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MICROPLASTICS IN THE ENVIRONMENT: SOURCES, IMPACTS, AND REMEDIATION STRATEGIES

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ABSTRACT

Microplastics—small plastic particles less than 5 mm—have grown to be a major environmental problem due to their persistence and widespread presence. This review looks at the primary sources of microplastics, including sources like industrial particles and secondary sources that result from the breakdown of larger plastic waste. From the physical harm they do to aquatic life to the bioaccumulation of dangerous compounds in food chains, microplastics have a substantial detrimental impact on both the environment and human health. Additionally, highlighted are the potential health risks associated with chemical exposure, ingestion, and inhalation. Numerous remediation techniques, including bioremediation methods, technological developments, cleanup campaigns, and preventative measures, are presented to solve this expanding issue. Despite tremendous advancements, Effective management is hindered by microplastic detection, quantification, and regulation. To lessen the negative effects of microplastic pollution on the environment and human health, this review highlights the importance of tackling the problem and the necessity of interdisciplinary cooperation and creative solutions.

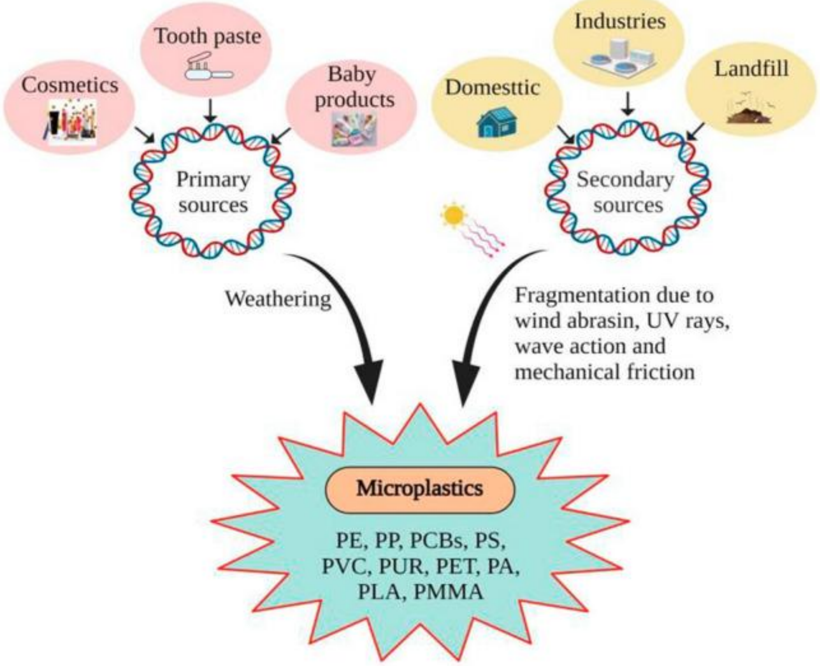
Keywords: *Microplastics, Environmental pollution, Plastic waste, Sources of microplastics*

INTRODUCTION

Due to the development of the plastics industry and the huge demand for plastic products in daily life, numerous plastic products are produced, used, and discarded worldwide [1]. In 2020, global plastics production reached almost 370 million metric tons (Mt), and Asia, North America, and Europe contributed 49%, 19%, and 15% of global plastics production, respectively. In 2016, the USA produced more than 42 million metric tons (Mt) of plastic waste; the annual per capita plastic waste generation is > 130 kg, and 90% of this waste is landfilled or incinerated (US EPA Office of Land and Emergency Management, 2019). MPs are plastic particles with a diameter of less than 5 mm. At the same time, NPs are nano-scale (≤100 nm) MPs that are formed due to abrasion, ultraviolet (UV) irradiation, hydrolysis,[2] and biodegradation. Different sources and weathering patterns can cause different MP shapes, including fragments, fibers, pellets, spheres, films, and foams. The chemical composition of MPs mainly includes polyethylene (PE), polystyrene (PS), polyvinyl chloride (PVC), polypropylene (PP), and other common plastic materials according to different plastic sources. However, the systematic classification of MPs according to the shape, size, chemical composition, and electrical charge still lacking [3].

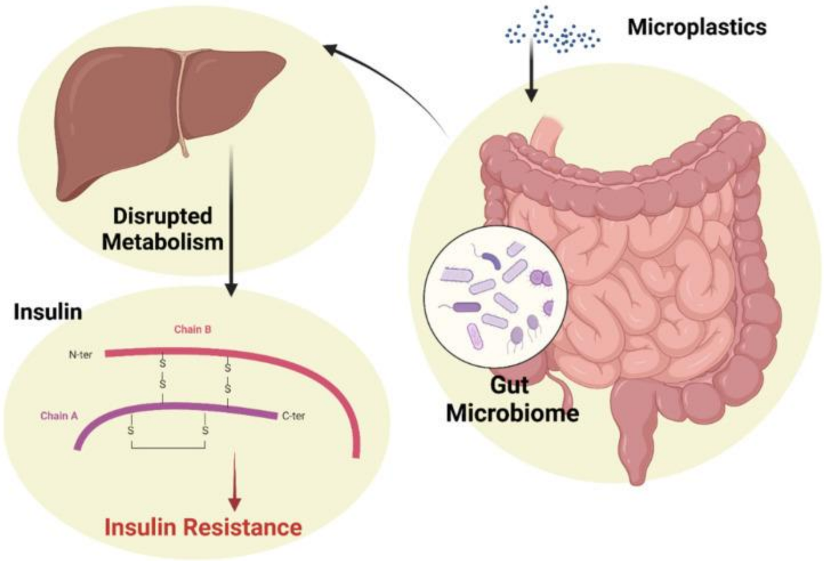
With the massive development of plastic materials, fragmented plastics have been adopted and named based on their size, origination, and process of fragmentations. Several researchers have begun to consider sub-scale plastics fragmentation, also known as "nano-plastics," various studies have set their upper size limits of 1000 nm or 100 nm. Further, small chunks of degrading plastic of 1–5000 µm in length are plastic as MPs in general. They were first discovered in German beer brands [4], water samples, and air samples [5]. Cosmetics, polythene bags and plastic containers, electrical appliances, goods packaging, glass, and many other items are significant sources of MPs. The distinction between primary and secondary sources must be considered when using sources for further research and mitigation. Plastic pellets in manufacturing industries, scrubbers, commercial cleaning abrasives, plastic resin flakes, plastic powder or fluff used to produce plastic goods [6], along with volatile particulate contaminants such as micro-polyester, nano Fe_3O_4, and SiO_2 from printing toners are the potential sources of primary MPs [7]. Likewise, secondary MPs originate from the breakdown of larger plastics subsequently into nano-, micro-, and macro sizes. Before being discharged into the environment due to weathering, such as exposure to wind abrasion, wave action, photodegradation, biodegradation, hydrolysis, and ultraviolet radiation from sunlight are the potential routes to generate secondary MPs [8]. Also, the fragmentation process, which emphasizes routes to generate secondary MPs, resulting from the gradual degradation of plastics in water, consists of three mechanisms: bio-fragmentation, assimilation, and biodeterioration showing emphasized, impactful MPs generation pathways [9]. The primary and secondary MP sources evolved from the different ways of plastic degradation, as depicted in Figure 1.

