Microplastics in our Environment: Impacts and Solutions – Review

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Review on invasion of microplastic in our ecosystem and implications

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Abstract

Today the world is going through the "Plastic Age." Nowadays, it is difficult to find a commonly used convenient item that is nonplastic. Plastic production and consumption, thus, increased exponentially and plastic emerged as one of the major concerns for waste management. Recent studies confirmed a faster rate of plastic degradation than previously believed under various conditions (e.g. saltwater, UV, soil interaction) that microplastic has become a new type of health-hazardous pollution source. Much research has been conducted since the discovery of the "Pacific Garbage Patch," and the scope has expanded from marine to soil, groundwater, air, and food chain. This article underwent a substantial amount of literature review to verify the degree of microplastic pollution progression in major pillars of the environment (aqueous, terrestrial, airborne, bio-organism, and human). Multiple kinds of literature indicated a high possibility of vigorous interaction among the pillars that microplastic is not stationary at the point of contamination but travels across the nation (transboundary) and medium (transmedium). Thus, only the waste reduction policy (i.e. production and consumption reduction) would be effective through a single national or local effort, while pollution and contamination management require more of a collective, if not global, approach. For these characteristics, this article proposes two most urgently required actions to combat microplastic pollution: (a) global acknowledgement of microplastic as transboundary and transmedium pollution source that require international collective action and (b) standardization of microplastic related research including basic definition and experimental specification to secure global comparativeness among data analysis. Without resolving these two issues, it could be very difficult to obtain an accurate global status mapping of microplastic pollution to design effective and efficient global microplastic pollution management policies.

Keywords

Microplastic pollution, soil, marine, air, food chain, groundwater

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Introduction

Since the commercialization of plastic materials to replace animal-derived materials such as elephants' ivory or tortoiseshell in 1862,[1] plastic penetrated every corner of modern life. Owing to its cheap and easy mass production capability than conventional materials (e.g. paper, glass, and metals), plastic products have created a "single-use culture." Fueled by the post-World War modern fast-moving lifestyle, it now is impossible to spend a day without using plastic of some kind. The outbreak of COVID-19 further expanded the use of plastic to "sanitation and safety."[2] The world now faces a new type of daily "safety measure" waste (i.e. personal protective equipment, test kits, vaccine syringes, and single-use cutlery) in addition to the conventional high volume of plastic waste traded for its convenience, low-cost, durability, unbreakable, heat resistance, and lightweight.

Due to the traditional belief around the "durability" of plastics, the major issues focused on how to secure enough landfill space to address rapidly increasing plastic wastes and how to capture illegally dumped plastic products in the early years. The agenda, however, got stirred with the discovery of the "Pacific Garbage Patch," also known as the Pacific Trash Vortex, in 1997 by Charles Moore on his sailing way back to California from Hawaii.[3] Unlike traditionally imagined plastic trash floating on the ocean surface or sunk in deep-sea sediments, the Garbage Patch revealed a "cloudy soupy zone in the middle of the Pacific Ocean" made of tiny bits of plastics, now termed microplastic.[4] As microplastic pollution gained research interest among academia, the scope of studies assessing the spread and impacts of microplastic also expanded from marine environment to fresh-to-groundwater, terrestrial habitats, and air. Reinforced by enhanced public awareness and international pressure, it also took less than a decade for many governments to adopt a microplastic reduction policy stance.[2]

The research, however, lacked time to fully ripe in depth that the state of global knowledge on microplastic is rather fragmentary and sparse than interdisciplinary and comprehensive.[5] Although any research is meaningful for its own purpose, it would be even better if each puzzle piece can collectively contribute toward a global knowledge map on microplastic. This paper, thus, attempts to review the nature of microplastic pollution progress observed and analyzed in various environmental fields (marine, soil, groundwater, air, and food chain) to deduce possible policy implications to best support research advancement in this newly emerged environmental challenge of this "Plastic Age."

