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ПЛАСТИКОВЫЕ ОТХОДЫ: ВЛИЯНИЕ НА ЭКОСИСТЕМУ ПЛАНЕТЫ

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Пластиковые отходы, несмотря на их универсальность и широкий спектр применения, создают серьезную угрозу для экосистемы планеты. Мировое производство пластика увеличилось с 1,5 млн т в 1950 г. до 335 млн т в 2016 г. Хотя уровень переработки пластиковых изделий растет, однако большая часть оставшихся по-прежнему выбрасывается в окружающую среду. Первоначально общественное внимание в основном было сосредоточено на крупных пластиковых отходах. В последние несколько лет мелкие пластиковые фрагменты, особенно микропластик, вызывают все большую обеспокоенность из-за их загрязнения и рисков для окружающей среды. Они оказывают негативное воздействие на компоненты окружающей среды и здоровье живых организмов, включая человека. По оценкам ученых, пластик составляет до 54 % (по массе) антропогенных отходов, выбрасываемых в природу. Эти отходы часто накапливаются в таких экосистемах, как океаны, реки, почвы и даже воздушная среда. Урбанизация, активное экономическое развитие и рост населения способствуют увеличению объемов пластикового загрязнения, что усугубляет глобальную экологическую ситуацию. Впервые проблема загрязнения пластиком была зафиксирована в 1960 г., когда его частицы обнаружили в кишечнике морских птиц. С тех пор ситуация только ухудшилась: в наши дни микропластик повсеместно встречается в морях, почвах, реках, озерах, в воздухе, на пляжах. Более того, его частицы выявлены в питьевой воде таких стран, как Германия, Норвегия, США, Китай и др., что подчеркивает глобальный масштаб проблемы. В статье анализируется литература, посвященная источникам микропластика в атмосфере, гидросфере и почве. Проводится оценка его распространенности в экосистемах в виде отходов различных форм, размеров и цветов. Уделено внимание негативному влиянию микропластика на такие живые организмы, как рыбы, морские черепахи и птицы. Рассматриваются позитивные шаги, направленные на снижение загрязнения: переработка отходов, использование экологичных материалов и повышение информированности общества.

Ключевые слова: пластиковые отходы; загрязнение окружающей среды; загрязнение воздуха; загрязнение почвы; загрязнение воды; микропластик; токсикологическое воздействие; здоровье человека; экологические последствия; устойчивое развитие.

PLASTIC WASTE: IMPACT ON THE PLANET'S ECOSYSTEM

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Plastic waste, despite its versatility and wide range of uses, poses a serious threat to the planet's ecosystem. Global plastic production increased from 1.5 million tonnes in 1950 to 335 million tonnes in 2016. Although recycling rates for plastic products are increasing, much of the remainder is still discarded into the environment. Initially, public attention was mainly focused on large plastic waste. In the past few years, small plastic fragments, especially microplastics, have become increasingly concerned due to their pollution and environmental risks. They have a negative impact on environmental components and the health of living organisms, including humans. It is estimated that plastic makes up to 54 % (by weight) of anthropogenic waste discarded into nature. This waste often accumulates in various ecosystems such as oceans, rivers, soils and even the air. Urbanization, rapid economic development and population growth contribute to the increase in plastic pollution, which worsens the global environmental situation. The problem of plastic pollution was first recorded in 1960, when plastic particles were found in the intestines of seabirds. Since then, the situation has only worsened; today, microplastics are ubiquitous in the seas, beaches, soils, rivers, lakes and air. Moreover, plastic particles have even been found in drinking water in countries such as Germany, Norway, the United States, China and elsewhere, highlighting the global scale of the problem. This article reviews the literature on the sources of microplastics in the atmosphere, hydrosphere and soil. It also assesses their prevalence in ecosystems in the form of waste of various shapes, sizes and colours. Particular attention is paid to the negative impacts of microplastics on living organisms such as fish, sea turtles and birds. In addition, positive steps aimed at reducing pollution are discussed: recycling, using eco-friendly materials and raising public awareness.

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; 3].