Figure 1:Types, sources, and the way of formation of primary and secondary MPs [10]



The effects of ingesting microplastics have been identified and classified by researchers into three stages: the first is related to the blockage and damage of the digestive system, the second refers to the release of toxic chemicals into the body, and the third stage is represented by the assimilation of these substances by organs and tissues. Due to the increased human exposure to microplastics, they can be absorbed into the body through various pathways and accumulate in organs such as the liver, kidneys, and intestine. Scientific studies have found that exposure to microplastics causes intestinal inflammation and liver metabolic disorders, but it is not yet known whether the damage and inflammation can cause the subsequent development of serious diseases. The mouse study found that daily exposure to microplastics has effects on the gut-liver axis, ultimately leading to insulin resistance and even diabetes (Figure 2). These results indicate the urgent need regarding the prognosis of insulin resistance after exposure to microplastics [11].

Figure 2:Insulin resistance and exposure to microplastics [12].



This review aims to explore the sources, impacts, and remediation strategies of microplastics in the environment, emphasizing their ecological and health consequences. It examines pathways through which microplastics enter ecosystems, their role in transporting pollutants, and their effects on organisms and human health. Current remediation strategies, such as filtration and biodegradation, are reviewed for their effectiveness and feasibility. Key research gaps include incomplete knowledge of sources, limited studies on long-term health impacts, ineffective large-scale remediation techniques, and inadequate policies for microplastic management. The review highlights the need for scalable solutions, advanced detection methods, and comprehensive regulations to address microplastic pollution sustainably.

PRESENCE AND SOURCES OF MICROPLASTICS WITHIN THE ENVIRONMENT

There are many ways in which plastics can be released to the environment, either as primary microplastics or as larger plastic items ("macroplastics") which will break down to form secondary microplastics (Figure 2). Primary microplastics from domestic products, such as microbeads, can be present in waste water and subsequently discharged to rivers, while nurdles can be lost to freshwaters during production processes. Examples of secondary microplastic sources include intentional release (illegal dumping), mismanaged waste (litter) or unintentional losses (e.g., fishing gear and loss of shipping cargo) [13], with the magnitude of different sources and pathways for microplastic release varying between the terrestrial, freshwater, and marine environments. Domestic products, such as microbeads, can be present in wastewater and subsequently discharged to rivers, while nurdles can be lost to freshwaters during production processes. Examples of secondary microplastic sources include intentional release (illegal dumping), mismanaged waste (litter), or unintentional losses (e.g., fishing gear and loss of shipping cargo) [13], with the magnitude of different sources and pathways for microplastic release varying between the terrestrial, freshwater, and marine environments.

Figure 3: Images of plastic pollution across a range of environments: (a) terrestrial, (b) riverine, (c) marine, and (d) coastal. Any large items can degrade to form secondary microplastics. Image attributions (a) PDPics on Pixabay CC-0, (b) BiH via Wikimedia Commons CC BY-SA 3.0, (c) Ben Mierement, NOAA NOS CC-0, and (d) Michael Dorausch on Flickr CC BY-SA 2.0 [14].

Emission sources:

Microplastics are released into the environment either as primary or secondary microplastics [15]. Plastics that are manufactured to be of a microscopic size are defined as primary microplastics. The sources of primary microplastics can be generally divided into several categories, mainly including facial-cleansers and cosmetics, air-blasting media, vectors for drugs, and virgin plastic production pellets [16]. However, there are still significant knowledge gaps on the sources of primary microplastics, particularly in the released amounts of each category. Secondary microplastics are microplastics eventually formed from larger plastic fragments after breaking down into smaller particles through physical, chemical and/or biological processes. Thus, the sources of secondary microplastics are both diverse and numerous [17].Environmental factors, such as temperature and sunlight, as well as the properties of plastic materials (e.g., size and density) will affect the degradation rate of macroplastics (> 5 mm) [16].Weathering is the primary Journal Pre-proof 8 process for plastic decomposition.Another important process is sunlight-induced photodegradation, which can lead to bond cleavage, thus causing degradation and oxidation of plastics. Plastic particles are also susceptible to breakage by mechanical forces, such as abrasion, fluctuation and turbulence [18]. In addition, when the external environment changes, such as at very deep ocean depths with low oxygen content and haline conditions in the low-energy marine environment of the benthic zone, the degradation rate of microplastics slows down significantly [19].Therefore, to identify the exact source of secondary microplastics in the environment, the source of macroplastics (> 5 mm) and related degradation processes in different environments should first be clarified. However, it is difficult to identify their exact sources because both macro- and microplastics are constantly moving in the environment and their degradation is a dynamic process [20].