Invasion of microplastic pollution in the ecosystem

Marine environment

The most common types of plastics found in marine environments are polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC).[6,7] There are two main processes, through which microplastics reach the marine environment. First, large plastics naturally degrade into microplastics in the marine environment, and second, the microplastics flow into seawater through rivers and other water cycles from the land.[6,8] The major source of large plastics in the marine environment is the fishery industry: fishing nets contributes approximately 640 thousand tons (10% of total marine wastes).[9] These fishing nets undergo biodegradation, photodegradation, or hydrolysis into microplastic less than 5 mm.[6,10,11]

Yet, beach waste is the largest contributor to marine microplastic pollution through plastic degradation.[12] This is because the low water temperature of saltwater slows the degradation process that the microplastic formation rate is lower in the far deep ocean. Contrarily, beach sand temperature rise up to 40 °C creating a faster photodegradation for plastic bottles dumped on the shore rather than floating in the Pacific Ocean.[6,12,13] Microplastics that reach the ocean floor from land usually are comprised of the wash-off of personal products, fabric from laundry, and particles from vehicle tires.[14] This finding matches the analysis result on marine microplastics collected from Playa Grande Beach, Canary Islands of Spain in 2020 to have comprised of PP and PE in the form of microplastic fragments, pellets, fiber and films.[13,15] As the gravity of marine plastic pollution was only revealed in 1997 with Pacific Garbage Patch, the history of marine microplastic pollution research is not very long. Old observation records on plastics of a few millimeters in size both on the ocean surface and inside of many saltwater fishes on the East Coast of the United States and the Southern part of the United Kingdom went unnoticed for almost 30 years.[16–18] It was Thompson's article published in Science in 2004 that first introduced the term, "microplastic,"[19] and triggered much research efforts in related fields.

Promisingly, the scope of marine microplastic research has been expanded to marine ecological microorganisms and food chains. Animals exposed to microplastic-concentrated water has been found to produce unhealthy egg and sperms, which resulted in 41% fewer larvae than the animals in clean water.[8] The Pacific Krill (Euphasea Pacifica) was observed to ingest its staple algae, as well as PE beads, ground to about the same size range with no evident foraging bias.[20] This infers a possibility of microplastic invasion into the food chain as krill, whether it is ingested via algae or plastic beads, is favored diet by predators and seagulls nearby. Some researchers further introduced the concept of "secondary nanoplastics" resulting from the biodegradation of microplastic through digestion and food chain accumulation.[14] Yet, many laboratory experiments and related research efforts still lean heavily toward "how much" and "what kind" of microplastic has polluted the marine environment. Thus, there currently is insufficient research on the effects of microplastic formation in marine environments that understanding on the possible consequences on marine ecology and human health is yet too low to be translated into effective policy.

Soil

Since the introduction of microplastic soil contamination[21] related studies expanded both in scope and volume.[22–27] The United Nations Environment Program (UNEP) further recognized the need to verify the consequences of microplastic pollution in the soil environment on World Environment Day.[28] Insofar, researchers focused on the hazardous effects of microplastics in soil and terrestrial ecosystems,[29–31] with emphasis on its rapid spreading rate in soil environments.[21,29,31,32] Recent studies worryingly indicated the possibility of 4 to 23 times higher microplastic concentration on land than in the ocean[24] due to many entry points such as microfibers from clothing, plastic beads from personal care products, biosolids,[33–37] reclamation sites in urban and industrial centers,[32] lake water flooding, road waste and illegal waste dumping,[38] tire wear,[39–41] atmospheric particles,[42] and fertilizers.[24,31]

Yet, there is a growing consensus that the agricultural ecosystem is the major pathway for microplastic in terrestrial environment[43,44]; the largest concerns involve wastewater irrigation and mulching used in agricultural activities.[45–48] The application of PE plastics in agricultural processes in 1938 revolutionized commercial crop productivity[49,50] but resulted in heavy microplastic soil pollution (approximately 10% of all agricultural soil).[51] The situation was exacerbated when the usage of sewage sludge as agricultural fertilizer became a standard management process. Studies estimate approximately 63,000 to 430,000 tons and 44,000 to 300,000 tons of microplastics have been discharged annually in Europe and North America, respectively.[31,32] Accounting for the vast physical coverage, the agricultural soil is also described as microplastic-contaminated large reservoirs in which airborne particles drop,[42] mostly likely in form of precipitation.[25,38,52]

