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Review

Fate and Impacts of Microplastics in the Environment: Hydrosphere, Pedosphere, and Atmosphere

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Abstract: Plastic litter is on the rise where plastic waste ends up in undesignated areas such as the coastal shorelines, where the plastic is exposed to environmental conditions. As a result, the degradation and decomposition of plastics occur, leading to the formation of smaller fragments of plastics, termed microplastics. Microplastics have recently been considered as an emerging class of contaminants due to their ecotoxicological impact on the aquatic environment as well as soil matrix. Microplastics are of a size less than 5 mm and are produced from either a primary source (such as plastic pellets, and beads in makeup products) or a secondary source (such as the wear and tear of normal-use plastics and washing of clothes and textiles). Microplastic pollution is spread across the hydrosphere, pedosphere, and atmosphere, and these environmental zones are being studied for microplastic accumulation individually. However, there exists a source–sink dynamic between these environmental compartments. This study reviews the available literature on microplastic research and discusses the current state of research on the fate and transport of microplastic in the hydrosphere, pedosphere, and atmosphere, explores the ecotoxicological impact of microplastics on aquatic and soil communities, and provides prospective future research directions and plastic waste management strategies to control microplastic pollution. While the fate of microplastics in the hydrosphere is well-documented and researched, studies on understanding the transport mechanism of microplastics in the pedosphere and atmosphere remain poorly understood.

Keywords: microplastics; hydrosphere; pedosphere; atmosphere; ecotoxicology

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1. Introduction

Plastic production began in the 1950s, resulting in plastic waste of 359 million tons globally in 2018 [1,2]. Plastic waste is estimated to further increase by 276 million tons by 2025 [3]. This increase in plastic waste will place a huge burden on the existing plastic management system because 78% of the plastic waste is handled via recycling, incineration, and landfilling and the remaining 22% remains as mismanaged plastic waste [4,5]. It is estimated that approximately 5.3 to 14 million tons of mismanaged plastic waste end up being discarded as litter along the coastlines each year, out of which 10% enters the hydrosphere and accumulates over time [3,6]. Plastic with sizes greater than 5 mm are called macroplastics [7]. Once exposed to the environment, macroplastics undergo weathering and degradation and result in the formation of microplastics with sizes less than 5 mm [8,9].

Environmental weathering results in plastic degradation in which long-chain polymers are broken into smaller ones [10]. Weathering mechanisms including abiotic degradation such as UV radiation, heat, and chemical reactions lead to plastic breakdown or fragmentation via mechanical stress or chemical oxidation [11]. Another notable degradation mechanism is the biotic degradation caused by enzymatic processes as well as bio-disintegration, in which plastics are fragmented into small pieces (e.g., the composting processes) [9].

Microplastics originate from various sources, and depending on their source, microplastics can be classified into primary and secondary microplastics [12,13]. Primary microplastics are minute plastic particles designed for commercial applications such as cosmetic products. These are mainly composed of polyethylene (PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET) polymer, and acrylic or polyvinyl chloride (PVC) [14–17]. Primary microplastics usually enter the aquatic environment through household sewage discharge or via air-blasting technology [18]. Other primary microplastic examples include the use of acrylic or polyester in paint products and high-pressure scrubbers [16,19].

Weathering and degradation of macroplastics result in the generation of secondary microplastics [20]. Exposure to ultraviolet (UV) radiation catalyzes the photooxidation of plastic, causing it to become brittle and fragment into microplastics [9]. One of the main sources of secondary microplastics includes effluent from wastewater treatment plants where they are found in the secondary treatment process of a wastewater treatment plant after passing through the primary unit [12]. Another source of secondary microplastics includes the wearing of plastics. Microplastics are released as a result of laundry activities where the microplastics present in clothing products are released into the water [21], the use of fishing gear including nets and ropes [22], tearing of rubber tires of automobiles [23] as well as the wear and tear of household items such as plastic home furniture [24].

Microplastics are of increasing concern due to the ecotoxicological risks they pose to aquatic and soil organisms as well as humans. Microplastic ingestion by a range of species can result in bioaccumulation and biomagnification through the food chain. Microplastics, possessing a size of less than 5 mm, are small enough to be readily consumed by marine organisms [25]. As a result, primary consumers will assimilate the microplastics, pass them on to their secondary consumers, and ultimately reach the human table, thus disrupting the food chain [26]. Furthermore, microplastics can act as carrier vectors for heavy metals and other pollutants such as polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) due to the hydrophobic nature of their surfaces [12,27,28].

After the Sustainable Development Goals (SDGs) were proposed by the United Nations (UN), innumerable advocates have shifted economy-based development strategies to measures that aim toward achieving an ever-lasting sustainable environment. The United Nations Sustainable Development Goals (UN SDGs) assigned Goal 14 specifically to conserve and use the oceans, seas, and marine resources sustainability and recognize microplastics as emerging contaminants [29]. There is abundant literature discussing the source and transport of microplastics in the hydrosphere, pedosphere, and atmosphere. However, the fate and transport of microplastics in the environment in total, along with their ecotoxicological impact on environmental organisms, are elusive. In this study, we collated the review of microplastics in the three main zones of the environment—hydrosphere, pedosphere, and atmosphere—and offer a single platform for readers to gain information on the fate and transport of microplastics in the environment. Therefore, this review aimed to provide a comprehensive understanding and the current state of research on (i) the fate and transport of microplastic in the pedosphere, hydrosphere, and atmosphere; (ii) the ecotoxicological impact of microplastics on aquatic and soil communities; (iii) the prospective future research directions and plastic waste management strategies to control microplastic pollution.