Microfibers from the washing process of the textile industry

Textile production and trade activities are a major contributor of microplastic pollution. Natural fibers, regenerated fibers, and synthetic fibers are three broad categories of textile fiber in the textile industry. Microplastic disposal from textiles contains >170% more synthetic fibers than natural. It was estimated that more than 42 million tons of synthetic fibers are produced annually by the textile industry with approximately 80% belonging to PES [21]. Awareness of synthetic textile fibers has grown because it received considerable negative pressure on the marine environment [22]. Microfibers mainly come from domestic and industrial washing processes of synthetic cloth. Studies showed that 35% of the identified MPs in the aquatic environment were attributed to microfibers derived from textile sewage [23].Over 700000 microfibers could be released from a 6 kg wash load of acrylic fabric under the domestic washing condition [24]. More than 1900 fibers could be shed from per wash of a garment, and all garments released > 100 fibers per liter of effluent. Up to 13 million microfibers released from PES and cotton textiles in the first machine washing and show decreased trend sequentially [25].Carney Almroth et al. (2018) compared microfibers shedding from acrylic, nylon and PES materials. Greatest amounts of microfibers were shed from PES fleece fabrics, 7360 fibers/m2 /L on average. In the same year, [26] quantified microfibers shedding from three synthetic fabrics. Compared with knitted PES and woven PP, the highest release of microfibers was observed by the wash of woven PES a typical 5 kg wash load of PES fabrics generated more than 6M microfibers. Mechanical and chemical stresses the release of MPs which cannot be blocked by wastewater treatment plants. The same research group also first estimated that there was an annual of 2.98×108 PES microfibers released into the water by washing per person while 1.03×109 to air by wearing PES garments. Direct release of microfibers into the air is of an order of magnitude to release into water [27].

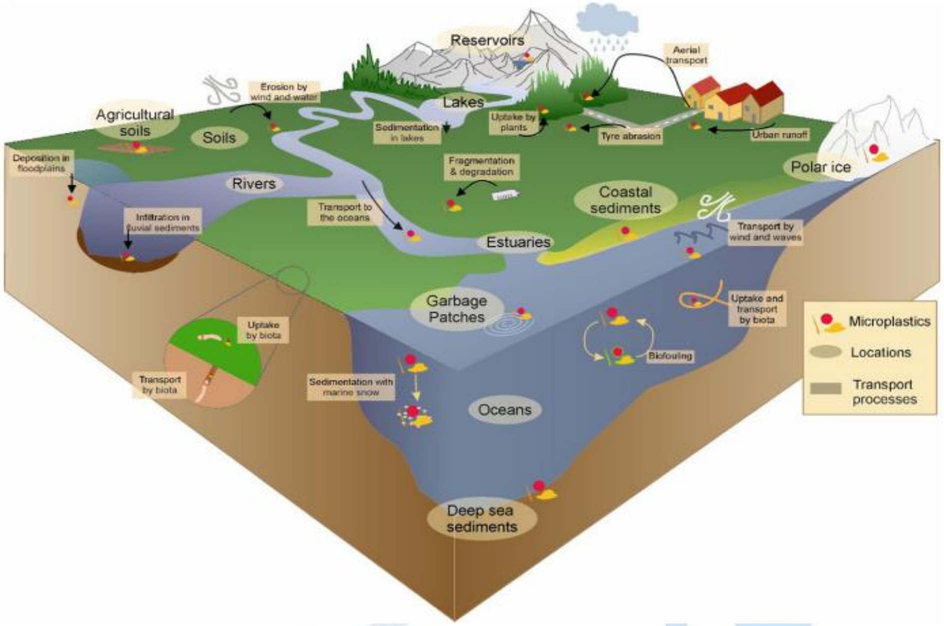
Microbeads from cosmetics and personal care products

Plastic microbeads have been widely added as an abrasive agent to a variety of personal care products (PPCPs), including scrubs and facial exfoliating soaps, shower gel and shampoos, skin creams, and liquid makeup. These microbeads can be directly released into the domestic sewage and escape from wastewater treatment plants (WWTPs) due to incomplete removal. Zitko and Hanlon. (1991) first identified the microbeads associated with MPs in PPCPs as a threat to the environment. Because of their sufficiently tiny sizes, aquatic organisms can readily ingest them and accumulate them throughout the food chain. The European Cosmetic Industry Association reported that there was an annual of 4130 t microbeads used in soap for European Union countries plus Norway and Switzerland. It was estimated that between 4594 and 94500 microbeads could be released in a single-use [28].

Microplastics from agricultural plastic films:

Soils, especially agricultural soils have been regarded as major sinks for microplastics [29]. Among the numerous sources of MPs entering into agricultural soils, plastic film and compost applications are suspected to be a significant source of the predominance of heterogeneous fragments and films in the terrestrial environment [30]. Plastic films have been extensively used as the shedding of greenhouses or mulching films. Over the past several decades, plastic mulch film is encouraged technology to promote resource use efficiency and food security[31]. In 2016, there were 4 million tons of agricultural plastics films in the global market, the value is expected to increase at an annual rate of 5.6% by 2030. However, due to their thin characteristics (8-50 μm thick) and lack of plastic recycling facilities, the residue plastic fragments will form continuous macro, micro, and nano plastics in soils by tillage, UV irradiation, and biodegradation. The consumption of mulch plastic film reached up to 2.29 million tons in China in 2011 and the area covered by plastic film reached up 184×105 hectares [32]. Huang et al presented a quantitative analysis of macro and microplastics in 384 soil samples across China. Interestingly, a highly significant linear correlation was observed between mulching film consumption and MPs abundance in soils.