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 [4], 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 [5], 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 [2], 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 poses a significant global environmental challenge for several reasons. The production, transportation, and disposal of plastics release substantial greenhouse gases, contributing to climate change. Moreover, plastic waste disrupts natural ecosystems and impacts carbon storage processes in soils and oceans, hindering the carbon cycle. Plastics can persist in the environment for centuries, with decomposition timelines ranging from 100 to 1 000 years, during which they pollute surrounding air and water. 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. Marine animals may mistake this particles for food, causing internal injuries, blockages, and starvation. 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 [3].

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; 4]. Microplastics can be classified into different size categories:

1. Large microplastics (1–5 mm) – The largest microplastic particles, visible to the naked eye. They often originate from the fragmentation of larger plastic debris, industrial resin pellets (nurdles), or microbeads used in personal care products.

2. Small microplastics (0.1–1 mm) – These particles are smaller and more difficult to detect without magnification. They can result from further degradation of plastic materials, synthetic fibers from textiles, or abrasion of rubber products (e. g., tire wear).

3. Nanoplastics (<100 nm**)** – The smallest plastic particles, often at the nanoscale, making them particularly concerning. Due to their minuscule size, they can penetrate biological membranes, enter cells, and accumulate in tissues, potentially leading to toxic effects on organisms [1–5].

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 [11] 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 [6].

The study referenced in [10] examined potential sources of microplastics in the atmosphere of 11 remote U.S. reserves and measured their deposition rates. The research focused on both primary microplastics, which are manufactured at a specific size (e. g., microbeads), and secondary microplastics, which arise from the breakdown of larger plastic items due to physical wear or ultraviolet exposure [6]. A total of 236 samples were collected after precipitation, and 103 samples were collected dry. Results showed microplastics in 98 % of all wet and dry samples. The particle sizes ranged from 4 to 188 μm, while fibers varied between 20 μm and ~3 μm, with an average width of 18 mm and depth of 6 mm. One key factor in the transportability of plastics is their relatively low density (0.65–1.8 g/cm³), which is lighter than that of soil particles (~2.65 g/cm³). Additionally, the larger surface area-to-volume ratio of plastic fibers increases their drag forces, which slows down their rate of deposition [10].

While atmospheric microfibers have recently been detected in Europe and the Arctic [9], the exact pathways through which primary and secondary microplastics (such as microfibers and particles) enter the atmosphere are still not fully understood. Data collected in recent studies were compared with previous findings from 2018, revealing that microplastics deposited through wet conditions come from different regions compared to those deposited dry. Larger and fewer microplastics were found in wet deposits, which showed a correlation with both dust deposition and population density, suggesting that regional storms play a key role in transporting and depositing these particles. On the other hand, dry deposition appears to be linked to large-scale global dispersion, pointing to the widespread transport of microplastics. These particles are often found far from their original production sites, even in remote areas like Antarctica, far from industrial hubs [6; 9]. Regional storms are particularly important for delivering larger plastics to national parks, with dry deposits making up over 75 % of the plastic mass found. This suggests that plastics, while possibly originating in urban centers, can accumulate in the atmosphere over time, traveling long distances before being deposited under favorable conditions, such as slower air mass speeds or the presence of mountain ranges [10].

The study in article [11] examined atmospheric microplastic deposits in a pristine mountain watershed in the French Pyrenees during the 2017–2018 winter. Over five months, samples were collected representing both wet and dry atmospheric deposits. The microplastics identified included fibers up to approximately 750 μm and fragments smaller than 300 μm. The daily average deposition rate was 249 fragments, 73 films, and 44 fibers per square meter. Air mass trajectory analysis revealed that microplastics were transported through the atmosphere from distances of up to 95 km. The findings highlight that microplastics can impact even remote, sparsely populated regions via atmospheric transport. During the monitoring period from January to March, the samples also contained fine orange quartz-like dust, which had characteristics typical of Saharan dust (grain size ~8 μm, color, and chemical properties), indicating that some of the microplastics may have originated from the Sahara, North Africa, or the Iberian Peninsula. 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 diversity in plastic composition could be attributed to factors such as the source of the plastic particles, which influences wind direction and strength, as well as the occurrence of storms and the length of calm periods in comparison to storm events. Polystyrene (PS), primarily in the form of fragments, was the most abundant plastic found in the samples, followed by polyethylene (PE). PS and PE are commonly used in single-use plastic products and packaging. Along with polypropylene (PP), these three plastics constitute the majority of atmospheric deposits at this location [11]. Numerous studies have indicated that controlled burning of various plastic materials, simulating open-air burning, generates a range of toxic compounds, including volatile and semi-volatile substances, organic compounds, and harmful metals [11; 13]. 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 [16].