2. Sources and Types of Microplastics

Depending on their source, microplastics can be categorized into primary and secondary microplastics, as summarized in Table 1. There are six major types of observed microplastics, based on their chemical composition and density including polystyrene (PS), low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), polyvinyl chloride (PVC), and polyethylene terephthalate (PET). All the rest can be categorized as "others" (e.g., nylon, polyester) [30,31]. The common sources of PS include cosmetic products (such as exfoliator beads found in facial scrubs), plastic furniture, kitchenware, single-use plasticware, and plastic packaging materials. Clingy plastic wraps and films, juice boxes, wire insulations, and disposable shopping bags are the sources of

LPDE. The main source of HDPE includes toys, shampoo bottles, recycle bins, cereal box liners, and pipe systems. For PP, the common sources include straws, fishing gear (nets and ropes), tapes, carpets, and camping items. PVC fittings and pipe accessories are the major sources of PVC. The main sources of PET include food packaging, take-away food containers, and textiles [32–35]. In addition to the differentiation based on the chemical composition and density, microplastics can also be classified based on shape. Therefore, microplastics may be categorized into pellets, microbeads, foams, fibers, films, fragments, and microfibers [36].

Table 1. Categories of microplastics and their applications.

Category	Common Applications	References
Primary source	These include plastic pellets, exfoliator beads present in facial scrubs and cleansers, sparkles found in nail polish and make-up products, and plastics used in air-blasting technology.	[14–17]
Secondary source		
Water and wastewater treatment plants discharge	Microplastics smaller in size may go untrapped in the primary unit of the wastewater treatment plant and enter the secondary units. These include microfibers from washing clothes.	[12,37]
Wear and tear from normal plastic use	Examples include the washing of clothes and textiles during laundry, fishing activities, wear and tear of rubber tires of automobiles, and degradation of household items and plastic furniture.	[21–24]
Airborne dust	These include plastic dust released from activities such as plastic manufacturing, the incineration of plastic waste, traffic emissions, weathering of roads and streets, and urban mining activities. Indoor airborne microplastics come from plastic items used in household including food packaging, plastic wear, and plastic furnishings.	[38–41]
Secondary microplastics	The decomposition and weathering of macroplastics generate secondary microplastics. For example, the degradation of plastic litter such as disposable plastic cutlery, plastic cups, and food containers that end up being dumped on coastal shorelines.	[9]

3. Transport of Microplastics

In the environment, microplastics can be transported through atmospheric or aquatic currents depending on their weight and density [42]. Rainfall, surface runoff, and ocean circulation are the possible routes that transfer microplastics from the pedosphere to the hydrosphere. Not only can microplastics be transported from land to water, but they can also travel from water to land due to ocean circulation [43]. Moreover, lighter and smaller microplastics can be carried by the wind as airborne microplastics and consequently be transported to remote areas such as glacier zones and high mountains. While lighter microplastics can be relocated across the pedosphere by wind, denser microplastics might accumulate or be buried in the pedosphere (soil) [13]. Heavy rainfall and surface runoff from agricultural lands and urban areas can transport microplastics to surface waters (the hydrosphere). Studies have shown that agricultural practices involving the use of plastic mulches to improve crop growth or domestic sewage sludge as a soil amendment may introduce microplastics to the soil [44,45]. Additionally, stormwater runoff carries the microplastics resulting from the normal wear of tires on the road to neighboring surface waters [13]. Moreover, airborne microplastics consisting of light fibers from clothes, landfills, and waste incineration can be transported over long distances to remote areas and be deposited via atmospheric fallout [46,47]. Figure 1 shows a schematic of the global distribution of microplastics in the environment. The following subsections discuss the fate of microplastics in the different environmental compartments: the hydrosphere, pedosphere, and atmosphere.

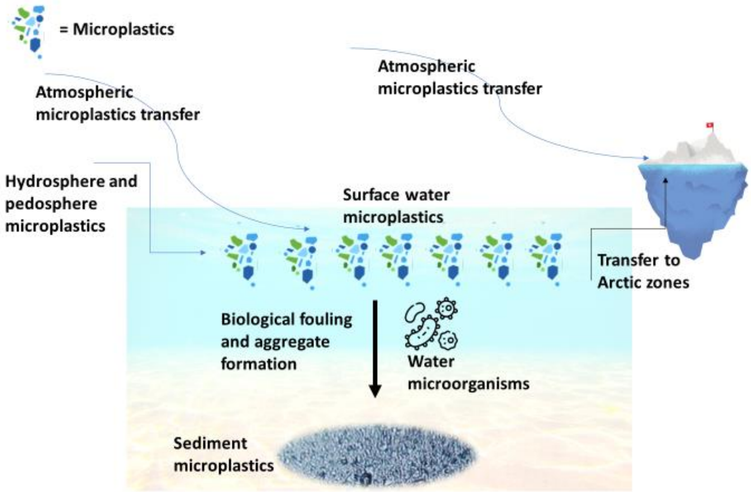

Figure 1. Microplastic distribution in the environment. The schematic represents the horizontal and vertical distribution of the microplastic in the hydrosphere. Water current and wind current result in the hydrosphere and atmospheric microplastic transfer, respectively, and result in microplastic transfer to remote areas such as Arctic zones.