Figure 4: MP transport in the environment [33].



Transport of Microplastics

In the environment, microplastics can be transported through atmospheric or aquatic currents depending on their weight and density. 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 [34]. 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) [17]. 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 [35]. Additionally, stormwater runoff carries the microplastics resulting from the normal wear of tires on the road to neighboring surface waters. 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 [36]. 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

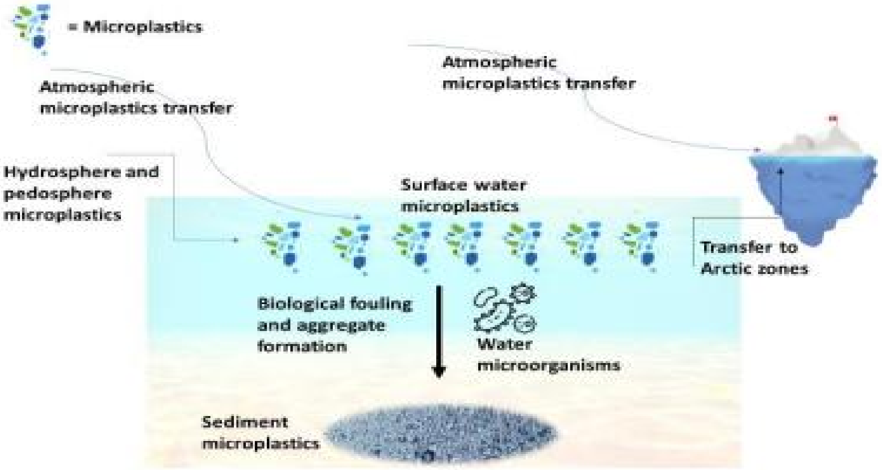


Figure 5: Microplastic distribution in the environment. The schematic represents the horizontal and vertical distribution of the microplastic in the hydrosphere. Water current and wind current result in the hydrosphere and atmospheric microplastic transfer, respectively, and result in microplastic transfer to remote areas such as Arctic Zones [37].

Table 1: Categories of micro plastics 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.	[38]
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.	[39]
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.	[40]
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 households including food packaging, plastic wear, and plastic furnishings	[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	[42]

Table 2: Distribution and abundance of microplastics in the environment. Due to the differences in sampling methods, the concentration units of microplastics were different.

Continent/ Ocean	Country/ Region	Location	Sample type	Particle size	Concentration	Reference
Asia	India China Qatar Japan China	Vembanad Lake Beaches along the coastline of Qatar East Asian seas around Japan Guangzhou section of the Pearl River	lake sediment beach sediment seawater freshwater	<5mm <5mm <5mm 20 mm-5 mm	96-496 items m-2 36-228 items m-2 3.74 ± 10.40 items m-3 379-7924 items m-3	[43]
Europe	Belgium Germany Italy	Belgian coast shoreline of the rivers Rhine and Main the Lagoon of Venice	beach sediment river sediment	38 mm-1 mm 63 mm-5 mm <1mm	92.8 ± 37.2 particles kg-1 322-615 particles kg-1 672-2175 particles kg-1	[44]

PATHWAYS OF HUMAN EXPOSURE TO MICROPLASTIC:

Microplastics pose a potential threat to human health due to their common existence in the environment and the reported toxic effects. It is important to understand the pathways of human exposure to microplastics. Oral intake, inhalation, and skin contact are the common ways (Figure 1). Among them, oral intake is the main exposure route. People are often exposed to microplastics in multiple ways simultaneously. Rillig et al. propose the concept of the "plastic cycle" in Science which means microplastics can migrate between different environmental media.The movement of microplastics increases the risk of human exposure.

Figure 6: Pathways of human exposure to microplastics.

Oral Intake

Microplastics exist in our daily necessities like drinking water, bottled water, seafood, salt, sugar, tea bags, milk, and so on [45]. Europeans are exposed to about 11,000 particles/person/year of microplastics due to shellfish consumption,30and according to food consumption, the intake of plasticparticles in the human body is 39,000−52,000 particles/person/year. Microplastics may also have been widely distributed in soil, especially in agricultural systems [46].They (especially with a negative charge) can get into the water transport system of plants, and then move to the roots, stems, leaves, and fruits. Once microplastics enter the agricultural systems through sewage sludge, compost, and plastic mulching,[47] they will cause food pollution, which may increase the risk of human exposure. Take-out food containers made of common polymer materials (PP, PS, PE, PET) are used widely, from which microplastics are found [48]. It is estimated that people who order take-out food 4−7 times weekly may intake 12−203pieces of microplastics through containers. In addition, research demonstrates that the surface of silicone rubber babyteats degrades when they are sterilized by steam, during which microplastic particles are released into the environment [49]. It is estimated that the total number of microplastics entering the baby's body during one year of normal bottle-feeding reaches about 0.66 million

Skin Contact

Microplastics are usually considered not to pass through the skin barrier, but they can still increase exposure risk by depositing on the skin.46 For example, the use of consumer products containing microplastics (such as face creams and facial cleansers) will increase the exposure risk of PE. The protective mobile phone cases (PMPCs) can generate microplastics during use, which are transferred to human hands. When children crawl or play, they may come into contact with microplastics on the ground. During the dermal exposure of microplastics, some typical plastic additives, including brominated flame retardants (BFRs), bisphenols(BPs), triclosan (TCS), and phthalates, may be absorbed [50].

