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Plastic Waste: Impact on the Planet's Ecosistem

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Abstract

Despite its versatility and wide range of applications, plastic waste poses a serious threat to the planet's ecosystem, affecting various components of the environment and the health of living organisms. Discarded plastic waste can accumulate in various natural habitats. Urbanization, economic development, and population growth are the main factors driving the increase in plastic waste. The first evidence of plastic in the wild was discovered in the guts of seabirds, reported in 1960, highlighting the extent of plastic's spread in ecosystems. This article analyzes literature to identify sources of microplastics in the atmosphere, hydrosphere, and soil. It provides an assessment of the prevalence of microplastics in the ecosystem in various forms, sizes, and colors of plastic waste. The impact of microplastics on various living organisms, including fish, sea turtles, and seabirds, is discussed. We also explore positive interventions aimed at reducing the negative consequences of plastic waste.

Keywords

Plastic waste, Environmental pollution, Air pollution, Soil pollution, Water pollution, Microplastic, Toxicological impact, Human health, Ecological consequences, Sustainable development

Introduction

Since its introduction in the early 20th century, plastic has revolutionized industries due to its durability, flexibility, and low cost. Used in everything from packaging to automotive parts, medical devices to electronics, plastics are integral to daily life. Most plastics are made from petrochemicals, though bioplastics are derived from renewable sources like corn starch or cellulose. Despite their benefits, the widespread use and disposal of plastic have caused serious environmental issues. First invented in 1860, plastic production began in 1907 and expanded significantly in the 1920s. By 1950, global production was around 2 million tons, reaching 368 million tons by 2019 [1,2].

Thus, plastic consumption has increased approximately 180-fold from 1950 to 2018. It is expected that plastic production will continue to grow exponentially in the future. According to source [3], global plastics production has grown exponentially: Over 380 million tons are produced annually, with about 50% of this volume consisting of single-use products that are discarded within a year of purchase. According to source [4], of the 275 million tons of plastic waste, between 4.8 and 12.7 million tons are dumped into the sea.

Plastics can generally be divided into "biological (also known as organic polymers)" or "engineering" plastics. According to source [5], about 4% of fossil fuels are used for plastics production. Discarded plastic waste can accumulate in various natural habitats. The first evidence of plastic in the wild was discovered in the guts of seabirds, as reported in 1960. Available data indicate a growing impact related to public health issues resulting from the current use of plastics.

Plastic pollution presents significant environmental and health risks. A large portion of plastic waste ends up in landfills, oceans, and natural habitats, threatening ecosystems and wildlife. Plastics accumulate in soil and freshwater, harming plants, animals, and microorganisms. On land and in water, wildlife faces dangers such as entanglement, ingestion, and

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suffocation. Marine animals may mistake plastic particles for food, causing internal injuries, blockages, and starvation. Microplastics, particles smaller than 5 millimeters, can absorb pollutants like pesticides and heavy metals, leading to bioaccumulation and toxicity in soil organisms. Additionally, microplastics have been detected in drinking water, seafood, and air, raising concerns about potential health impacts on humans, including the possibility of ingesting these particles through food [1,3].

Plastic pollution is considered a global environmental crisis for several reasons. The production, transportation, and disposal of plastics contribute to greenhouse gas emissions, exacerbating climate change. Additionally, plastic pollution can disrupt the natural carbon cycle by degrading ecosystems and altering the balance of carbon storage in soils and oceans. Plastic can take from 100 to 1,000 years to decompose, polluting the air and water around landfills as it breaks down. Thin films less than 20 microns thick clog drainage systems in many cities, causing uncontrolled flooding during the rainy season. Plastic waste is estimated to kill a million marine creatures every year. The clogging of plastic bags has led to bans on the use of thin plastic bags in light industry during retail sales in many countries [2].

This article analyzes literature to identify sources of microplastics in the atmosphere, hydrosphere, soil, and living organisms. It provides assessments of the prevalence of microplastics in the ecosystem in various forms, sizes, and colors of plastic waste. The impact of microplastics on various living organisms, including fish, sea turtles, and seabirds, is discussed. We also explore positive interventions aimed at reducing the negative consequences of plastic waste.

Impact on the Atmosphere

The study [6] conducted field investigations on unregulated plastic burning based on measured PM2.5 emissions. It was found that the burning process leads to the unintentional release of 0.92 ± 0.53 Mt of aerosols worldwide, with most emissions originating from developing countries. The largest amount of aerosols is produced by China (166 ± 96 kt), followed by India (112 ± 64 kt), Brazil (85 ± 49 kt), Indonesia (72 ± 41 kt), and the Russian Federation (58 ± 33 kt). Even in Europe, a small portion of unregulated burned plastic waste unexpectedly releases 30 ± 17 kt of aerosols. These aerosols generated from unregulated burning of commercial plastics contain numerous hazardous chemicals, which unintentionally released 705 ± 378 t of PAHs, 23 ± 11 kg of PCDDs/Fs, and 487 ± 135 kg of PCBs worldwide, respectively. The results show that people living in developing regions are at higher risk of toxic exposure from plastic burning than those living in developed regions [7].