3.1. Fate of Microplastics in the Hydrosphere

The hydrosphere is the primary sink for microplastics, where human activities such as tourism and wastewater treatment result in depositing microplastics in aquatic habitats [48]. For instance, seven million microplastic items are released every day into the aquatic habitat via wastewater treatment plant effluents [48,49]. Depending on the physical properties (e.g., shape and size), density, and chemical composition, microplastics can either accumulate in the hydrosphere (i.e., their immediate source of disposal) or travel to other remote environment areas such as glacial zones through various transport mechanisms [50–52]. Among the microplastics present in the hydrosphere, 70% of them are stored in the sediments of the aquatic body, and approximately 15% of microplastics remain in the suspended form [28]. The mechanisms for the fate and distribution of microplastics in the hydrosphere are not well-defined due to the degree of variation in the different plastic degradation pathways as well as the water dynamics such as ocean currents and wind currents, the velocities and intensities of which depend on climatic conditions. However, two probable pathways for microplastic distribution in the hydrosphere have been proposed: horizontal and vertical distributions.

Horizontal distribution is governed by water circulation velocity, precipitation, and wind current, which determine the transport of plastic litter from the pedosphere into the hydrosphere [53–55]. Upon entering the aquatic environment, plastic litter is exposed to ocean current abrasion, abiotic disintegration, or biotic degradation. Microplastics of different shapes, sizes, densities, and chemical compositions are formed, and those having a density greater than the surrounding water will sink to the bottom of the aquatic system, whereas the lighter ones can remain suspended in the surface water [32]. The diameter of the microplastics affects its transport under different water dynamics, which determines the horizontal distribution of the microplastic. For example, the river bed slope in the Rhine river resulted in the transport of microplastics over longer distances due to the increased velocity as the result of the river bed slope [56]. The water conditions such as river bed form, the flow velocity of sea, river, ocean and other water bodies, water level, and water current impacts the transport of microplastics in the hydrosphere. In the case of rivers, dam and reservoir constructions can affect the water velocity and impact the fate of microplastics [57]. Based on the velocity and flow direction of the regional wind and water currents, the suspended microplastics can either return to the coastal shorelines/beaches or be transported to remote regions [12,48,58], and the microplastics will remain suspended at the water surface. As per data from 2010, approximately 5–13 million tons of macroplastics enter the hydrosphere (ocean) [3], and 7–35 thousand tons of microplastics remained in suspended form [59].

Another distribution pathway is vertical distribution, where heavier microplastics sink to the water bed including seabeds, riverbeds, and ocean beds. Vertical distribution in the hydrosphere includes vertical turbulent mixing, which is governed by the water velocity and flow of direction; biota transfer, which depends on the movement of aquatic organisms; biological fouling and aggregate/cluster formation, which is governed by the presence of organisms present in the hydrosphere including microorganisms, bacteria, plankton, and algae [32,60,61]. Biological fouling and aggregate formation are affected by a number of factors such as microplastic characteristics (type, chemical composition, surface morphology) as well as hydrosphere characteristics (temperature, pH, types of microbes present) [62–65]. For example, in the Arabian Gulf, the surfaces of PET and PE microplastics underwent biofouling as a result of the presence of different microbes and plankton [66]. The process of biological fouling mainly comprises three steps: first, the microbes and nutrients present in the hydrosphere attach to the microplastic's surface [67]; subsequently, extracellular polymeric substances are released by the microorganisms to form a biofilm that further attracts other marine invertebrates and aquatic life; second, the attached microbes release extracellular polymeric substances (EPS) to further attract more microbes and nutrients [68]; finally, a clustered mass of microplastics with flocculant and nutrients eventually becomes denser and sinks to the bottom.

Table 2 summarizes the studies on the occurrence and identification of microplastics in the hydrosphere including sediment, deep-sea [69,70], shorelines [71], freshwater, river [72], oceans [42,73], and coral reefs [74]. The deep-sea has been termed a global sink for microplastics, as evidenced by the first experimentally-based study conducted by Woodall et al. [69]. The vertical distribution of microplastics results in the accumulation of microplastics in the sea sediments, and a study conducted by Van Cauwenberghe [75] suggested deep-sea sediments as the hot spot for microplastic accumulation. Other studies have reported microplastics in the sediments in the range of 8 pieces/kg to 600,000 pieces/kg sediment [76,77]. Another potential sink of microplastics in the hydrosphere is coral reefs. An area of ~250,000 km^2 has been shown to assimilate microplastics at the annual rate of 1.5 ± 1.9 % from surrounding waters during their growth [74].

Table 2. Occurrence of microplastics (MPs) in the hydrosphere.

Location	Sink Type	Sample Collection	Analysis	Result Summary	Reference
Mediterranean Sea, South West Indian Ocean, and North East Atlantic Ocean.	Deep sea sediments	12 sediment cores and 4 coral samples were sampled	MPs were extracted by sequential extraction using sodium chloride solution. The MPs were characterized using FTIR.	All samples contained MPs. Characteristics of MP: diameter <0.1 mm, and fiber shaped.	[69]
Sandy beaches of Australia, Oman, Chile, USA, Philippines, Portugal, Azores, Mozambique, and the United Kingdom.	Shoreline	Shoreline sediments were sampled up to a depth of 1 cm.	MPs were extracted using sodium chloride solution followed by filtration. The MPs were characterized using FTIR.	MPs concentration of 8–124 MPs per 1000 mL of the sediment was quantified. These included PS, PP, PE, acrylic, and polyamide fibers.	[71]