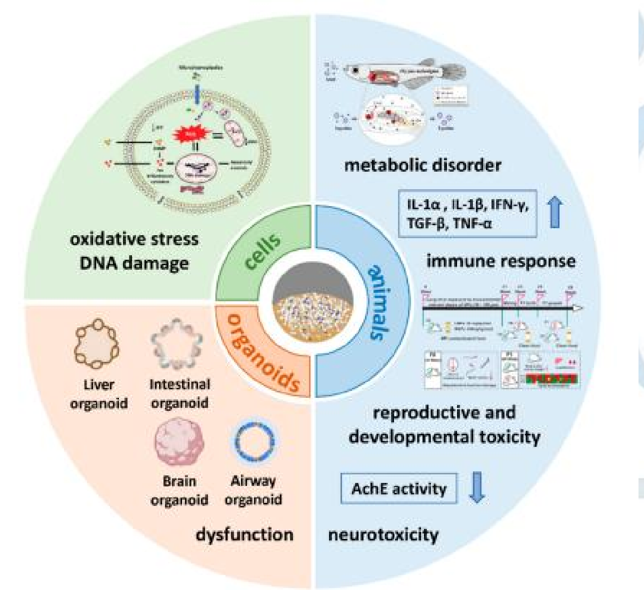


Figure 7: Toxicity mechanism of microplastics. Cells: oxidative stress and DNA damage. Reproduced with permission from ref [51]. Copyright 2021 Elsevier. Organoids: dysfunction. Animals: metabolic disorder, immune response, neurotoxicity, as well as reproductive and developmental toxicity. Reproduced with permission from ref [52]. Copyright 2021 Elsevier. Reproduced from ref [53]. Copyright 2022 American Chemical Society.

Reproductive and Developmental Toxicity.

The effect of microplastics on reproduction is reflected in the development of germ cells and embryo quality. For example, Liu et al. find that PS exposure affects the development of female mouse follicles and the maturation of oocytes, reducing the quality of oocytes. And Hu et al. report that microplastics might cause adverse effects on pregnancy outcomes through immune disorders.98 Deng et al. find that after long-term exposure to environmentally relevant doses of PS, sperm quality significantly decreases, which affects the fertility of male mice. In addition, Park et al. show that the number of live births per dam and the sex ratio and body weight of pups in groups treated with PE are notably altered [54]. What's more, they suggest the IgA level as a biomarker for harmful effects following microplastic exposure.

Neurotoxicity.

Microplastics are also toxic to the neural development. Inhibition of acetylcholinesterase (AchE) activity is the most reported neurotoxic effect after the exposure of microplastics. In a study of juvenile fish, the microplastics inhibit the activity of AchE, increase lipid oxidation in the brain, and change the activities of energy-related enzymes, eventually causing neurotoxicity. Prüst et al. also report that microplastics cause the abnormal behavior of nematodes, crustaceans, and fish. Yang et al. discovered that PS (70 nm) can pass through the epidermis of larvae and enter into the muscle tissue.95 It can destroy nerve fibers, decrease the activity of AchE, and exert great adverse effects on larval movement. Besides, Jin et al. reveal that after chronic exposure to PS at environmental pollution concentrations (100 and 1,000 µg/L), the blood-brain barrier of mice is damaged, and learning and memory dysfunctions occur [55].

Ecological impacts of microplastics on soil biota

How do microplastics affect soil microorganisms?

The interaction of microplastics with soil microbiota remains largely unexplored. Only a few studies have investigated the effects of microplastics in soil systems, mainly on overall microbial activity, bacterial transport, and the spread of antibiotic-resistant genes (ARGs). PP particles (7% and 28%) were reported to have a positive effect on soil microbial activity [56], while polyacrylic (0.05–0.4%), polyester (0.05–0.4%) and PS particles (1 mg kg^{-1}) showed a negative effect [57]. Since polymer type, shape, size, and concentration varied in these studies, it is difficult to draw a general conclusion on the toxicity of microplastics based on their features. Modified soil structure and microbial community composition have been proposed to be the possible reasons for altered microbial activity in these studies, however no direct evidence/linkages have been provided or observed. Further investigations are needed to improve our understanding of the effects and mechanisms of microplastics on soil microbial metabolism and activity. The effect of microplastics on the transport and deposition of soil microorganisms has not been intensely examined, but some insights may be gained from the study by [58]. The authors found that PS particles had a negligible effect on Escherichia coli transport in quartz sand under low ionic strength conditions. In contrast, plastic particles stimulated bacterial transport under high ionic strength conditions. They proposed that the adsorption of plastic particles onto cell surfaces and the repelling effect were the main drivers for the increased cell transport induced by plastics at the nanoscale (20 nm), while plastics at the microscale (2 µm) mainly increased cell transport by competing for deposition sites on the sand. Further research is needed to investigate how microplastics affect microbial movement in real soil systems. The Spread of ARGs is an increasing concern, due to its potential adverse effects on human health. Studies based on aquatic ecosystems reveal that microplastics can serve as hotspots of gene exchange between phylogenetically different microorganisms by introducing additional surfaces, thus having the potential to increase the spread of ARGs and antibiotic-resistant pathogens in water and sediments [59]. In soil ecosystems, the presence of PS microplastics (0.1%) has been shown to increase the retention time of antibiotics and ARGs [60]. More evidence is needed to conclude whether microplastic pollution facilitates the transmission of ARGs in soil environments.

How do microplastics affect plants?

When it comes to plants, people are concerned about two questions: whether the plants can absorb and accumulate micro plastics, and how micro plastics affect plant growth and food quality. Currently, such information is scarce, possibly because it is difficult to identify micro plastics in plant tissues and the effect on crops has not attracted enough attention. Small-sized micro plastics can likely overcome cell wall and membrane barriers. The possibility of plant uptake of microplastics can be investigated with the aid of fluorescent microbeads. For example, a cell culture-based study demonstrated that nano-scale[61].