In the study [12], laboratory experiments were conducted on the burning of industrial polymer materials, simulating open fire conditions. The experiment utilized various types of plastics, including poly(vinyl chloride) (PVC), low-density polyethylene (LDPE), high-density polyethylene (HDPE), polystyrene (PS), polypropylene (PP), and polyethylene terephthalate (PET). Smoke and solid particle samples (soot) were collected on filters, and solid ash residues were produced under controlled combustion at temperatures between 600–750 °C. The analysis focused on the emissions of solid particles, persistent free radicals embedded in the polymer matrix, heavy metals, and other elements in both soot and ash samples. Results revealed that all plastics combust easily, generating charred residues, solid ash, and black smoke particles. Toxic persistent carbon- and oxygen-centered radicals were found in both soot particles and ash residues, which are known to have harmful effects when inhaled. Heavy metals such as lead (Pb), zinc (Zn), chromium (Cr), nickel (Ni), and cadmium (Cd) were detected at low levels, while higher concentrations of lithophile elements like sodium (Na), calcium (Ca), magnesium (Mg), silicon (Si), and aluminum (Al) were present in soot and ash residues [7].

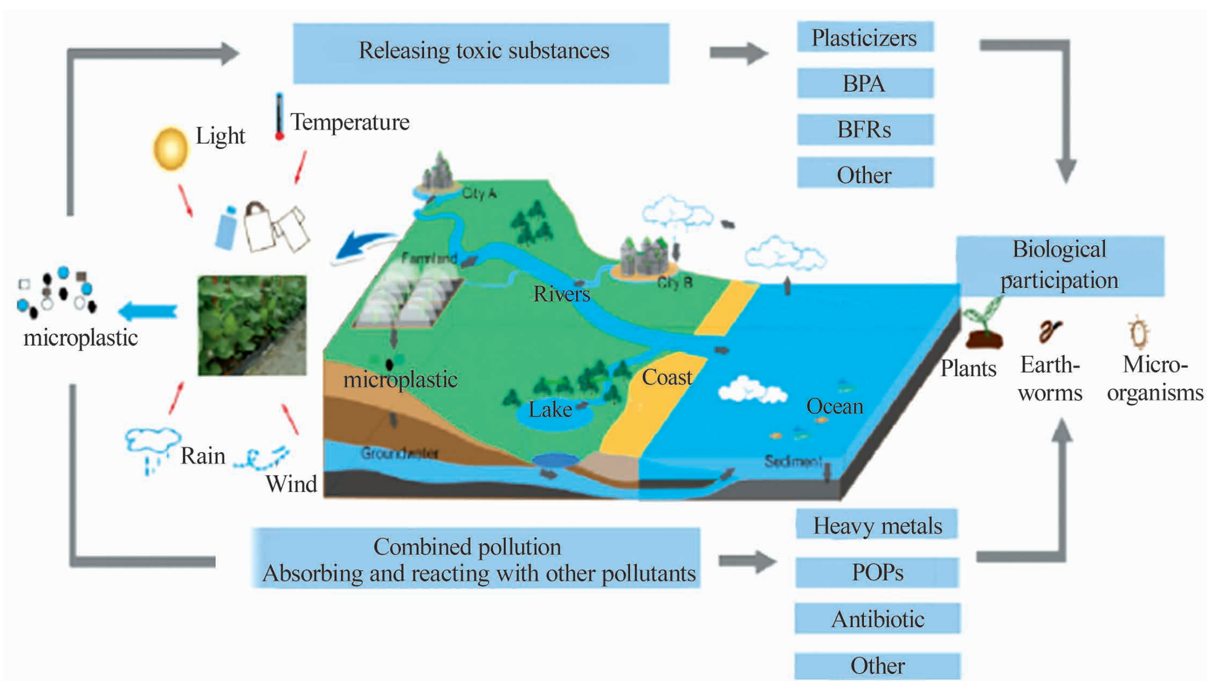
Understanding the primary mechanisms behind plastic emissions into he atmosphere is essential for creating scalable solutions. While the full ecological impact remains unclear, it is an unavoidable issue that will become increasingly evident. To effectively reduce the potential risks posed by microplastics in the environment, both the scope of the solution and the degree of global cooperation required call for widespread involvement from the international community [10].