Microplastic soil pollution has been found to alter the physical properties of soil, reduce soil fertility, and destroy resident microbial communities. Altogether, the contamination impairs soil quality and nutritional circulation[53–56] to infertile the crops,[57] damages the reproductive growth of plants,[58] and exhibits plant ecotoxicity and genetic toxicity.[59] It has been shown that macro and microplastic residues in soil have a negative effect on wheat (*Tricum aestivum*) growth.[58] In addition, the germination rate decreased when exposed to microplastics using Cress seeds, indicating that microplastics can physically block the pores of the seeds and interfere with moisture absorption, delaying germination.[57] Intracellular absorption of nanoplastics (20 and 40 nm) in tobacco BY-2 plant cell culture was confirmed by fluorescent microplastic images.[60] In addition, evidence of attachment, absorption, accumulation, and migration of microplastics within edible plant lettuce was observed using fluorescent markers.[61] As such, there is still not much information on microplastic accumulation by plants in the soil, and research on quantifying microplastics in more plant species is needed.[62]

In addition, microplastics ingested by earthworms were found to travel through the food chain, which may pose a potential threat to terrestrial predators and even humans.[63] Despite the seriousness of microplastic pollution hazard posed to soil biodiversity, ecosystem function, and food security, there currently is limited knowledge on the environmental impact of microplastics on actual soil, or how microplastic-polluted soil impedes nutritional circulation.

Groundwater

Groundwater is another important water resource as it accounts for 97% of accessible freshwater[64,65] that deserves an increase in quality management efforts. Yet, microplastic pollution research on groundwater only began in 2017 as groundwater traditionally was considered as impenetrable.[66] The first study subjected karst areas, the most vulnerable to aquifer pollution, to verify the existence of microplastic contamination in groundwater.[66] Since then, the experiments focused on the microplastic pollution progress investigation (e.g. concentration, polymer type, shape, and color) by the surrounding environment and geology of the aquifer.[67] Among various inflow pathways of microplastics into the aquifer, ranging from sinkholes, groundwater wells (pumping), seawater infiltration, and vertical transport by soil organisms or rainfall,[44,56,68] surface water is known to be the critical passage.[69,70] Although research on this important carrier, surface water, took its course a decade prior to groundwater in 2007, it still is in the early stage.[71–73] The findings deduced four major cases through which microplastic enters surface water: discharged residuals from unsuccessful decomposition or filtration during the wastewater treatment processes, run-offs, flooding and tidal inflows.[24,74,75]

To understand the transport and retention of microplastics in the hyporheic zone (i.e. groundwater-surface water interaction zone), studies adopted colloidal transport model analysis under various environmental conditions (e.g. chlorine concentration, ion strength, and microplastic particle size change).[76–81] Research has also been expanded to develop a new upgraded microplastic transport model tailored for groundwater passage investigation from the conventional colloidal model.[76,82] The analysis results reported increasing average microplastic concentration in deeper layers of sediments with decreasing particle size.[83] As PP and PE are the dominant microplastic polymers collected from surface water, followed by PS, PET, PA, PCV, and PU, the two are the most common types detected also in groundwater.[80,84] The difference is observed from shape: while the majority takes fiber form in surface water, most are decomposed into fragments under 50 μm in groundwater.[65,67] Such difference satisfies research conclusions that surface water contributes the most to the microplastic pollution in groundwater and the geological environment surrounding groundwater acts as a natural filter against large pollutants.

Accounting that the major uses of groundwater are agricultural and drinking purposes, microplastic contamination poses a serious threat to human health, possibly worse than food. Furthermore, there is a growing concern about the effects of microplastic pollution on smaller organisms (microorganisms, troglofauna, and stygofauna) inhabiting in groundwater environment.[85–87] Yet, research on microplastic pollution in groundwater is limited to the verification of causes and subjects rather than the aftereffects or remedies to contamination.[88,89] Furthermore, much of the currently conducted microplastic transport modeling experiments are bounded within the laboratory that their actual application is still questionable. In this light, microplastic pollution-related research on groundwater environments can be categorized as being in its primitive stage and possess much room for expansion and development.