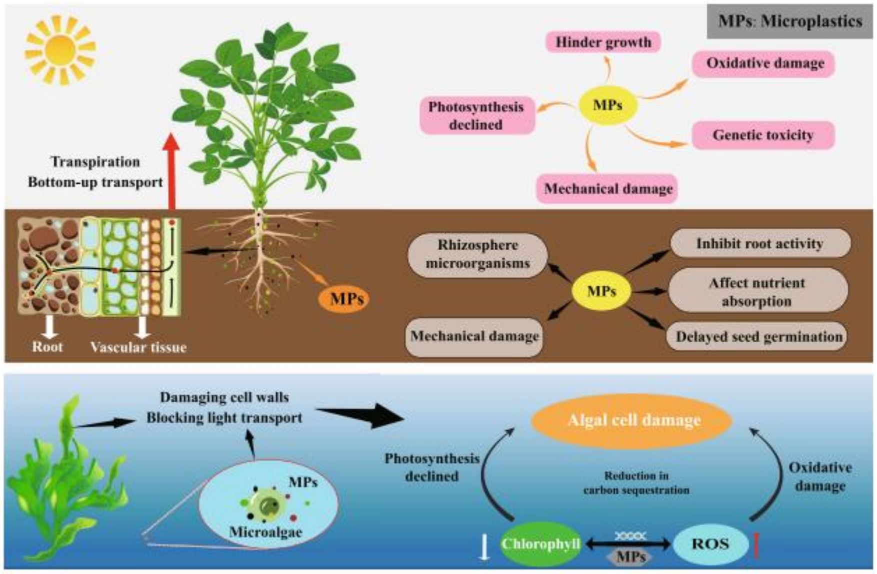
Microplastic itself is also organic carbon

The fact that MPs are particles that contain a lot of carbon, typically around 80%, makes them fairly unique with other global change factors, potentially except for pyrogenic carbon. MP carbon is thus already present in our soils, probably still making up only a tiny proportion of total soil organic matter carbon in most cases [62], but this could change in the future, and for specific ecosystems, such as urban and agricultural areas, since MP appears to be resistant to microbial decay compared to plant residues. A relatively small annual input compared to the large input by plants can translate to a quantitatively relevant accrual over long periods of time, as observed for pyrogenic carbon [63]. None of the current methods for assessing soil C are routinely able to distinguish soil organic matter carbon from this MP-C; this is troubling, since soil organic C storage is an ecosystem service, but even though MP-C is undeniably also organic carbon, it does not have the same origin and functionality as the rest of soil organic carbon, and it should not “count” in this context. We should separate these 2 organic carbon sources, but methods to do so routinely are not available, since MP quantification protocols are still being developed and refined. MP particles, once they arrive at the soil surface, can quickly become incorporated into the soil matrix [64], MP forms its own cycle [65], main features of which are slow MP decomposition, and potential loss to other environmental compartments, e.g., via leaching to groundwater or via erosion to lower slope positions. The following sections, covering different spatiotemporal scales from large to small, are about the effects the accumulating MP may have in soil

Plant growth and net primary production

MP can affect plant growth through a variety of different mechanisms, which are thought to be indirect via the effect MP has on soil and soil biota. Examples of such indirect effects are changes in soil structure and bulk density, which can affect root penetration resistance, changes in water holding capacity, and others. Biodegradable plastics might induce nutrient immobilization as these carbon-rich particles are being decomposed by the soil microbial community. In addition, key plant symbionts, such as root-colonizing mycorrhizal fungi, might be affected by MPs or their effects on soil physicochemical properties. In some cases, resulting effects of MP on plant growth have been positive, but there are also reports of negative effects [66]. Such differences are explained by the fact that different MPs (including their chemical additives, some of which might be toxic), soils, and plants were used in these different studies, but it is not clear how each of these factors contributed to observed effects. Nor is it clear whether even major mechanisms by which MP may affect plant growth are understood. MP likely has different effects on different plant species in a plant community, which would explain the shift in grassland plant community composition that was observed following addition of MP fibers to soil [67].

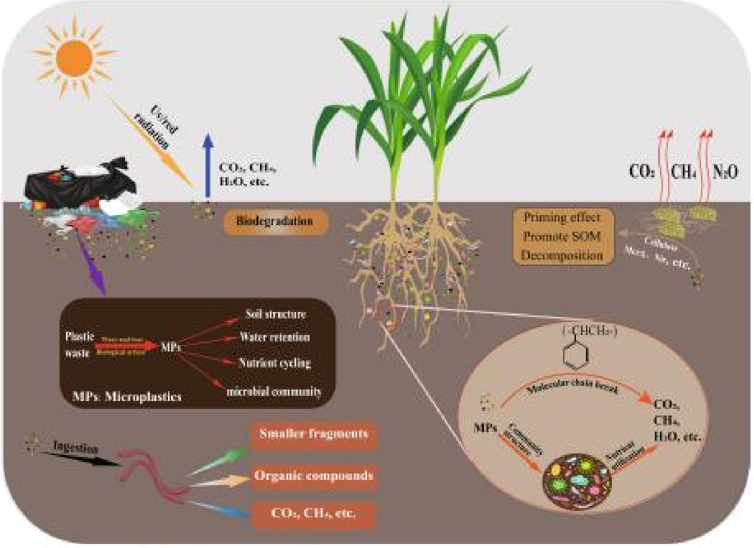
Figure 8: The toxic effects of microplastics on plants linked to reduced photosynthetic activity and CO2 sequestration potential [68].



Affecting the decomposition process

MP changes important physicochemical soil properties that are important environmental parameters for soil biota: the size of soil aggregates (mean weight diameter), soil porosity (aeration), and water holding capacity. Changes in microbial community composition have been observed in several cases and can have cascading effects on litter decomposition. Changes in microbial activity (e.g.,[69]) can be linked to (i) altered physicochemical soil properties; (ii) direct toxic effects of MP, its additives, or sorbed contaminants (in case of negative effects); and (iii) supply with microbially available organic carbon and nitrogen for some plastic types. The carbon in MP can cause a “priming” effect, i.e., increased microbial activity with potential changes in nutrient availability and dissolved organic C, but the large C: N ratio of most types of MP can also induce the immobilization of nutrients, and thus decrease microbial activity. Specific MP types, such as tire wear particles, are able to change the soil pH with consequences for the availability of nutrients and heavy metals [70]. There are direct effects of the presence of MP on soil biota that play a crucial role in decomposition. Key organisms for the incorporation of litter into the soil are earthworms (Lumbricidae). MP can cause skin lesions, increase mortality, and reduce reproductive rates in earthworms, thus reducing the transport of organic matter into deeper soil layers. Earthworms are a larger group of the soil biota with actual intake of MP particles and potentially fragmenting MP particles during digestion. Upon excretion, these particles become available to other soil organisms of the food web, e.g., smaller decomposers, such as microarthropods [71].