The literature [8] investigated potential sources of microplastics in the atmosphere of 11 remote U.S. reserves and their deposition rates. The study quantitatively assessed the deposition of primary and secondary microplastics. Primary microplastics are defined as plastics that were manufactured within a specific size range (e.g., microbeads), while secondary microplastics result from the fragmentation of larger pieces of plastic due to physical abrasion or exposure to ultraviolet light [7]. 236 samples have been taken after precipitation events, and 103 samples were dry. According to the data, microplastics were present in 98% of all wet and dry samples. The particle size range was diverse, from 4 to 188 µm, while fiber sizes ranged from 20 to ~3 µm, with an average width and depth of 18 and 6 mm, respectively. One reason for the transportability of plastics is their density (0.65-1.8 g/cm^3), which is lower than that of soil particles (~2.65 g/cm^3). Plastic fibers have a higher surface area-to-volume ratio, increasing drag forces and reducing deposition speed [8].

Although atmospheric microfibers have recently been recorded in Europe and the Arctic [9], the pathway of primary or secondary microplastics (microfibers and particles) into the atmosphere remains unclear.

The obtained data were compared with data from 2018. It was found that wet-deposited microplastics originate from different regions than those deposited in dry conditions. It was observed that microplastics deposited in wet conditions are larger in size and fewer in number, correlating with both dust deposition and population density. This observation reflects the role of regional storms in transporting and subsequently depositing microplastics. Dry deposition indicates that plastics deposited in dry conditions are subject to large-scale global dispersal [8].

The long-distance transport of microplastics, reminiscent of the global dust cycle but clearly anthropogenic in origin, indicates the widespread presence of a human footprint in the composition of the atmosphere. According to studies, microplastics can be found far from their original production sites and sources, indicating their presence in remote Antarctica or areas distant from industrial centers [7,9].

Regional storms play an important role in delivering larger plastics to national parks, with dry deposits comprising > 75% of the deposited plastic mass. This result suggests that, although urban centers may be the initial source, plastics accumulate in the atmosphere over longer periods, are transported over great distances, and are deposited under favorable conditions. These favorable conditions include lower air mass speeds or intersections with mountain ranges [8].

The article [6] presented data from observations of atmospheric microplastic deposits in a remote, untouched mountain watershed (French Pyrenees) during the winter period of 2017-2018. Samples were collected over 5 months and represented both wet and dry atmospheric deposits. Fibers up to ~750 µm and fragments < 300 µm were identified as microplastics. A relative daily count of 249 fragments, 73 films, and 44 fibers per square meter was deposited on the watershed. Air mass trajectory analysis shows the transport of microplastics through the atmosphere over distances of up to 95 km. This study also proves that microplastics can reach and impact remote, sparsely populated areas through atmospheric transport.

Samples collected during the monitoring period from January to March contained visible amounts of fine orange quartz-like dust. This dust had the size (average grain size ~8 µm), color, and characteristic chemical properties typical of Saharan dust. Fine dust and other solid particles, which potentially include some microplastic particles, may originate from the Sahara, North Africa, or Iberia. This further illustrates the distance that plastic particles are capable of traveling.

The length of plastic fibers found in atmospheric deposition samples suggests a predominant fiber length of 100-200 µm and 200-300 µm. The longest fiber identified as plastic in this mountain field study was 3000 µm.

The composition of plastic deposits varied during the study period. The complexity of the plastic composition may be related to the source of plastic particles (and thus the direction and strength of the wind), the occurrence of storms, and the duration of calm days compared to storm events. The predominant plastic found in the samples was polystyrene (PS) (in the form of fragments), followed by polyethylene (PE). PS and PE are used in many single-use plastic items and packaging materials. PS, PE, and PP are the three largest sources of atmospheric deposits at this site [6].

Most studies have shown that controlled burning of various plastic materials, simulating open-air burning, results in the formation of a range of toxic compounds, including volatile, semi-volatile substances, organic compounds, and toxic metals [6,10]. The distance over which microplastic particles can be transported is currently unknown, and further research based on events is needed to determine the source and vectors of atmospheric microplastic particle transport [11].

In the study [12], laboratory experiments were conducted on the burning of industrial polymer materials, simulating open fire conditions. Common types of plastics used in the experiment included poly(vinyl chloride) (PVC), low- and high-density polyethylene (LDPE, HDPE), polystyrene (PS), polypropylene (PP), and polyethylene terephthalate (PET).

Soot samples from smoke and ash residues from controlled combustion at 600-750 °C were analyzed for solid particles, persistent free radicals, heavy metals, and other elements. All plastics burned easily, forming charred residues, black smoke, and solid ash. Both smoke particles and ash contained harmful carbon- and oxygen-centered radicals, known for their toxicity when inhaled. Low concentrations of toxic heavy metals like Pb, Zn, Cr, Ni, and Cd were found, while higher levels of lithophile elements such as Na, Ca, Mg, Si, and Al were detected in soot and ash. The burning of plastics, which make up around 20% of household and toxic waste, has become a significant environmental concern [13,14].