Air

Interest in research on microplastic atmospheric pollution increased when the first signs were detected in Grand Paris in 2015.[90] Since this identification, primary research efforts acknowledged the possible causal relation between airborne microplastic fallout and urban wastewater/freshwater microplastic contamination.[42,90,91] Another strand of comparative studies in remote areas with almost no anthropogenic activities (such as the Pyrenees, a nature-preserved mountain in France) further suggested the likelihood of microplastic atmospheric transport in a similar pattern with particulate matters.[42,52,92,93] Specifically, the meteorological factors and cloud formation process (atmospheric currents) are found to be the most vital conditions that determine the length and time of microplastic atmospheric transport.[94–96] The atmospheric microplastic fallout concentration is observed to be higher on rainy days and Winter seasons compared to Summer and Spring.[42,90,91,94,97]

Their low density and very small size allow long buoyant time,[42,98] and there seems to be free interchange occurring between airborne, terrestrial, and aqueous microplastic. Strong wind and spray emission releases significant amounts of microplastics formed either through degradation in seawater or various economic activities on land into the atmosphere,[42,90,99–101] while the airborne falls into vast land or oceans under appropriate climate conditions (e.g. precipitation).[102] Although the exact interaction between extreme weather conditions (e.g. hurricanes, typhoons, cyclones, and monsoons) and airborne microplastics has yet to be identified, dust storms have been identified to play a key role in atmospheric microplastic transportation.[103] Erosion of synthetic materials (e.g. tires, fibers, building materials) is found to be the major source of airborne microplastic,[42,90,100] followed by building materials, waste incineration, fertilizers made of sludge, abrasive powders, and 3D printing.[104–106] Accordingly, fragments, films, and fibers[97,106–110] made of PE, PP, PS, and PET are the most common shapes and types of microplastic found in the atmosphere.[106,108]

Recently, the research scope of microplastic pollution in the air has expanded to include the impacts of airborne microplastics on human health and the environment.[108,110–113] A number of studies suggest a higher risk from indoor microplastic contamination than outdoor as is the case with many other typical air pollutants' health risks.[42,108,112,113] This is because pollutants typically require a certain inhalation concentration to exert health-hazardous reactions such as interstitial lung diseases.[112] Although such findings are still too broad to understand the movement and consequences of airborne microplastics, one thing clear is that microplastic air pollution is transboundary, transmittable to other mediums, and health hazardous. The world, thus, requires more collaborative research in the field to deduce policy recommendations for global cooperation. In this light, standardizing key experiment definitions, protocols, and specifications is an urgent task, especially in aspects regarding air pollution.

Food

Food research began when nonpollen particulates spotted in honey and sugar were identified as microfibers and fragments,[114] which raised the possibility of microplastic existence in nature as much as being inserted during the food manufacturing process. In 2014, microplastic was detected in local beer sold in Germany,[115] which triggered related research together with the findings that ocean creatures have been exposed to marine plastic waste for years. It was found that floating marine plastic waste is ingested by planktonic organisms and eventually travel across the food chain from trophic level to higher level.[6,116,117] Other research revealed that microplastic can reach marine mammals both directly from surrounding particles and indirectly through contaminated prey,[118] which may result in decreased body defenses through cell damage.[119] As microplastic ingestion by copepod and Euphausiacea (krill) were verified,[19,120–125] experiments on bivalves raised for human consumption were conducted to understand how close microplastic pollution has approached human's everyday lives.[125] Food items from which microplastic wastes are detected include: bivalves and various fishes,[126] salt,[127] dry fishes,[128] mussels,[129] tap water and beer,[130] and milk.[131]