Impact on Soil. As early as 2012, researchers first assessed the potential of soil contamination with microplastics [16]. 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 [16].

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 [13]. 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 (Fig.) [12; 14].

In some 2016 studies, 0.03–6.7% of plastic was found in the surface layer of soil along roads in industrial zones [14; 16].



Microplastics and soil [12]

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 [13; 14; 16]. Plastic mulching is widely used for preserving heat, retaining water, fertilizers, and improving soil in agricultural activities [12; 16].

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 [13].

Article [13] 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 [13] 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 [14] 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 [15] 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 [16] 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 [14; 15].

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 [22].

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) [22; 24].

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; 22].

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 [21], 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) [21].

In [22] 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 7^{th} 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 [24], 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 12^{th} 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 [22; 23].

In [24] 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. These findings highlight potential health risks, as microplastics can enter the human body primarily through drinking water, which serves as a significant exposure pathway.

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 [22]. Ingested microplastic particles are already associated with harmful effects on animals, raising concerns about similar consequences for humans.

Plastic and living organisms. Microplastics are widespread in marine environments. For example, fibers have been detected in the deep waters of the northeastern Atlantic at 70.8 particles/m³. Due to their small size, they easily enter marine organisms [27]. Along the Turkish Mediterranean coast, 1,822 microplastic particles were found in the digestive tracts of 1,337 fish, mostly fibers (70 %) and hard plastics (20.8 %). In China, MPs were detected in 26 fish species, making up 55.9–92.3 % of plastic debris per species. Marine fish are especially prone to ingesting particles under 500 μm, increasing bioaccumulation risks. Higher MP concentrations have been observed in deep-sea fish, though both pelagic and demersal species are affected, facilitating microplastic transfer through marine food webs [23; 24; 27].

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 [26]. 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 [29; 26].

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 [26]. 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 [26].

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 [26].

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 [35]. 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 [35; 31].

In the study [39] marine organisms such as Mytilaster lineatus and Amphibalanus improvisus were examined as biomonitors of MP pollution in the Caspian Sea. Samples were collected from nine areas along the coastal waters of the southern Caspian Sea between July and September 2022. A total of 25 specimens of Mytilaster lineatus and 25 specimens of Amphibalanus improvisus were collected from each area. The study revealed that microplastics were detected in all analyzed organisms. On average, 1.69 ± 0.79 particles per individual or 7.96 ± 3.231 particles per gram of wet weight were found in M. lineatus, while 1.8 ± 0.9 particles per individual or 35.18 ± 35.33 particles per gram were found in A. improvisus. Most of the detected microplastics were 1000–3000 μm in size, primarily composed of polyamide, and had a black fibrous shape.

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 [32], 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 [32].

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].

Microplastics as carriers of toxic substances. Microplastics are essential carriers for a range of potentially hazardous substances, including metals like Pb, Cd, Fe, Mn, Zn, Cu and ect. as well as hydrophobic organic contaminants such as polyaromatic hydrocarbons (PAHs), organochlorine pesticides, and polychlorinated biphenyls.

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].

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 [35].

Studies [31] 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 [34].

The study [10] 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 [27] 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.

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 [33].