Identifying key mechanisms underlying plastic emissions into the atmosphere is the first step in developing scalable solutions. The consequences for ecosystems are not yet fully understood but are inevitable in the near future. If we want to mitigate the potential hazards posed by microplastics in the environment, both the scale of the solution and the level of required cooperation demand global community participation [8].

Impact on Soil

As early as 2012, researchers first assessed the potential of soil contamination with microplastics [11]. Statistical data from 2016 showed that approximately 63,000 and 44,000 tons of plastic products were used annually on agricultural lands in Europe and North America, respectively [11].

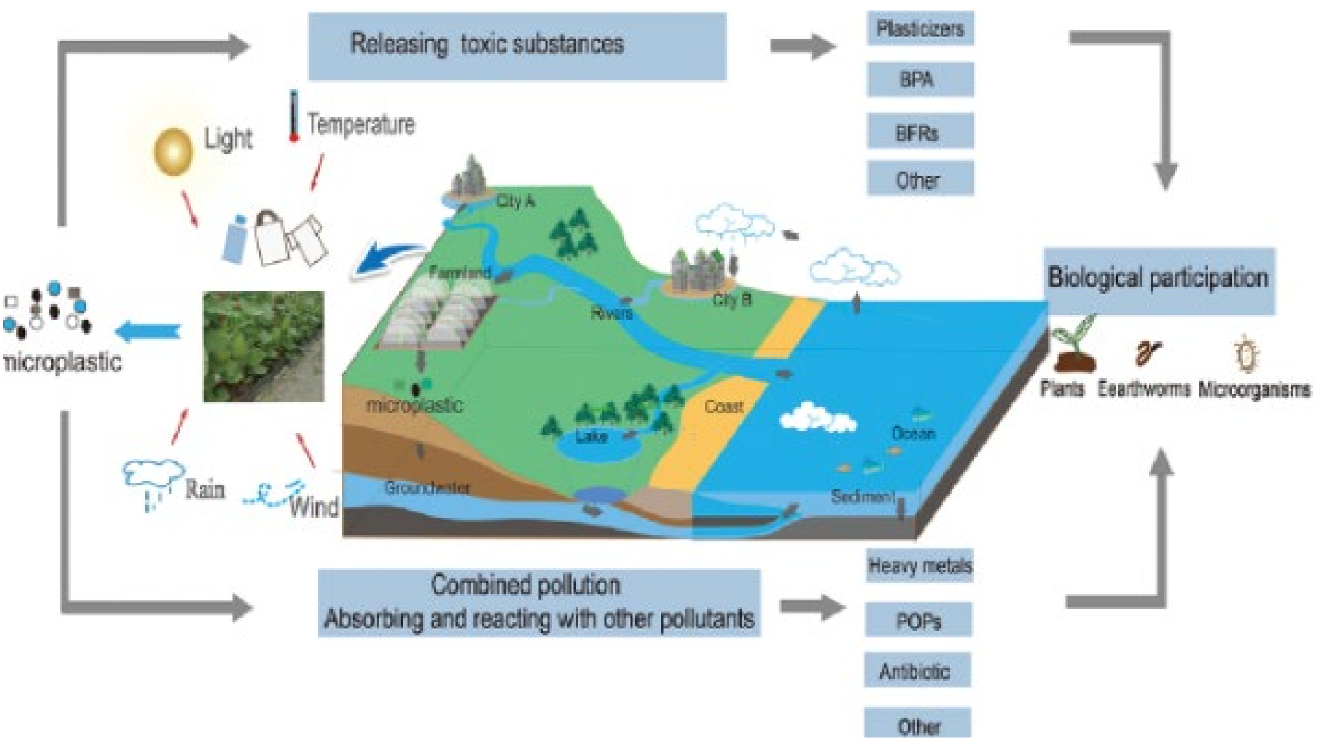

Figure 1: Microplastics and soil.

According to a 2018 study, it was estimated that about 44,000-300,000 and 63,000-430,000 tons of MP annually enter agricultural lands in North America and Europe through wastewater [12].

If plastic is not recycled and discarded immediately after use, most of it persists in the environment for tens to hundreds of years. Moreover, plastic will break down into smaller plastics under the influence of physical, chemical, and biological factors [10]. Plastics can fragment into MPs under UV radiation and elevated temperatures on the soil surface, degrade by insects and gut microorganisms, and migrate deeper into the soil due to soil organism movement and anthropogenic activities (Figure 1) [12,15].

In some 2016 studies, 0.03%-6.7% of plastic was found in the surface layer of soil along roads in industrial zones [11,15].

It was estimated that MPs in soil mainly arise from irrigation with wastewater; sediments that enter the soil ecosystem. Plastic film in agricultural production is the main source of MPs in agricultural soils, for example, vinyl tunnels, plastic film mulching [10,11,15]. Plastic mulching is widely used for preserving heat, retaining water, fertilizers, and improving soil in agricultural activities [11,12].

Furthermore, under the action of wind and water, some MPs migrate horizontally to other parts of the land or into the atmosphere or rivers. Others remain and can be transported vertically in the soil, eventually being transported to deep soil. MPs in the soil can adsorb other pollutants, such as persistent organic pollutants and heavy metals, making them more harmful in the long term, they can adsorb some contaminants (such as pesticides, antibiotics, and heavy metals) and transport them to organisms, which can have a strong toxic effect [10].