Figure 9: The impact of microplastics on soil greenhouse gas emissions [72].



Current Remediation Strategies

Education campaign

we believe a strong education campaign will focus not only on providing information about microplastics. There is an implicit assumption in the idea that once people become educated about a problem, they naturally begin to look for solutions—the assumption being that the former entails the latter. Hopefully, this false assumption has become abundantly clear with the case study of the climate crisis. Because of the success of the various misinformation campaigns and propagandas pieces disseminated by the fossil fuel industry over the years to delegitimize efforts to curb the climate crisis—many movements which broadly pertains to any ecological or environmental issue will by proxy face the same oppositional schools of thoughts which face climate crisis activists. This is likely to be the biggest threat to any education campaign. We therefore propose the following plan.

What to Say in the Campaign?

First, we must address the denial of science tactic which is the first line of opposition. With the case study of the climate crisis, it is not immediately apparent to a lay audience why rising temperatures is an issue. The true impact is abstract and not immediately tangible. It is much more difficult to explain to someone why they should care about the climate crisis than it is to convince someone why they should not [73].

- In order to convince someone that rising temperatures is a bad thing, the audience needs to be educated on the complex interplay between the environmental impact caused by the weather changes, then the cascading ecological disaster caused by habitats becoming unviable, then the resulting issue of drought, famine, plague etc caused by collapse of various food webs.
- In order to convince someone that rising temperatures is a good thing, the audience needs to be told it makes winters less cold so there is less snow to shovel.

Headline which could catch the attention most.

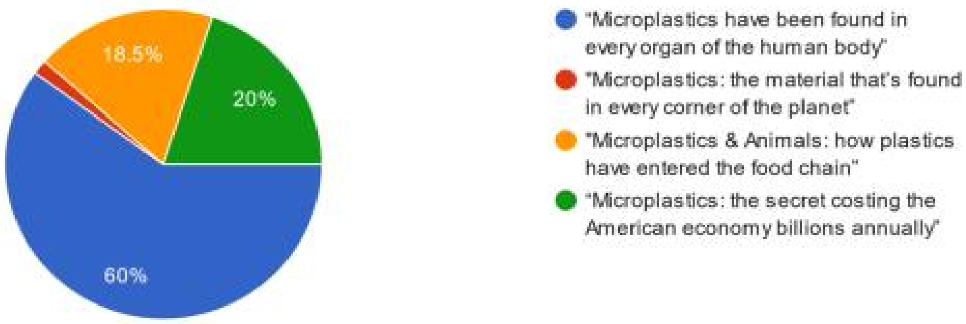


Figure 10: More than 60% indicates that "Microplastics have been found in every organ of the human body" as the most concerning headline—illustrating that the environmental, ecological, and economic impact of microplastics is far outweighed by the health concerns.

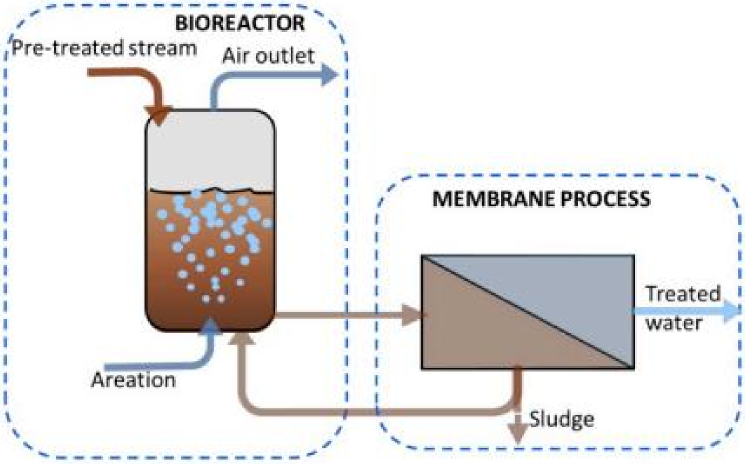
Plastic Alternatives

According to recent research, the alternative that holds the most promise is biopolymers. These biopolymers can be genetically engineered or naturally derived. There is a promising idea to use animal waste byproducts to create a biofilm alternative. In one study, animal waste was used to create a biopolymer out of whey protein which will degrade, as opposed to their plastic, petrochemical counterparts that do not degrade but instead create microplastics [74]. Similarly, the idea of bioplastics has surfaced as a potential solution. Bioplastics might sound similar to biopolymers, but make no mistake, there is a difference. Bioplastics are a "subset of biopolymers" which means that "all bioplastics are biopolymers, but not all biopolymers are bioplastics. Renewable bioplastics are plastic polymers created from renewable organic compounds like starch, sugar, and natural fibers [75]. Further, bioplastics are classified on either their composition or biodegradability: there are bioplastics created from renewable and non-fossil fuel sources (the starch, sugars, etc.) and are not biodegradable, there are bioplastics that are fabricated from carbon emission sources and are biodegradable, and there are bioplastics made with both renewable compositions and biodegradability [76]. One study researched the effect of bioplastics on soil, using earthworms as a test study. Where microplastics restrict plant growth, this study found that bioplastics do not limit soil biota and encourage root growth [77].

