish, researchers detected nano-sized (300 nm) polyvinyl chloride (PVC) particles in liver tissue, with the characteristic peak of the C-Cl bond at 650 cm^{-1} (Raman& Krishnan, 1929). Raman also allows the analysis of wet samples without the need for drying, making it ideal for studying interactions in aquatic environments (Gillibert *et al*., 2019). But the main challenge lies in fluorescence resulting from dyes or organic impurities, which may overwhelm the Raman signal. To solve this problem, lasers with a longer wavelength (e.g. 785 nm) are used or chemical fluorescence quenching techniques are applied (Van Cauwenberghe *et al*., 2015).

4. Scanning electron microscope with dispersive energy analysis (SEM/EDX): SEM provides high-resolution images (down to 1 nm) of the particle surface, while EDX complements the analysis by determining the elemental composition. In a study on marine sediments, SEM revealed microcracks on the surface of polyethylene (PE) particles resulting from mechanical abrasion, while EDX showed deposition of elements such as calcium and sulfur on the surface, indicating chemical interactions with the surrounding environment (Napper & Thompson, 2016). However, SEM/EDX cannot identify polymers that are mainly composed of carbon and hydrogen (such as PE or PP) without distinct elemental labels (Oßmann *et al*., 2019).

5. Advanced nanoparticle technologies: Raman Tweezers and AFM-IR: To analyze NPls in liquids, techniques such as Raman Tweezers are used, which combine optical manipulation of particles (using a laser) and their Raman analysis without the need to immobilize them on a surface (Gillibert *et al*., 2019).This method is non-destructive, but it is expensive and requires high technical expertise (Schwaferts *et al*., 2020).

In short, the choice of method depends on the nature of the sample and the aim of the study. For example, if the goal is to determine the total mass of the polymer in a complex sample, Py-GC/MS is an ideal choice (Primpke *et al*., 2020). If the study focuses on the physical and chemical properties of individual particles, the combination of SEM and Raman may be more effective (Schmidt *et al*.,2021). As technologies develop, these tools are expected to become more accurate and faster in detecting the environmental and health impacts of M/NPLs .

7. Conclusion & Future Perviews:

Microplastic and nanoparticle pollution pose a multidimensional environmental challenge, as their harmful impact extends from aquatic systems to human health and the integrity of the entire food chain (GESAMP, 2019). These particles can be found everywhere, from the deep ocean to our drinking water, because they come from different sources, like the breakdown of big plastic waste and direct release from products we use. The problem is made worse by the difficulty in finding nanoparticles smaller than 100 nm, which can easily enter living tissues and cause significant harm.

Despite the remarkable development in the field of alternative biodegradable materials (Rujnic-Sokele & Pilipovic, 2017) and innovative processing technologies such as nanomembranes (Han et al., 2021) and enzymatic degradation (Yoshida et al., 2016), the effectiveness of these solutions remains insufficient to keep pace with the ever-increasing volume of plastic pollution. This delay is partly due to the absence of a unified global regulatory framework (UNEP, 2018), as well as a lack of community awareness of the dimensions of this problem, which hinders the implementation of comprehensive prevention strategies.

Meeting this environmental challenge requires close cooperation between various stakeholders, as it is the responsibility of researchers to develop more accurate techniques for detecting nanoparticles in complex environments and devise effective treatment solutions (Zhang et al., 2020; Puteri et al., 2025). Governments ought to implement stringent regulations and provide backing for Applied Research in this field (European Commission, 2019). For its part, the industrial sector should adopt environmentally friendly alternative materials and reduce dependence on traditional plastics in manufacturing processes (Ellen MacArthur Foundation, 2017).

The comprehensive solution also includes the development of new polymeric materials with improved properties and a specific life cycle, aimed at preventing the emission of nanoparticles into the environment (Gigault et al., 2018), both from conventional recyclable polymers and biodegradable materials used in various applications such as agriculture, food packaging and pharmaceuticals (Garcia & Robertson, 2017). It also needs more research to create standard methods for collecting and analyzing samples (Prata et al., 2019), examine the long-term effects of nanoparticles on water ecosystems (Rochman et al., 2016), and understand how these particles interact with other pollutants like heavy metals and chemicals (Brennecke et al., 2016). New technology, especially in artificial intelligence, can help tackle this problem by creating smart systems that can analyze a lot of environmental data and find plastic particles in different samples. However, the final solution requires an integrated approach that combines scientific innovation, effective legislation and community awareness (Borrelle et al., 2020), where public awareness of the dangers of plastic pollution should be promoted and sustainable practices encouraged at all levels. Only through this organized collective effort can we mitigate the devastating effects of plastic pollution on ecosystems and preserve biodiversity for future generations (Gambino et al., 2025).

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