Article [10] comprehensively investigated microplastics in agricultural soils in Northwest China. Microplastics were found in all soil samples from Shaanxi Province, indicating significant soil contamination. MP concentrations ranged from 1430 to 3410 particles/kg. Fibers and small particles (0-0.49 mm) were the predominant types and sizes, respectively. Polystyrene (PS), polyethylene (PE), polypropylene (PP), high-density polyethylene (HDPE), polyvinyl chloride (PVC), and polyethylene terephthalate (PET) particles were detected in the agricultural soils.

The authors' research [10] also demonstrates a correlation between microplastic content in agricultural soils and soil planting type and climatic factors. The study results confirmed high MP levels in agricultural soils and showed that agricultural activities likely caused this MP soil contamination.

Study [15] investigated microplastic contamination of agricultural lands in the suburbs of Wuhan, central China. The study found that MP concentrations near suburban roads were 1.8 times higher than in residential areas, posing a potential threat to vegetable cultivation along roadsides. Results showed that microplastic content ranged from 320 to 12,560 particles/kg of dry weight. Microplastics less than 0.2 mm in size predominated, accounting for 70% of the total volume. Fibers and microbeads were the main types of microplastics. Polyamide (32.5%) and polypropylene (28.8%) were the dominant polymer types identified.

In article [16], soil samples from 15 agricultural lands in Schleswig-Holstein, northern Germany, were analyzed to examine the abundance, distribution, and composition of MPs in the size range of 1 to 5 mm. Particle content in sampling units ranged from 0 to 217.8 MPs per kg of dry weight, with an average content of 3.7 ± 11.9 MPs per kg of dry weight per unit area. While MPs were found in all study sites, only 34% of the sampling units contained synthetic particles.

Comparing German and Chinese data suggests significantly lower microplastic contamination levels in German agricultural soils. However, the size range of MPs considered in the German study was limited.

Study [11] examined 20 agricultural sites near Shanghai for microplastics (20 mm-5 mm) and mesoplastics (5 mm-2 cm). Three replicate soil samples were collected from shallow (0-3 cm) and deep (3-6 cm) soil layers at each site. Microplastic content was 78.00 ± 12.91 and 62.50 ± 12.97 particles/kg in shallow and deep soils, respectively. Mesoplastic counts were 6.75 ± 1.51 and 3.25 ± 1.04 particles/kg in shallow and deep soils. 48.79% and 59.81% of these micro/mesoplastics were < 1 mm in size in shallow and deep soils, respectively. Fibers, fragments, and films were the main microplastic morphologies, predominantly black or transparent. Higher concentrations and larger sizes of micro/mesoplastics were found in the topsoil compared to deeper soil. Polypropylene (50.51%) and polyethylene (43.43%) were the dominant polymers, suggesting that plastic mulching and wastewater sediment are major sources of microplastic contamination in these agricultural lands.

Studies in 2016 and 2019 demonstrated a significant impact on soil enzyme activity. Furthermore, these studies concluded that MPs can alter key ecological functions and biogeochemical processes in the soil environment. Research in 2017 investigated how MP accumulation accelerates the enzymatic activity of organic compounds containing phosphorus, nitrogen, and carbon, allowing them to accumulate in dissolved form [12].

Study [17] examined the effects of polyethylene microplastics, polyethylene resins, and plastic additives on soil nitrogen content, physicochemical properties, nitrogen cycle functional genes, microbial composition, and nitrogen transformation rates. Polyethylene microplastics and additives increased dissolved organic nitrogen, while polyethylene resin decreased it and showed a higher microbial biomass. It was proven that plastic additives, unlike polyethylene microplastics and resin, hinder organic decomposition and microbial immobilization of soil nitrogen. They have a significant, specific impact on microbial community structure, inhibit nitrogen transformation rates, and ultimately affect the nitrogen cycle.

The study mentioned in [18] reports that, under constant moisture conditions, soil microbial biomass, enzyme activity, and functional diversity tended to decrease with increasing concentrations of plastic mulch residue. Given the widespread and often improper use of plastic mulch in some agro-ecosystems, studying the soil microbiome can provide insights into the long-term consequences of plastic pollution on land.

According to research cited in [12], MPs in soil are responsible for disrupting soil structure, reducing the soil's infiltration capacity for rain and irrigation water, and negatively affecting the soil's water retention capacity. 2018 research indicates that MPs in soil significantly alter soil structure, including its porosity. In large quantities, these particles or fibers fill and block soil pores, ultimately reducing the soil's infiltration capacity. This disrupts nutrient cycling in the soil, alters microbial structure, and ultimately affects crop growth.

Agricultural and urban soils are considered major reservoirs for MPs. Plastic residues from mulching, over time and through environmental weathering, break down into MPs. These MPs disperse in the soil and associate with other pollutants like heavy metals, pesticides, and persistent organic pollutants, causing combined toxic effects on soil flora and fauna. These MPs can ultimately be transported to rivers, oceans, and other water bodies via agricultural runoff, spreading contamination to other ecosystem components such as rivers and lakes [15,16].