Table 2. *Cont.*

Location	Sink Type	Sample Collection	Analysis	Result Summary	Reference
Southern Ocean, North Atlantic Ocean, Gulf of Guinea, and Mediterranean Sea.	Deep-sea sediments	Sediment samples were sampled up to a depth of 1.2–4.8 km.	MPs were extracted using wet sieves, followed by density floatation using sodium iodide solution. MPs were characterized using micro-Raman spectroscopy.	MPs of size 75–160 microns were found in the samples.	[75]
Irish continental shelf	Marine sediments	Sediment box cores were collected from 11 sites up to a depth of 4.5 cm.	MPs were extracted by density flotation using sodium poly tungstate. MPs were characterized using FTIR.	62 MPs were recovered from 10 stations out of 11.	[70]
Western North Atlantic Ocean and Caribbean Sea	Regional water gyre	6100 surface plankton net tows were sampled.	MPs were handpicked. The characterization method was not mentioned.	MPs were identified in the ocean gyre.	[42]
Laboratory experiment	Coral reefs	4 reef-building coral species were exposed to PE (200 particles/L). Research duration-18 months.	MPs were extracted from the coral reefs using sodium hypochlorite. MPs were characterized using a microscope and FTIR.	Coral reefs can trap MP in their tissue as well as the skeleton.	[74]
Northeast Pacific ocean	Surface water	Zooplankton samples collected from the surface water (n = 595).	MPs were sieved and handpicked. They were characterized using a microscope and FTIR.	MPs were identified in all the samples.	[77]

3.2. Fate of Microplastics in the Pedosphere

In the literature, most of the research as focused on the hydrosphere as a sink for microplastics, and very few studies have discussed the role of the pedosphere as a potential sink for microplastics. For example, a European farm was reported to be able to deposit an average of 50,000 tons of microplastics annually [44,78]. In light of such a finding, the destructive impact of microplastics on soil organisms (both flora and fauna) should be further investigated. There are two potential sources of microplastics contaminating the pedosphere: domestic and agricultural activities. Domestic activities such as tourism result in the disposal of plastic products and single-use plastics that accumulate on land as plastic litter. As per the data, the plastic litter predominantly consists of at least 90 million daily grocery bags [79], which end up as mismanaged plastic waste. Once exposed to the environment, plastic litter undergoes deterioration and releases microplastics into the soil. It has been estimated that around 300 million tons of microplastics are present in the soil [80]. Another potential source of microplastics in the pedosphere relates to agricultural activities such as the application of polymer-coated fertilizers, slow-release fertilizers, composting, organic fertilizers, plastic mulches (made up of polyethylene), and irrigation water containing microplastics (usually synthetic fiber) [13,81–86]. Liu et al. [87] reported that over two decades, the concentration of wasted plastic mulch in China's agricultural field has increased by four times (up to 1.2 million tons). Plastic mulch and other fertilizers added to the soil undergoes numerous weathering processes, thus releasing MPs in the soil [83]. Browne et al. [71] found that the composition of the synthetic fiber in the wastewater consisted of polyester (67%) and acrylic (17%), which was similar to the composition of textiles, which implies that the main source of microplastics in the wastewater was from washing clothes. Sewage sludge is treated by anaerobic digestion and aerobic composting and the sludge-fertilizer thus formed is applied to the soil [88]. These microplastic-contaminated sludge fertilizers introduce MPs into the pedosphere [89]. For example, Zhang et al. [90] reported that the utilization of sludge-based fertilizer resulted in an increase in the microplastic concentration in the soil by approximately 60 times. Agricultural runoffs tend to transport the microplastics to nearby water bodies, but a portion of the microplastics can be entrapped in the soil.

The fate and transport of microplastics in the soil are not well-reported. The movement of MPs in the soil is complex and is primarily governed by bioturbation (i.e., the transfer of microplastics from the surface soil into deeper layers) (Figure 2) [91]. Bioturbation is mediated by soil fauna such as earthworms, soil larvae, and vertebrates (e.g., moles, mice, snakes, and rabbits). These soil faunae can mediate soil vertical mixing via burrowing actions (mimicking a mechanical mechanism) or by ingesting the microplastics and translocating them into deeper soils while moving downward [91,92]. Several experimental studies show the transport of microplastics in the soil via bioturbation. For example, Zhu et al. [93] reported that the scraping and chewing actions of mites and collembola on plastics resulted in the migration and transport of MPs in the soil. Earthworms result in the migration of MPs both by external attachment as well as an internal attachment (via ingestions and excretion), thus facilitating the lateral and vertical transport of MPs in the soil [92,94]. Other routes of MP transport in the soil include root movement and expansion [91,95], tillage activities [96], and the harvest of tuber crops such as potatoes and carrots. The downward movement of microplastics would also be influenced by several parameters including the wetting–drying cycle, soil pore space, soil type, moisture content, precipitation, temperature, and leaching [97,98]. The shape, size, and composition of the microplastics also determine their transport in the soil. Certain microplastics such as polystyrene can form aggregates with soil under the influence of soil organic carbon, pH, and the cation exchange capacity of the soil [99,100]. However, more research is needed to gain deeper insights into the influence of soil properties and external factors on the migration of MPs in the soil.

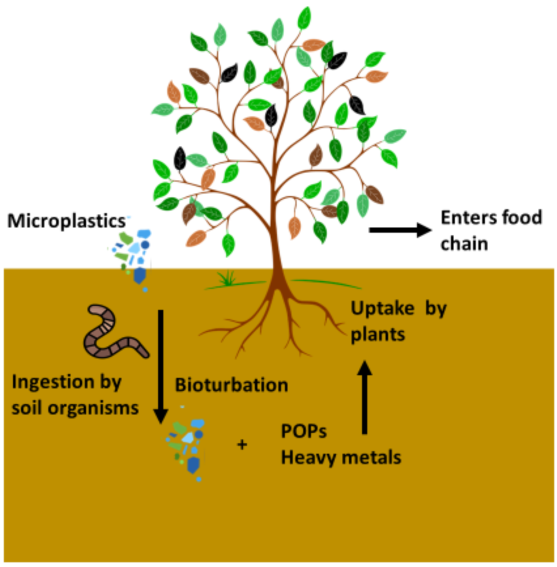

Figure 2. Microplastic transport in the soil. Bioturbation and ingestion by soil organisms are the main routes for microplastic transfer into deeper soil layers. As a consequence, microplastics interact with the POPs and heavy metals present in the soil, which can be bioavailable to plants.