The article [40] mentions the term «plasticosis» to describe a recently discovered disease directly linked to microplastic exposure and its toxicological effects in seabirds. The unintentional ingestion and accumulation of microplastic particles in the digestive system lead to chronic inflammation, causing significant tissue alterations. This disease, named «plasticosis», was first identified in Ardenna carneipes seabirds inhabiting Lord Howe Island, Australia. Additionally, aside from scar tissue formation, plastic exposure has been associated with slowed chick growth, changes in blood chemistry, and severe tissue damage in seabirds.

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. In the world we live in, plastic is ubiquitous. Without proper disposal methods, dumping or burning these polymers can cause serious risks, such as heart failure, serious respiratory problems including asthma and emphysema, vomiting, kidney or liver damage, and reproductive system damage. Unfortunately, there is no single effective method to address the issue of plastic pollution of the ecosystem. Although the potential risk associated with plastic waste will likely vary depending on the type of plastic, they still have a negative impact on the environment. Today, a range of measures are being used to address these issues, including: recycling technologies, legislative initiatives, public and corporate initiatives, international cooperation.

There are currently several technologies available for the management of solid plastic waste. These include chemical, physical, and biological treatment methods. However, each has its own drawbacks. Chemical methods cannot be used in large-scale operations because the chemicals used to break down plastic create huge amounts of chemical waste. The waste incineration process (a physical method) eliminates the need for landfills and produces energy that can be used for other purposes. However, the gases released during the combustion of plastic waste are extremely hazardous and can cause a number of respiratory diseases. Biological methods of converting organic polymers into methane and manure through microbial intervention are applicable to certain groups of waste. Unfortunately, not all plastic can be replaced with biodegradable plastics today [41].

Legal regulations target reducing plastic waste through bans on single-use plastics, mandatory recycling, and eco-friendly packaging requirements. Phasing out single-use plastics could cut aquatic plastic waste by 40 %. The EU set a 55 % plastic recycling target by 2030. Denmark pioneered a plastic bag tax, while Germany will introduce a «plastic tax» in 2024. France will ban plastic-wrapped newspapers from 2025 but postponed restrictions on styrene-based products. Norway banned plastic straws and cutlery in 2021 and Taiwan aims to eliminate single-use plastics in restaurants and businesses by 2030 [41; 42].

In 2013 China introduced a temporary restriction on waste imports, calling it the «Green Fence». In 2017, China announced a ban on the import of non-industrial plastic waste. Following the 2019 G20 summit in Osaka, Japan committed to reducing marine plastic waste. To prevent pollution of Boracay, the Philippine government closed the island to tourists from April 2019 for 6 months [41].

Programs aimed at gathering plastic waste like bottles and packaging can be organized, with designated collection points and specialized disposal efforts. For instance, the «Ocean Cleanup» initiative works to remove plastic debris from oceans and rivers using floating barriers and filtration systems. The Ocean Plastics Initiative (PI) seeks to promote sustainable plastic production and consumption, ultimately aiming for a waste-free plastics economy. NGO One Island One Voice led a massive effort by more than 20 000 people to clean up 120 beaches around the popular Indonesian island of Bali in March 2018 [34–38; 41].

Article [43] discusses how technology and policy can jointly address microplastic pollution. For instance, plastic fees and taxes have funded cleanup efforts in U. S. cities like Oakland and Washington, D.C. Technological solutions complement policies by tracking emissions and reducing harmful chemicals, especially in synthetic textiles. Examples include wastewater treatment projects like «GoJelly», which uses jellyfish mucus to capture microplastics, and laundry filters like «Cora Ball» and «Fibre Free». Household filtration systems such as «Lint LUV-R» and «Showerloop» further aid in microplastic removal from domestic water sources.

Based on all of the above, we begin to understand the global nature of the ongoing pollution. It is safe to say that not only we but also the next generation will face the consequences. Each of us has the opportunity to influence this situation by being careful about the environment.

Conclusion

Plastic waste pollution poses a significant threat to both ecosystems and human health, necessitating urgent and impactful actions to mitigate its effects. 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: To reduce the environmental impact of plastic waste, it is essential to lower plastic consumption, improve waste management systems, and increase public education on environmental responsibility. These actions are crucial in minimizing the harmful effects of plastic pollution on ecosystems and human health.

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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