Impact on the Hydrosphere

Plastic has become an important component of human life, widely used in packaging, construction, and consumer goods production. According to 2017 studies, 8.3 billion metric tons of plastic were produced between 1950 and 2015. According to UNEP studies from 2017 and 2018, 12% of plastic waste is incinerated, 9% recycled, and 79% discarded in landfills [19,20].

Unfortunately, the presence of plastics in the aquatic environment is inevitable, especially considering modern plastic usage and waste management practices. For example, the main sources of ocean plastic pollution are land-based sources (70-80% of the pollution). MPs can reach seas and oceans through various pathways: River and atmospheric transport, beach littering, and directly through marine activities such as fishing, shipping, and aquaculture [21].

Once in the marine environment, unmanaged plastic waste never disappears. Its low degradation rate and chemical stability increase the accumulation rate of plastic in millions of tons in the marine environment. Larger pieces of plastic waste break down into smaller particles due to mechanical degradation, oxidation, fragmentation, and ultraviolet radiation. Thus, macroplastics (> 25 mm) break down into microplastics (< 5 mm) and then into nanoplastics (< 1 µm) [21,22].

Despite the fact that plastic components come in various forms, a 2020 study showed that more than 64% of plastic particles in surface waters are in the form of fibers, with the rest being fragments [20]. Given the size of plastic particles, it can be assumed that plastic waste is present not only in water but also in biota (e.g., fish, turtles, bivalves) and sediments [19,21].

MPs, when entering marine organisms, simultaneously cause numerous negative effects on their vital activities. Moreover, MPs and the additives they contain are transferred through the food chain from the lower trophic levels to the upper ones in the marine environment, and eventually to humans. Therefore, every process, from the sources of MPs entering the marine ecosystem to their impact on marine organisms, should continue to be studied by researchers and closely monitored [19,20].

In a 2024 study [23], samples from the northeastern coast of Venezuela (NECV), the Pacific and Arctic Oceans (PAO), and the Gulf Stream (GSC), each of 0.5 liters in volume, were examined. According to the data obtained, the overwhelming majority of plastic pollutants in individual samples of seawater from the NECV, PAO, and GSC regions were MPs smaller than 6 micrometers in size. The concentration of MPs in the NECV samples was approximately 10 times higher than in the PAO and GSC samples. Moreover, the concentration of MPs was significantly higher along the northeastern coast of Venezuela compared to the less anthropogenically impacted stations in the Pacific and Arctic Oceans and the Gulf Stream. Qualitative and quantitative analysis of the polymers in the NECV, GSC, and PAO samples showed the presence of micro-polymers in the following order (PP > PcCu > PS > PE > PET) [23].

In [21], plastic waste data were analyzed across three marine compartments of the South American Atlantic coast in Latin America, the Caribbean, and South America. This study highlighted that Brazil, the largest country in South America, ranked 7th among the countries discharging microplastic waste into the oceans from rivers. Despite this, 80% of emissions came from only 75 rivers. Five major hotspots for microplastic waste discharge from Brazil into the Atlantic Ocean were identified: The La Plata River estuary between Argentina and Uruguay; Guanabara Bay; the Amazon River; the São Francisco River; and the Tocantins River. Domestic wastewater was identified as the primary source of these materials entering the ocean, particularly in densely populated coastal areas such as the Bahia Blanca estuary (Argentina) and the bays of Guanabara and Todos os Santos (Brazil). The most common polymers in the samples were microfibers of polyethylene (PE) and polypropylene (PP). In studies collecting macroplastics from beaches, these materials accounted for an average of 70% of items larger than 25 micrometers.

According to [22], among the 25 trillion plastic particles present on the surface of the world's oceans, the Indian Ocean contains 4 billion MPs/km^2. This is partly due to the fact that India ranks 12th in terms of its contribution to ocean waste disposal, with a coastline of about 8,000 km, and in 2022, India was estimated to produce about 25,903 tons of plastic waste per day.

For a deeper understanding of plastic presence not only in the water column but also in marine organisms, oysters, known as effective filter feeders, are the most suitable model as bioindicators of plastic pollution. Thanks to their efficient filtering capabilities, contaminants can accumulate in oyster bodies, which have limited self-cleaning and expelling capabilities.

Studies in the Wadden Sea show widespread microplastic contamination in benthic-feeding seabirds, specifically common eiders and shelducks. Almost all eiders (92.9%) and shelducks (95%) had ingested plastic, primarily small, colorful threads (< 5 mm). This indicates regular ingestion and excretion, highlighting significant habitat contamination. High microplastic levels, coupled with declining bird populations, raise concerns about potential health risks. Long-term ecotoxicological studies are needed. The UN Environment Programme and UNESCO are developing monitoring guidelines for ocean plastic pollution. Regional studies and hydrodynamic modeling are crucial for assessing the impact of land-based plastic input [21,24].