Table 3 summarizes the field monitoring work on the occurrence of microplastics in the soil matrix. Zhou et al. [101] investigated the distribution of microplastics in the coastal shorelines of Bohai Sea and Yellow Sea of China. Various types of microplastics were found in the sampled soil including PE, PP, and PS with an average concentration of 7350 MP/kg. Zhang and Liu [96] conducted a study on the vegetable farmlands and riparian forest zone around Dian Lake, China, and found microplastics in the soil aggregate fractions with an average concentration of 18,760 MP/kg. Corradini et al. [102] investigated microplastic contamination in agricultural fields in Chile and found that the microplastic concentration in the soil increased with the increasing rate of the application of sludge-based fertilizer. In the suburbs of Shanghai, microplastics were detected in the soils of the rice–fish co-culture ecosystem (8.1–12.5 MP/kg) and vegetable farmlands (65.1–90.9 MP/kg) [103,104].

Table 3. Occurrence of microplastics (MPs) in the pedosphere.

Location	Sink Type	Sample Collection	Analysis	Result Summary	Reference
Bohai Sea and the Yellow Sea coastlines, Shandong Province, East China.	Coastal beach soils	Soil samples (n = 120) were sampled from 53 sites along the coastline (~3000 km).	MPs were extracted by density separation using sodium chloride and sodium iodide solution. The MPs were characterized using stereomicroscope, SEM, and ATR-FTIR.	MPs of size <5 mm were found in all samples in the range of 1.3–14,712.5 MP/kg soil. These included PE, PP, and PS.	[101]
Vegetable farmlands and riparian forest zone around Dian Lake, Yunnan, China	Greenhouse soil and forest zone soil	Soil samples were collected (n = 50).	MPs were extracted using sodium iodide solution followed by hydrogen peroxide. The MPs were characterized using a stereomicroscope.	MPs were identified in the range of 7100 to 42,960 MP/kg. The size of 95% of the sampled MP is in the range of 1–0.05 mm. These predominantly included plastic fibers.	[96]
Agricultural fields (n = 31) in Chile where sludge-based fertilizers were applied.	Agricultural soil	Top soil (0–25 cm) was sampled from each agricultural field.	MPs were extracted by density separation using sodium chloride and zinc chloride. MPs were characterized by stereomicroscope.	MPs of size 0.16–10 mm were found in the samples. These predominantly included fibers (>97%).	[102]
Vegetable farmland, Shanghai, China.	Vegetable soil	Soil samples (n = 3) were collected from shallow (0–3 cm) and deep soils (3–6 cm).	MPs were extracted using sodium chloride solution followed by hydrogen peroxide. MPs were characterized using a stereomicroscope and µFTIR.	MPs of size 20 microns–5 mm were found in the samples. These predominantly included fibers, fragments, film, and pellets.	[103]
Shanghai, China.	Soil from rice–fish co-culture ecosystem	1 kg of wet soil was collected from each site (n = 3).	MPs were extracted using sodium chloride solution followed by hydrogen peroxide. MPs were characterized using a stereomicroscope and µFTIR.	MPs of size <5 mm were found in the samples. These predominantly included fibers, fragments, film, and granules.	[104]

3.3. Fate of Microplastic in the Atmosphere

Since the hydrosphere and pedosphere are possible sinks for microplastics, attention has been extended to exploring the transport pathways from the origins to the ultimate sink for microplastics. Thus, the microplastics in the atmosphere become an issue of interest [105,106]. Microplastics with a small size and low density can be suspended in the wind current and transported over a long distance [107]. It has been reported that airborne microplastics, also known as atmospheric microplastic particles, can be transported from ocean surfaces in low-latitude zones to remote areas including the Arctic zones [43,108–111]. The available studies on atmospheric microplastics are limited and do not provide a clear understanding of the fate and distribution of microplastics in the atmosphere because most of the studies have been short-term monitoring works. For example, Dris et al. [46] and Klein and Fischer [110] conducted experiments to identify and characterize microplastics in the atmosphere over 12 months. Therefore, long-term monitoring works on atmospheric microplastics are deemed necessary.

Atmospheric microplastics are considered a category of emerging contaminants given the rising concern that the inhalation of microplastics can be detrimental to human health [112–116]. During the outbreak of the COVID-19 pandemic, surgical masks were worn, which became a new source of microplastics. These masks, which were composed of PP, PE, and PS, presented a direct route of inhalation that reaches the human lungs [11,117,118].

The distribution and transport of atmospheric microplastics are governed by the wind current speed and directions, up/down drafts, convection lift, and turbulence. They affect the transport and fate of microplastics between the various environmental compartments—the hydrosphere, pedosphere, and atmosphere [105,111]. Atmospheric microplastics can travel to remote areas and be deposited through the precipitation of rain and snow. Since rain and snow precipitation are two probable pathways for atmospheric microplastic deposition, more research is needed to understand the impact of rainfall/snowfall events and draw correlations between microplastic deposition and climatic conditions. Microplastics have reached remote areas including Arctic Sea Ice (38–234 particles per cubic meter) [52], Fram Strait [119], the Italian Alps (Forni Glacier, 74.4 $\pm$ 28.3 particles per kilogram of sediment) [109] as well as the Vatnajökull ice cap in Iceland [120]. In the Arctic zones, snowfall is one of the primary methods of atmospheric deposition for microplastics. The mechanism of microplastic entrainment in glacier ice has been proposed by Van Sebille et al. [121], who indicated that microplastic scavenging might occur during the ice formation process. Ice crystals are formed that cover the surface of the sea. Subsequently, continuous agglomeration of thick ice crystals occurs, resulting in the storing of more microplastics in deeper layers of the ice crystals.