Since the identification of microplastics from salt through a case study in China,[127] micro-Fourier Transform Infrared Spectroscopy (μ-FT-IR) analysis has been adopted to distinguish the type of plastic present in food and beverage. Supported by technical advancement, the related research scope has been expanded to verify that plastic residuals penetration into food occurs throughout the entire food preparation period: mulching film used in agriculture is absorbed by wheat,[58] microplastic present in groundwater is transferred to drinking water,[132] microplastic exist in various drink packed in plastics bottles,[133] plastic tea bags released microplastic in hot water,[134] raw meat absorb microplastic from pressed PS used in packaging,[135] and microplastic was released from various plastic containers, plates, cutlery, and cups under various conditions.[136,137] Other researchers raised further concerns about the possibility of microplastic turning poisonous once ingested internally (adhesive to other chemicals and cohesive to metals or bacteria).[121,138–141]

So far, microplastic-related research on food has expanded much in both quantity and subjects. Yet, the research scope and purpose are still limited to existence verification in items that are commonly consumed by people, either directly ingested food or plastics used in food packaging and cutlery.[135,142,143] The aftereffects of the microplastic present in these eatable conditions are still unknown as much as the process or degree of absorption once these microplastics successfully reach the human body (Table 1).

Microplastic pollution as global agenda

Transboundary and transmedium characteristics of microplastic pollution

As elaborated in the previous section, microplastic pollution is not a point-specific phenomena that remain at the point of origin until managed, but more of a transboundary, transmedium like conventional particulate matter air pollution or dichloro–diphenyl–trichloroethane (DDT) pollution.[106,157] Recent analytical results that reported 28% of marine microplastic pollution originated from road vehicle movements (tire wearing) further emphasized the need to understand the relationship between air circulation and the transportation of airborne microplastics.[158,159] Thus, there now is a growing concern calling for a comprehensive study on the dynamic interaction and transport among different environment mediums and locations to identify microplastic pollution cruising through the ecosystems[156] possibly taking different forms.

While the sea spray process and air bubble bursting on the ocean surface contribute to atmospheric microplastic pollution,[106,160,161] airborne microplastics also are deposited in terrestrial or aquatic environments that may end up in the human body through food chain accumulation[104,106] (Figure 1). Microplastic pollution from precipitation can spread over long distances through atmospheric transport, which can also spread microplastic pollution to remote uninhabited areas.[92,162] Soil and water basins act as a sink for microplastic[14] receiving airborne microplastic fallouts and more generated from various anthropogenic activities. Microplastics, thereon, invade hidden pillars of the ecosystem like the food chain and groundwater.[22,38,162] Raindrops falling from the atmosphere

Table 1. Literature review on microplastic pollution in research fields (marine, soil, groundwater, air and food).

Location	Sampling	Polymer types	Size	Shape	Color	Concentration (abundance)	Reference
Marine							
Maine Bay, USA	Sea surface	Rayon and PE	5–282 mm	Fiber	Black (62%), blue (15%), red (13%), and colorless	0.60 ± 0.25 n/m^3	14
Great Barrier Reef Marine Park, Australia	Sea surface	PE, PP, PS, and EVA	0.4–82.6 mm	Pellet	White, colorless, and blue	4.96 ± 0.27 n/m^3	144
The North Atlantic	Sea surface	PE, PS, and PP	1–100 mm	N/A	N/A	1.6 ± 0.5 n/m^3	145
Daebu Island, South Korea	Beach	PP, PE, PS, EVA, and PUF	0.3–5 mm	N/A	N/A	Summer: 272,349 (±357,535) n/m^3 and winter: 10,318 (±6247) n/m^3	146
Soil							
Franconia, Germany	Farmland	PE, PP, and PS	1–5 mm	Film, fragment and fiber	N/A	0.34 ± 0.36 n/kg^{-1}	147
Shanghai, China	Farmland	PP, PE, and PES	1.91 ± 0.13 mm	Fiber, fragment and film	N/A	78.0 ± 12.9 n/kg^{-1}	148
	Agricultural	N/A	20 mm (width)	Fiber	N/A	600–10,400 n/kg^{-1}	149