In [22], 500 samples of Saccostrea cuccullata oysters were examined. Samples were taken from 5 sites in the intertidal zone along the Gujarat coast, India. It was found that each sample contained microplastic particles, with a concentration of 2.72 ± 1.98 MPs/g. A negative correlation was found between shell length and the amount of MPs. Predominantly fibers were registered in all research samples. The main colors were black, blue, and red microplastics, measuring 1-2 mm in size. The polymer composition of the MPs was identified as polyethylene terephthalate and polypropylene. The intertidal zone of Shivrajpur showed the highest recorded MP level, followed by Dwarka, Veraval, Diu, and Vanakbara. Based on the chemical composition of these identified polymers, potential sources of MPs in the ocean may include plastic waste, fishing activities, and sealants.

Microplastics in drinking water have garnered attention following reports of their widespread detection worldwide. Records of microplastics in freshwater environments continue to expand and update, especially in rivers, lakes, reservoirs, and groundwater. Targeted studies on the presence of microplastics in drinking water began in 2018, initially focusing on bottled water. Despite the late start, knowledge of microplastics in drinking water is rapidly growing [25].

In [20], tap water samples were studied. The study showed that up to 83% of them contained microplastic fibers. In terms of composition, 2023 studies showed that polyethylene, polyester, propylene, polyamide, and polyethylene terephthalate were detected in drinking water in descending order of concentration [20]. These results raise concerns about potential health risks since microplastics can enter the human body through drinking water, which is the main route of microplastic exposure [20,25].

Microplastics have been found in drinking water worldwide, including bottled water, tap water, and water from treatment plants in Europe, Asia, and the Americas. The concentrations of microplastics vary due to differences in study methodologies. The most common types identified were fibrous and fragmented particles made of polyester, polyethylene, polypropylene, and polystyrene, with sizes typically under 10 micrometers. The levels of microplastics varied by region and water type, and the color of the particles was generally not emphasized in the studies [25].

The collected data shows that microplastics are widespread in drinking water, with recorded concentrations varying greatly. Further research is needed to improve sampling and analysis of microplastics in drinking water, especially nanoplastics. There is a need to better understand the occurrence and fate of microplastics throughout the water supply chain. The results of previous and subsequent studies provide baseline information on MP contamination levels, which can be used to monitor the future impacts of MP contamination [21]. Ingested microplastic particles are already associated with harmful effects on animals, raising concerns about similar consequences for humans [20].

Plastic and Living Organisms

According to numerous studies, microplastic particles are widespread. For example, microplastic fibers were found in the deep waters of the northeastern Atlantic Ocean at a concentration of 70.8 particles/m^3. Due to their small size, microplastics can easily enter a wide range of marine organisms [26]. Along the Mediterranean coast of Turkey, 1,822 MP particles were extracted from the stomachs and intestines of 1,337 fish specimens, with the majority of ingested particles represented by fibers (70%) and hard plastics (20.8%). In different species of coastal (21) and freshwater (6) fish in China, MPs were found in 26 species, making up 55.9-92.3% of the total plastic specimens of each species. Studies have shown that marine fish are particularly prone to ingestion of small microplastics (< 500 micrometers), which makes them more susceptible to bioaccumulation. In some cases, a higher concentration of microplastics in the intestines was noted in fish collected from deeper waters. However, the ingestion of microplastics has been observed in both pelagic and demersal fish species. Therefore, the risk of microplastic ingestion and subsequent bioaccumulation and transfer along food chains in marine ecosystems exists [20,22,24,26].

The presence and impact of plastic waste on organisms have been increasingly studied in recent years. During the production of plastics, various chemicals are added to improve the mechanical, chemical, and physical properties of the products. Additives are chemical substances introduced during manufacturing to perform various functions [27]. These chemicals include antioxidants, lubricants, corrosion inhibitors, plasticizers, adhesives, thermal stabilizers, and flame retardants (FR). It is known that plastics contain 10,000 different chemicals in the form of "chemical additives" that are not covalently bonded to the original polymers [27-29].

More than 2,500 additives have been identified in the global market. These chemicals have attracted attention due to the growing amount of plastic waste being discharged into the ocean, leading to the leaching of these additives and potential impacts on biota [27]. However, only 25% of plastic additives are characterized as potentially hazardous to the environment. Since plastic additives are not covalently bonded, they can freely leach into the environment. Due to their presence in various environmental conditions, additives possess significant ecotoxicity. There is an inevitable threat of human exposure to plastic additives as they are part of the "big three" - air, water, and food [27].

Thus, both solid particles and chemical additives leached from microplastics (MPs) contribute to environmental MP pollution. The global plastic additives market is expected to grow at an average annual rate of 5.7% from 2021 to 2028, with the market size increasing from $51.04 billion to $75.20 billion [29]. Therefore, several knowledge gaps remain concerning chemical additives in plastics, including their presence, transfer, human exposure, and the risks associated with these additives for human health and ecosystems [29].