Table 4 summarizes the available literature on atmospheric microplastics. Strong wind and rainfall events resulted in the deposition of atmospheric microplastics in the urban cities of Paris and Hamburg, where ~120 MP/m^2 and 275 MP/m^2, respectively, are deposited daily [110,122]. Cai et al. [47] reported the deposition of atmospheric microplastics in the city of Dongguan, China, which comprised both non-fibers and fibers (mean 244 MP/m^2 daily). Atmospheric deposition was found to be higher in coastal areas where wind currents are stronger (e.g., in Yantai, a coastal city in China), and an atmospheric microplastic deposition of 602 MP/m^2 per day was reported [123]. In remote areas, atmospheric deposition can be lower compared to the microplastic source because there is a possibility of microplastics being deposited during long-distance transport. In the Pyrenees Mountains, an average microplastic particle deposition of 365 MP/m^2 per day has been reported [108]. Higher atmospheric microplastic deposition can be correlated to higher human activities. For instance, Shanghai has a higher population density and industrialization compared to Paris. Liu et al. [109] reported that Shanghai experienced a greater atmospheric microplastic deposition of 4.18 MP/m^3 whereas Paris experienced an atmospheric microplastic deposition of 2.84 MP/m^3.

Table 4. Occurrence of microplastics (MPs) in the atmosphere.

Location	Sample Type	Analysis	Result Summary	Reference
Paris, France	Atmospheric fallout	A stainless-steel funnel was used for the continuous sampling of microplastics. Samples were then filtered. The MPs were characterized using a stereomicroscope and μFTIR.	MPs of various sizes were found in the samples (predominantly 200–600 μm (42%) and 600–1400 μm (40%)). Atmospheric microplastic deposition of 120 MP/m^2 per day. These included fibers.	[46]

Table 4. *Cont.*

Location	Sample Type	Analysis	Result Summary	Reference
Shanghai, China	Suspended atmospheric microplastics	A suspended particulate sampler was used to collect the samples. MPs were characterized using a stereomicroscope and μFTIR.	MPs were identified to have a maximum deposition rate of 4.18 MP/m^3. The size of more than 50% of the sampled MP is in the range of 23–500 μm. These predominantly included PET, PE, and rayon.	[111]
Pyrenees Mountains, Europe.	Atmospheric dry and wet deposition	MPs were characterized using a stereomicroscope and μRaman.	Average microplastic particle deposition of 365 MP/m^2 per day. These predominantly included PS, PE, PP, PVC, and PET.	[108]
Yantai, China.	Atmospheric deposition	MPs were characterized using a stereomicroscope and μFTIR.	MPs of size 100–300 μm were found in the samples. Atmospheric microplastic deposition of 602 MP/m^2 per day. These predominantly included fibers.	[123]
Dongguan city, China.	Indoor and outdoor dust	MPs were characterized using a stereomicroscope and μFTIR.	Atmospheric microplastic deposition of 244 MP/m^2 per day. These predominantly included PP, PE, and PS.	[47]
Hamburg, Germany.	Atmospheric fallout	MPs were characterized using μRaman.	Atmospheric microplastic deposition of 275 MP/m^2 per day. These included predominantly PE.	[110]

4. Impacts: Implications on the Soil, Water, and Biological Communities

This section reviews the impact of microplastics present in the hydrosphere and pedosphere on aquatic organisms and soil organisms. Atmospheric microplastics eventually enter the hydrosphere or pedosphere upon deposition, therefore, the impact of atmospheric microplastics is not discussed separately.

4.1. Ecotoxicological Impact on Aquatic Biota

Microplastics are considered emerging contaminants due to their ecotoxicological impact on aquatic biota. Because of their small size, microplastics can be readily taken up by aquatic organisms including fishes, invertebrates as well as coastal birds and animals [124]. Many studies have been conducted on fish to understand the fate of bioavailable microplastics in aquatic organisms. Table 5 lists several studies exploring the effect of microplastic ingestion on aquatic organisms. Studies on fish such as European Bass, Goldfish, Fathead minnow, and Japanese medaka have confirmed the presence of microplastics (such as PS, PVC, and PE) in their organ tissues [125,126]. In addition to fish, microplastics were also detected in springtails, shrimps, and oysters [127–129]. The ecotoxicity of microplastics impacts the health of the exposed aquatic organisms in different pathways including a reduction in growth, dysfunction of the reproductive system, and influence on the egg's hatching [130,131], causing physical, chemical, and biological damage to aquatic organisms. Examples of physical damage include damage to the gastrointestinal tract, which can lead to the organism's death and affect the mortality rate [132–134]. Chemical damage includes the impact on the enzyme activities in organisms. For example, in the presence of PE and heavy metal chromium (Cr), the uptake of Cr in Common Goby fish increased, which led to a decrease in acetylcholinesterase (AchE) enzyme activity and resulted in acute toxicity [135]. Examples of biological damage include gene manipulation and the development of resistance genes for antibiotics and heavy metals [136]. Microplastics enter the food chain and result in biomagnification where the microplastics are initially ingested by primary consumers (e.g., small fishes, algae), and eventually reach the secondary consumers (e.g., larger fishes and birds), ultimately reaching the tertiary consumers (humans). As a result, microplastics translocate through the food chain and disrupt it [137]. Microplastics may also act as vector carriers for heavy metals and environmental pollutants. They can adsorb these pollutants and mediate their transfer into the environment, thus exposing aquatic organisms to these pollutants [138]. For example, PE microplastics have been shown to interact with co-pollutants such as zinc oxide, resulting in increased microalgal growth in the marine environment [139]. Microplastics are also found in larger aquatic biotas such as whales [140], seals [141], sea urchins [142], walruses [143], and turtles [144].