(Continued)

Table 1. (continued)

Location	Sampling	Polymer types	Size	Shape	Color	Concentration (abundance)	Reference
Mellipilla, Chile			0.97 mm (length)				
Shanghai, China	Paddy	PE, PP, and PVC	0.02–1 mm (domain)	Fiber, fragment and film	N/A	10.3 ± 2.2 n/kg^{-1}	[150]
Groundwater							
Illinois, USA	Karst aquifer	PE	<1.5 mm	Fibers	Blue and/or colorless (65%), red (15%), and gray (13%)	15.2 n/L (max)	[66]
Victoria, Australia	Alluvial aquifer	PE, PS, PP, PVC, PET, PC, PMMA, and PA	18–491 μm	Fragments and fibers	N/A	38 ± 8 n/L	[67]
Tamil Nadu, India	Wells & borewells	Nylon (PA, 35%), PE (55%), and PET (10%)	0.11–12.5 mm (mean: 0.6 ± 1.4 mm) and <1 mm (34% domain)	Fibers, foam, pellets, films, and fragments	Colorless (53%), white (30%), blue (10%), gray (5%), and yellow (2%)	4.2 n/L (median) and 10.1 n/L (max)	[151]
Krakow, Poland	Deep well (untreated potable water)	N/A	0–0.045 mm	Fragments	Blue and green	N/A	[152]

(Continued)

Table 1. (continued)

Location	Sampling	Polymer types	Size	Shape	Color	Concentration (abundance)	Reference
Air							
Greater Paris, France	Urban outdoor atmospheric fallout	N/A	100–5000 μm	Fibers and fragments	N/A	30–100 n/100 m^3	90
Asaluyeh County, Iran	Outdoor	N/A	100–1000 μm	Fiber, spherules, fragment and film	White-transparent: >70% blue–green	0.3–1.1 n/m^{-3}	153
Central London	Outdoor	PAN, PES, PA, PP, PVC, PE, PET, PE, PUR, and PPR	75–100 μm	Fragments, films, granules and foam	N/A	59 ± 32 $n/m^2/d$ (mean)	154
South Korea	Indoor/ outdoor	PE, PP, PA, PES, AR, and PS	Indoor: 20.1–6801.2 μm and outdoor: 20.3–4497.4 μm	Fibers, fragments, and film	N/A	Indoor: 0.49–6.64 (3.02 ± 1.77) n/m^3 and outdoor: 0.45–5.16 (1.96 ± 1.65) n/m^3	155
Food							
North Sea, Germany/ Brittany, France	Bivalves (*Mytilus edulis* and *Crassostrea gigas*)	N/A	5–10 mm/11–15 mm	N/A	Red and blue	0.36 ± 0.07 n/g (*Mytilus eduli*) and 0.47 ± 0.16 n/g (*Crassostrea gigas*)	125
China	Table salt (sea salt, lake salt, and rock/well salt)	PET, PE, and cellophane	45 μm–4.3 mm	Fiber and fragment	Black, red, blue, and white	550–681 n/kg (sea salts), 43–364 n/kg (lake salts), 7–204 n/kg (rock/well salts)	127

(Continued)

Table 1. (continued)

Location	Sampling	Polymer types	Size	Shape	Color	Concentration (abundance)	Reference
Spain	Table salt (sea salt and rock/well salt)	PET, PP, and PE	30 µm–3.5 mm	Fiber	Black, red, blue, and white	50–280 n/kg (sea salt), 115–185 n/kg (well/rock salt)	[156]
Mexico City, Mexico	Beer, soft drinks, energy drinks, and cold tea	PA, PEA, and ABS	0.1–3 mm	Fiber and fragment	Blue, red, brown, black, and green	ND–28 ± 5.29 n/L (beer), ND–7 ± 3.21 n/L (soft drinks), ND–6 ± 1.53 n/L (energy drinks), and 1 ± 0.57–6 ± 2 n/L (cold tea)	[133]

N/A: not available/reported; ND: not detected; PA: polyamide; PE: polyethylene; PES: polyester; PP: polypropylene; PS: polystyrene; PVC: polyvinyl chloride.
Source: Author tabulated.