Additionally, metal-based catalysts used in the production of water bottles can enter drinking water. The release of antimony (Sb), used as a catalyst in industrial PET plastic bottles, has been demonstrated at high temperatures (60-85 °C). Since Sb can cause health effects (nausea, vomiting, and diarrhea), it is advisable to avoid using plastic bottles of this type and storing them at elevated temperatures that degrade water quality. Another study showed the accumulation of Zn in the earthworm Lumbricus terrestris exposed to Zn-associated PE fragments, with Zn desorption in the synthetic earthworm gut being higher from these MPs (40-60%) than from soil (2-15%) [30].

These chemicals have been found in aquatic ecosystems as well as in various organisms exposed to them. In ecosystems, the impact of additives on species occurs when microplastics or additives bioaccumulated in prey species are ingested, inhaled, or absorbed through the skin from the surrounding water. This exposure causes a range of potentially adverse effects, such as inhibition of microalgae growth, reduced fertilization and reproduction in mussel species, and increased mortality in fish species. Some additives have already been restricted in certain countries due to their potential to disrupt the endocrine system [27].

Microplastics can act as carriers, accumulating and transferring organic pollutants and heavy metals on their surfaces, leading to the bioaccumulation of contaminants and toxins in the aquatic environment [31]. Translocation of MPs through the gastrointestinal tract has been demonstrated in laboratory studies on crabs and mussels. The presence of MPs in tissues outside the gastrointestinal tract in fish has yet to be evaluated. However, one study reported the presence of MPs in the liver of fish fed with plastic particles [30]. Many studies have shown that microplastics are highly efficient adsorbents of hydrophobic/hydrophilic organic pollutants [31,32].

Recently, attention has focused on the role of microplastics in the adsorption of heavy metals from aquatic environments. Lead, a metal that can cause diseases in humans, such as mental retardation, kidney and nervous system damage, cancer, etc., is widely used in the electroplating, steel, electrical, and explosives industries. However, as far as is known, little effort has been made to study the adsorption role of microplastics for lead ions and related mechanisms [31].

Studies [32] show that depending on the physicochemical properties of MP surfaces, adsorption behavior can vary significantly. Therefore, the adsorption process of Pb^{2+}, Cu^{2+}, and Cd^{2+} metals on MPs should be easily influenced by other environmental media. For example, pH can significantly affect metal sorption on MPs, while ionic strength has relatively little effect on this process. It has been found that the sorption affinity of the three metals to model MPs followed the order of HDPE > PVC > LDPE > PP. Moreover, Pb^{2+} demonstrated significantly stronger sorption than Cu^{2+} and Cd^{2+}, which is explained by strong electrostatic interactions. This study shows that depending on the surface physicochemical properties of MPs, sorption behavior can vary significantly, providing additional information about the behavior of MPs as metal carriers.

Wastewater and cultivation zones are typical sources of heavy metal pollution, and microplastics may be key carriers of its transport in marine systems. A study on the adsorption of heavy metals (lead, copper, and cadmium) by microplastics found that various types of plastics-polyvinyl chloride (PVC), polypropylene (PP), polyethylene (PE), polyamides (PA), and polyoxymethylene (POM)-differ in their ability to adsorb these metals. PVC and PP exhibited higher adsorption compared to PA, PE, and POM. The adsorption was influenced by factors like ion concentration, adsorption time, and particle size. The study also noted competition between different heavy metals for adsorption sites on microplastics, with varying selectivity, suggesting the need for further research on this process [33].

The study [8] examined the adsorption behavior of trace elements (Cd, Cr, Cu, Co, Ni, Pb) on polyethylene (PE) and found that aged PE has higher adsorption capacity than primary PE. It was established that pH value and residence time of microplastics in the environment are important factors influencing the metal ion adsorption capacity on PE under freshwater conditions. The amount of adsorbed lead(II) decreased with increasing sodium chloride concentration but increased with increasing pH. Adsorption efficiency was about 91% at pH 6.

Previous studies confirmed that heavy metal ions can adsorb onto primary PS beads (polystyrene) and aged PVC fragments (polyvinyl chloride) in seawater. Additionally, 2012 studies confirmed that plastic resin pellets can be a significant transport vehicle for metals in the marine environment.

The study [26] examined the relationship between microplastics and polycyclic aromatic hydrocarbons (PAHs) in marine organisms from Sanggou Bay. The results showed that the concentration of microplastics and PAHs ranged from 1.23 ± 0.23 to 5.77 ± 1.10 items/g, and from 6.98 ± 0.45 to 15.07 ± 1.25 μg/kg, respectively. The analysis of PAH concentrations in organisms revealed the presence of 16 types of PAHs, with 2-3 ring compounds, particularly naphthalene, contributing the most. Microplastics ranging from 30 to 500 μm showed a particularly strong positive correlation with the human risk posed by PAHs, suggesting that smaller microplastics may adsorb more PAHs, thereby contributing to increased human health risks. Six types of microplastic components were identified in the organisms of Sanggou Bay, including polystyrene (PS), polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), cellulose, and cellophane. The main microplastic component in organisms is PE, with a proportion ranging from 37.1% to 56.1%. Additionally, important microplastic components include cellulose, polyethylene, and polypropylene.