Table 5. Impact of microplastics on aquatic biota.

Organism	Aquatic Biota type	Type of MP	Impact	Reference
Dunaliella salina	Marine microalgae	PE	MPs interact with zinc oxide and leach the pollutant, thus making it unavailable for the microalgae. This resulted in enhanced microalgal growth.	[139]
Common goby (*Pomatoschistus microps*)	Fish	PE	The presence of microplastics along with heavy metal chromium (Cr) resulted in a decrease in acetylcholinesterase (AchE) activity.	[135]
Japanese medaka (*Oryzias latipes*)	Fish	PE	Disruption of the normal functioning of the endocrine system.	[145]
European sea bass (*Dicentrarchus labrax*)	Fish	PVC	Intestinal damage.	[146]
European sea bass (*Dicentrarchus labrax*) larvae	Fish	PE	Injuries and ulceration in the intestines.	[147]
Goldfish (*Carassius auratus*)	Fish	PS, PE	MPs were detected in the digestive tract.	[125]
Fathead minnow (*Pimephales promela*)	Fish	PS	MPs suppress the immunity of fish.	[126]
Marine copepod (*Tigriopus japonicus*)	Invertebrate	PP	MP ingestion and reduction in their fecundity.	[127]
Insects (*Trichoptera*, *Plecoptera*, and *Coleoptera*)	Invertebrate	Polyester	MP accumulation in the invertebrates.	[133]
Gammaridae, *Asellidae*, *Tubificidae*, and *Chironomidae*	Invertebrate	PE, PP, PVC, and others	MP accumulation in the gut.	[134]
Shrimps (*Metapenaeus monoceros*, *Parapeneopsis stylifera*, and *Penaeus indicus*)	Invertebrate	PP, PE, polyamide, nylon, polyester, and PET	MPs were detected in the gastrointestinal tract and gut.	[128]
Oysters (*Ostrea edulis*)	Invertebrate	HDPE	Ingestion of HDPE resulted in greater respiration rates in oysters, affecting the mortality rate.	[129]

Table 5. *Cont.*

Organism	Aquatic Biota type	Type of MP	Impact	Reference
Sea urchins	Invertebrate	PE	MP ingestion detected.	[142]
Humpback whale (*Megaptera novaeangliae*)	Mammals	PE, PP, PVC, PET, nylon	Microplastics accumulated in the gastrointestinal tract.	[140]
Green turtle (*Chelonia mydas*)	Reptile	PS, PE	The presence of microplastics in the beach sand resulted in disruption of the nesting ground for turtles and a delay in egg hatching.	[144]
Walrus (*Odobenus rosmarus*)	Animal	PE, PP, polyamide, polyester, acrylic	MP detection in the walrus feces.	[143]
Fur Seals (*Arctocephalus australis*)	Animal	Microfibers (type of MP not determined)	MPs were detected in the seal feces.	[141]

4.2. Ecotoxicological Impact on Soil Biota

Microplastics can act as carriers for environmental contaminants such as persistent organic pollutants (POPs) [148]. POPs are present in wastewater effluents, urban runoffs, and leachates from landfill. POPs that are commonly present in agricultural soil include polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), pesticides, and herbicides [149]. Microplastics can absorb and transfer the POPs and pose a threat to the pedosphere biota. In a study by Bakir et al. [150], the interaction between PVC, PE, and various POPs were investigated, showing that a plastic–POP mixture poses a considerable environmental threat. As previously mentioned, microplastics can absorb heavy metals on their surface. If the soil environment is contaminated with heavy metals, microplastics may act as vector carriers for the heavy metals and mediate their transfer into the deeper soil layers or make it available to the plants for uptake after their entrance to the soil media [151]. The interaction between heavy metal and microplastics is governed by their chemical and physical characteristics such as specific surface area and molecular polarity [152]. Microplastic accumulation in soil has a detrimental effect on the animals residing in the pedosphere. Microplastics are not readily digested by animals and it is difficult for them to pass the undigested microplastics through their gut, thus leading to microplastic accumulation in the animals' bodies [153–156]. For example, mice residing in soil contaminated with PS exhibited intestinal damage and reduced metabolic rate [157]. However, smaller organisms such as earthworms can digest microplastics, but microplastics might damage their intestinal tract and impact their survival [93,158]. Table 6 lists the recent studies on the effects of microplastics on the soil biota. The summarized results show that the predominant ecotoxicological effect of microplastics on the soil biota includes growth and reproduction inhibition, damage to the gut lining, an increase in mortality rate, damage to enzyme activities, and decreased immune responses [45,103,159]. Microplastics also have detrimental effects on plants. For example, wheat and spring onions showed reduced root and shoot biomass when growing in soil contaminated with LDPE, PS, HDPE, PP, and PET [160,161]. More research is needed to understand the role of microplastics on soil biota.

Table 6. Impact of microplastics on the soil biota.