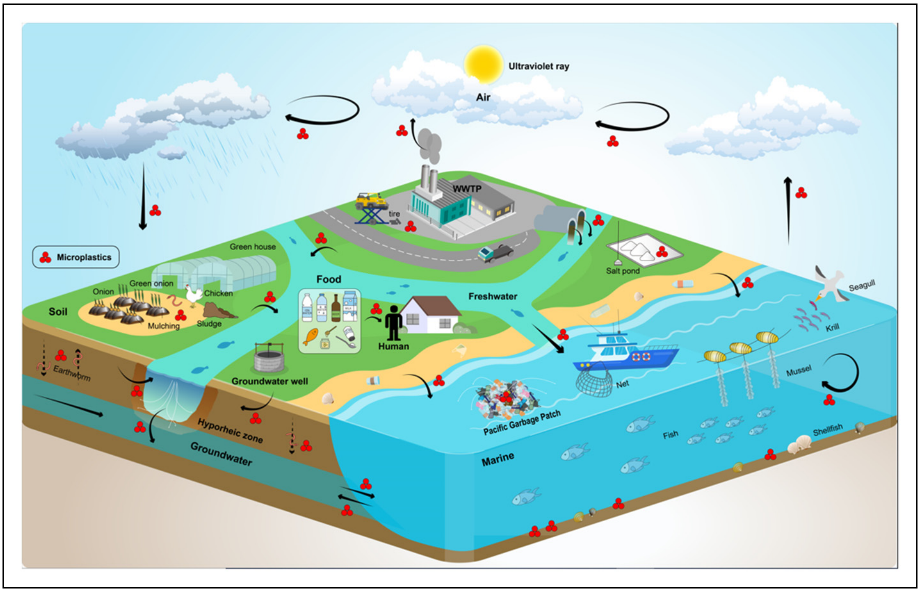

Figure 1. Microplastic transport and circulation throughout environmental pillars.

are recharged into aquifers through soil or stream bed sediments (hyporheic zone).[56,163] In addition, in areas where tidal motion is active, microplastic enter the aquifer through seawater infiltration.[164]

The natural adaptation patterns have also been observed, which, in turn, confirm the prolonged effects of microplastic pollution: marine microorganisms are now utilizing plastic parts floating on marine surfaces as a new type of habitat[11] as the portion of plastic waste surface coverage increased exponentially for them to persist on traditional ways. Several marine ecologists have further experimented on the consequences of microplastic ingestion by marine animals and reported that the survival instincts of perch larvae exposed to microplastic pollution were weakened.[165] The observed microplastic concentration from Southern Bluefin tuna in Tasmania revealed that microplastic accumulates along the marine food chain in a similar manner to the famous mercury poisoning.[144] A study on the effects of microplastic-contaminated sewage sludges and mulching also revealed different onion growth patterns depending on the type of microplastic exposed.[166] It has also been found that plastics on surface soil can be integrated into the deep soil by the latent activity of earthworms,[21] which indicated the possibility of debris plastics and microplastics combined in the surface soil can be transported into deeper layers by the activity of soil organisms such as collembolans, insects, and plants.[44,54,167–169] Lwanga et al.[63] reported that the highest microplastic concentration was observed in chicken feces, especially in chicken sandbags (a popular food ingredient in many countries), in the nutritional migration study on microplastic in house garden soil, earthworms, and chicken excrement.