It is widely known that seafood is one of the most beneficial food sources for humans, mainly due to its high protein content. Unfortunately, it is also reported that microplastics enter, are absorbed, or bioaccumulate in marine organisms. For example, in the study [34], more than 200 µm were found in the digestive tract of 277 out of 390 individuals from 26 different species of edible fish, mollusks, and crustaceans. According to the study, no signs of bioaccumulation were found in the muscle tissue of fish, mollusks, and crustaceans. The research results confirm that carnivorous species suffer the most from microplastic ingestion. Carnivorous species had the highest prevalence of plastic ingestion, at 79 ± 9.4%, followed by planktonic species at 74 ± 15.5%, and detritivores at 38 ± 36.9%, suggesting trophic transfer [34].

A major concern is the possibility of marine organisms mistaking these microplastics for food and indiscriminately consuming them, thereby being exposed to many hazardous pollutants, including persistent organic pollutants (POPs), such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs), and dichlorodiphenyltrichloroethane (DDT), as well as heavy metals, which adsorb onto their surfaces from the environment. These additives also become bioavailable to marine biota upon ingestion and can have various harmful effects on marine life, such as altered metabolic and reproductive activity, reduced immune response, oxidative stress, cellular or subcellular toxicity, inflammation, and cancer [35].

Recent studies highlight seafood consumption as a major pathway for microplastics to enter the human body. While the health risks of microplastic pollution are a concern, the long-term effects remain largely unknown. More research is needed to fully understand these impacts and develop effective solutions. As awareness of the issue grows, there is increasing demand for measures to reduce plastic use and improve waste management to protect both human health and the environment.

Solutions

The issue of plastic waste demands significant attention and requires comprehensive solutions. Here are several key efforts and approaches being applied to address this problem [31,33,36-38]:

Recycling technologies

Efficient recycling: Advanced recycling technologies, such as pyrolysis, chemical recycling, and mechanical recycling, can be employed.

Sustainable production: Implementing closed-loop production cycles for plastic products to minimize waste and ensure the reuse of materials.

Legislative initiatives

Regulations and standards: Legislative initiatives may include bans on single-use plastic items, mandatory recycling requirements, and the establishment of standards for environmentally friendly packaging. The EU's packaging waste regulations were introduced in 1994, with a plan to achieve 55% plastic recycling by 2030. Denmark became the first European country to introduce a tax on plastic bags. Germany is set to introduce a "plastic tax" in 2024, which will first be collected in 2025. In France, the sale of newspapers and magazines in plastic packaging will be prohibited by law from January 1, 2025. Norway banned certain single-use plastic items, including plastic straws and disposable cutlery, in July 2021. In 2023, Pakistan adopted the "Single-Use Plastic Ban Rules," aimed at phasing out single-use plastic products across the capital, Islamabad.

Financial incentives: Encouraging recycling and innovative solutions in the field of plastics through tax breaks, subsidies, or funding for research into environmentally friendly materials.

Innovative methods

Automation and robotics: Using automated systems for more efficient plastic waste sorting.

Nanotechnology: Developing nanotechnologies to enhance plastic recycling, including creating new types of biodegradable plastics and technologies for efficiently breaking down plastic at the molecular level.

Public and corporate initiatives

Collection and disposal campaigns: Organizing programs to collect plastic waste, such as plastic bottles and packaging, creating collection points, and conducting special disposal campaigns. Programs like "Ocean Cleanup" aim to remove plastic waste from oceans and rivers. Other initiatives work towards a waste-free plastic economy.

Educational programs: Raising awareness about the harm caused by plastic waste, methods of recycling, and the need to reduce the use of single-use plastics.

International cooperation

International agreements: Establishing international agreements and standards for managing plastic waste, collaborating on research and development of new recycling technologies.

Global projects and research: Participating in international projects and research on new methods of recycling and reducing plastic waste, including innovations in biodegradable plastics and disposal systems.

Plastic pollution poses serious environmental and health risks. Effective solutions require global cooperation, innovative technologies, legislative action, and education. Reducing plastic consumption and improving waste management are essential to protect ecosystems and human health. A collective global effort is vital for ensuring a sustainable future.

Conclusion

Plastic waste pollution poses a serious threat to ecosystems and human health, requiring immediate and effective measures to address the problem. The key points identified in this work are as follows:

1. The Scale of the Problem: Plastic waste permeates all corners of the planet, accumulating in both oceans and land, leading to severe environmental consequences.
2. Environmental Consequences: The breakdown of plastic into micro-particles threatens biodiversity, and absorbed toxins can enter food chains, posing a risk to both animal and human health.
3. Human Health: Toxic substances released from plastic waste can accumulate in the human body through food and water, creating potential health threats.
4. Need for Action: Reducing plastic consumption, developing effective waste management systems, and educating the population on environmental responsibility are key measures for reducing the impact of plastic waste on the biosphere.
5. Global Approach: Solving the problem requires joint efforts at the international level, including the development of international agreements and standards aimed at reducing plastic pollution and protecting the environment.

In conclusion, to minimize the negative impact of plastic waste on the biosphere and humanity, not only is a change in consumer habits necessary, but also the active implementation of innovative technologies and policies that promote sustainable plastic waste management. Only through the combined efforts of the international community can we ensure the well-being of our planet for the future.

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