Organism	Soil Biota Type	Type of MP	Impact	Reference
Wheat (*Triticum aestivum* L.)	Plant	LDPE	Adverse impact on plant biomass, thus affecting vegetative and reproductive growth.	[161]

Table 6. *Cont.*

Organism	Soil Biota Type	Type of MP	Impact	Reference
Spring onion (*Allium fistulosu*)	Plant	PS, HDPE, PP, PET	Changes in the leaf traits and plant biomass.	[160]
Mice	Residing animals	PS	Reduced metabolic rate. Intestinal damage.	[157]
Terrestrial snail (*Achatina fulica*)	Residing animals	PET	Liver damage and misfunctioning of liver enzymes. Disruption of digestion.	[155]
Soil nematode (*Caenorhabditis elegans*)	Worms like animals	PS	Disruption of motion and reproduction. Growth disruption.	[132]
Soil springtail (*Folsomia candida*)	Worms like animals	PE	Decrease in reproduction rate. Damage to gut microbes.	[153]
Soil springtail (*Lobella sokamensis*)	Worms like animals	PE, PS	Locomotion disruption.	[154]
Earthworm (*Eisenia fetida*)	Worm	LDPE, PS	Increase in enzyme activities including catalase and peroxidase.	[27]
Earthworm (*Enchy-traeuscrypticus*)	Worm	PS	Decrease in body mass and damage to the intestinal gut lining.	[93]
Earthworm (*Eisenia andrei Bouché*)	Worm	PE	Reduced immune response. Gut damage.	[45]

5. Prospective Future Research Directions and Plastic Waste Management Strategies

Microplastics are regarded as a category of emerging contaminants and pose an ecotoxicological threat to aquatic, soil, and atmospheric ecosystems. In this review, the fate and distribution of microplastics in the major environmental compartments (i.e., the hydrosphere, pedosphere, and atmosphere) were discussed. While atmospheric microplastics can be transported over a long distance via the wind current and are eventually deposited into the hydrosphere or pedosphere, the ecotoxicological effects of microplastics in the aquatic and soil habitat were summarized. Based on the discussion in the manuscript, perspectives on future research directions and plastic waste management strategies are outlined. (a) Currently, most of the microplastic research focuses on the aquatic environment. However, the microplastic distribution and accumulation in the pedosphere and atmosphere remain to be explored. The pedosphere as well as the atmosphere are involved in the microplastic source–sink dynamics, therefore, future research could focus on these environmental compartments including large-scale monitoring and quantification. (b) Only limited studies have been conducted to monitor soil data to understand the distribution of microplastics in the pedosphere or atmosphere. The data relating to the transfer of microplastics through the deeper soil layers or the atmosphere are not as extensive as those available for the hydrosphere. Therefore, an attempt could be made to fill in this gap to enhance the understanding regarding the movement of microplastics in the environment. (c) As previously mentioned, microplastics may act as vector carriers for other contaminants (e.g., POPs and heavy metals). There is a knowledge gap on the adsorption and desorption mechanism of these contaminants onto the microplastics, which need to be further investigated. (d) From the investigations reviewed in this manuscript, the microplastic extraction and analytical techniques primarily consisted of initial microplastic separation, followed by digestion and characterization using microscopic images or FTIR. Aquatic, soil, and atmospheric microplastics are being collected from different environment matrices. The microplastic extraction and analytical techniques should be standardized for the different environmental scenarios to characterize the microplastics qualitatively and quantitatively. It may not be scientific enough to use the same detection and characterization protocols for the microplastics extracted from these three diverse environmental zones.

(e) The ecotoxicological impact of microplastics on the soil biota, especially earthworms, has been well-reported and studied. However, only limited papers have discussed the impact on plant species. Since microplastics can be bioavailable for plant uptake, they can also carry certain contaminants. Therefore, it is important to study the effect resulting from microplastics on plant performance. (f) The impact of microplastics on tertiary consumers such as soil animals (e.g., poultry and rabbits) is missing. Since these animals can be a source of food for humans, it is important to conduct field studies to examine the accumulation of microplastics in soil animals. (g) The atmospheric transport of microplastics plays an important role in the transport of microplastics in the environment. However, the transport mechanism of microplastics within the air is not well-studied, nor is it known to what extent atmospheric microplastic deposition results in aquatic or soil contamination. Therefore, further research is needed to fill this gap in source–pathway–sink processes. Since atmospheric microplastics can be deposited via snowfall in the glaciers where they can be stored, studies should be implemented to measure the atmospheric microplastic flux to quantify its contributions to the glaciers' sink.

Having outlined the prospective future directions on microplastics, we hereby discuss different strategies for plastic waste management to control microplastic pollution. Government plays an important role in reducing microplastic pollution and to promote sustainable plastic waste management. Here are a few actions that can be taken at the government level. (a) Identify the responsibilities of different states and municipal corporations in the production, use, recycling, and disposal of plastic wastes, and implement corrective measures such as environmental taxes for sectors generating plastic pollution. (b) Raise the public awareness of microplastic pollution and its impact through education and workshops. This includes creating a nexus of collaborations between environmental protection organizations, non-governmental organizations, and scientists to initiate public participation. (c) Limit the flow of plastics wherever possible such as reducing/prohibiting the use of single-use plastics. (d) Collaborate with researchers to understand where plastic pollution can be prevented early in the life span of plastic production. For example, improved microplastic removal processes in wastewater and sewage treatment will help reduce the amount of microplastics from entering aquatic and terrestrial habitats. (e) Limit the use of microplastic-contaminated wastewater for irrigating agricultural soils and develop a protocol to monitor the usage of sludge-based fertilizers. (f) Promote the use of biodegradable plastics such as polyhydroxyalkanoates (PHA) and poly(lactic) acid (PLA) that can be derived from microorganisms and microalgae [162] or natural fibers rich in polysaccharides, lipids, and proteins [2]. In summary, controlling the microplastic release at the source is necessary to prevent aquatic and soil biota exposure to microplastics.

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