Prerequisite to address microplastic pollution together

Despite the growing number of literature addressing various aspects of microplastic pollution, it is still difficult to "stand on the shoulders of giants (Isaac Newton)" due to the absence of standard operating protocols for microplastic analysis.[157] Researchers across the world are adopting different terminology, size, meaning and apparatus that a direct comparison and contrast among the results is limited. One prime example of a currently lacking global consensus or standard is the absence of a global definition/classification of microplastic. While the most frequently cited definition goes "microplastics are plastics that are <5 mm in length," as proposed by Zhu et al.,[169] there is no clear lower boundary that many researchers indicate only the lower limit of the sampling method or processing apparatus. This variation results in incomparable or incompatible data collection, which consequently poses risks to global knowledge sharing for complete microplastic pollution mapping. Another example is the inconsistency in an itemized subject definition of microplastic: while rubber, some fibers, and paint particles are not considered as plastic by many polymer chemists,[170] others name abrasion of vehicle tires (19% natural rubber and 24% synthetic plastic rubber polymer) as major contributors to microplastic pollution. This inconsistency may cause confusion in data collection with different total numbers undermining analysis results reliability.

Additionally, there still are many missing puzzle pieces in each environment medium for a comprehensive microplastic pollution mapping. In marine microplastic pollution, for example, it is very likely for microplastics to sink below and endanger deep sea or marine ecosystems beyond the surface water as density increases by adhering to marine microorganisms or others.[6,8,10] Despite a growing consensus, there are not many studies addressing the deep ocean floor or its potential consequences on marine ecosystems. Airborne microplastics are transported a long distance through air circulation system and are deposited on the terrestrial or aquatic environment under appropriate meteorological conditions such as rainfall and snowfall.[92,94,161,171,172] Yet, the effects of extreme weather events (e.g. cyclone, hurricane, and monsoon) and climate change on microplastic pollution have yet been scrutinized. Similarly, despite the occurrence of microplastic in soil being ingested[173] or transferred to other soil organisms,[32] the possible toxic side effects of microplastics on living organisms, including human health, have yet to be fully explored. As demonstrated, the research in groundwater contamination is in such an early stage to discuss the loopholes.

The most urgently required step, however, is to achieve global consensus to treat microplastic pollution as another kind of transboundary and transmedium pollutant that calls for a global approach. The absence of the exact term, "microplastic pollution," on the global agenda (such as the Sustainable Development Goals of the United Nations or the Intergovernmental Oceanographic Commission of UNESCO) impedes cooperative international efforts including the collection and exchange of related data and knowledge.[174] It is also important to realize there is no reason for microplastic pollution to be less severe in developing or less-developed countries than in developed regions. Accounting for the effects of environmental policy in general terms, it is a logical deduction to expect a worse scenario under relatively fewer sensitive governments (i.e. heavier use of plastics for cost reduction). Yet not much research has been conducted in these regions for low interest. This is another reason to push microplastic pollution on the global agenda for collective efforts: such global attention will pressurize international organizations and local governments to monitor microplastic pollution circulation in these regions, thus, contributing toward global microplastic generation and circulation reduction.

Conclusion

The discovery of the "Pacific Garbage Patch" in 1997 changed the entire view on plastic pollution and the world realized the presence of microplastics in our daily lives. Nothing comes for free, and convenience demands payment of some sort. The world enjoyed the Plastic Age of convenience and now faces the Climate Change Age and the Pollution Management Age. Microplastic pollution is one of the items that require global efforts to Reduce (initial generation), Stop (transboundary and transmedium transport), Recover (damages done), and Shift (toward a sustainable living style). The world needs more information to design these international collaborative actions into policies and regulations. The first step for this is to acknowledge transboundary and transmedium characteristics of microplastic pollution and to stipulate the term in global actions. Global acknowledgment will trigger the standardization of research protocols, scopes, and experimental specifications to enable more concrete and comparative research in related fields. Once research data and volume reach a threshold, the research interest will naturally expand to developing and less-developed countries, beyond currently interested governments, for global status mapping of microplastic pollution. Microplastic pollution, in short, calls for more comprehensive and comparative scientific data and analysis interpretation to be translated into effective and efficient policy drivers, another cornerstone toward a Sustainable Development Age to avoid future environmental crises.

Author contributions

HK designed most of the research analysis input, and HSR, JM, NAK, CY, JHY, and ML wrote the manuscript. HK review and editing. HK resources, project administration, and funding acquisition. ML, HSR, JM, NAK, CY, and JHY edited the manuscript. All authors have read and agreed to the published version of the manuscript.

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