Filtration Systems

A widely known filtration technique is called Ultrafiltration, or UF. Membrane bioreactors show lots of promise. UF is a cleaning system that cleans and permits the reuse of wastewater and discharges waters with high levels of toxins in them; water from industries that deal with compounds like steels, plastics, resins, paper, pulp, food, and beverage. UF is successful due to its high molecular weight cut-off, a characterization method of a filter to describe pore size distribution, and the capabilities of the internal membranes. UF is a potentially feasible option because this filtration system gets dirty water back to drinking water standards with a relatively low energy consumption, high separation efficiency of ninety to one hundred percent removal, and compact plant size [74]. UF is just one removal and filtration technique developed that could potentially be implemented for microplastic remediation. Some of the others include but are not limited to, granular activated carbon filters, carbon block filters, reverse osmosis filters, and then there are the membranes. Specifically, membrane reactors, these biologically engineered and developed structurals might hold the most promise when wanting to solve truly clean microplastics from water in an environmentally friendly manner. There are many different types but the few this team studies are the following: Membrane Bioreactor (MBR), Dynamic Membrane (DM), Biocatalytic Membrane Reactor (BMR), and an anaerobic membrane bioreactor (AnMBR)

Figure 11: the role of MBR removal in wastewater treatment plants Photo taken from [74].



MBRs are already involved in the experimentation processes for filtering microplastics and have been performing well in not only the waste-water treatment industry, but food, pharmaceutical, biorefinery, and biodiesel production industries as well. Intrinsically, when humans want to clean their water, their first thought is to filter or boil the dirty water first. Seeing as the entire ocean is unable to be boiled at once, filtration is left. While this idea of mass filtration of large bodies of water works in theory, to clean every drop of water on the planet, solely relying on filtration methods will ultimately fail. Decreasing the generation of microplastics will be imperative to solving this facet of the microplastic issue. Additionally, a more proactive solution might be most beneficial in this case. Current remediation techniques are reactive - the microplastics come to the filter and the filter will react. The development of a technology that can navigate earth's aquatic environments and almost go hunting for microplastics could potentially start to help clean water.

Textiles

Textiles are one of the largest contributors to microplastics in the air and are the most likely reason that the concentration of microplastics inside is much larger than the concentration of microplastics outside. Refraining from producing fabrics with plastics in them, like microfiber [78] and polyester, would significantly decrease the microplastic contamination from this industry. Much of the literature suggests that textiles composed of synthetic materials and fabrics are an enormous source of microplastics both indoors and outdoors [79]. Using organic fiber fabric instead of plastic-filled materials like microfiber or polyester will certainly assist in lowering concentrations of microplastics or even decreasing the amount of microplastics generated.

Conclusion:

Because of their widespread distribution and harmful effects on ecosystems, human health, and biodiversity, microplastics have become a major environmental problem. They enter terrestrial, marine, and atmospheric systems and come from a range of sources, such as industrial operations, plastic debris, and personal care items. Because of their small size, organisms can easily absorb them, which can result in bioaccumulation and perhaps harmful effects. A multifaceted strategy including preventive, mitigation, and remediation techniques is needed to address this problem. Important preventative actions include lowering the manufacturing of plastic, encouraging sustainable substitutes, and putting strict waste management regulations into place. Innovative filtering systems, bioremediation, and adsorption are examples of advanced remediation technologies that show promise in reducing microplastic contamination. More research is necessary to provide scalable, economical, and ecologically friendly solutions. Legislators, businesses, researchers, and individuals must work together to reduce microplastic pollution and save the environment for the coming generations

REFERENCES

P. Gimeno et al., “Identification and quantification of 14 phthalates and 5 non-phthalate plasticizers in PVC medical devices by GC-MS,” J. Chromatogr. B Anal. Technol. Biomed. Life Sci., vol. 949–950, pp. 99–108, 2014, doi: 10.1016/j.jchromb.2013.12.037.

Y. Huang, Q. Liu, W. Jia, C. Yan, and J. Wang, “Agricultural plastic mulching as a source of microplastics in the terrestrial environment,” Environ. Pollut., vol. 260, 2020, doi: 10.1016/j.envpol.2020.114096.

Q. Gan, J. Cui, and B. Jin, “Environmental microplastics: Classification, sources, fates, and effects on plants,” Chemosphere, vol. 313, 2023, doi: 10.1016/j.chemosphere.2022.137559.

“Liebezeit G, Liebezeit E (2014) Synthetic particles as contaminants in German beers. Food Addit Contam A 31(9):1574–1578. https:// doi.org/10.1080/19440049.2014.945099”.

“The Lancet Planetary Health (2017) Microplastics and human health– an urgent problem. Lancet Planet Health 1(7):e254. https://doi. org/10.1016/S2542-5196(17)30121-3”.

“Andrady AL (2011) Microplastics in the marine environment... - Google Scholar”, [Online]. Available: https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=Andrady+AL+%282011%29+Microplastics+in+the+marine+environment.+Mar+Pollut++Bull+62%3A1596–1605&btnG=

“Jujun R, Jia L, Zhenming X (2013) Improvements of the recovery line of waste toner cartridges on environmental and safety performasnces. Environ Sci Technol 47(12):6457–6462. https://doi.org/10.1021/es305311k”.

“Gewert B, Plassmann MM, MacLeod M (2015) Pathways for degradation of plastic polymers foating in the marine environment. Environ Sci Process Impact 17(9):1513–1521. https://doi.org/ 10.1039/C5EM00207A”.

“Emadian SM, Onay TT, Demirel B (2017) Biodegradation of bioplastics in natural environments. Waste Manage 59:526–536. https:// doi.org/10.1016/j.wasman.2016.10.006”.

P. J. . ed. Kershaw, “GESAMP (2015). ‘Sources, fate and effects of microplastics in the marine environment: a global assessment,’” (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UNEP/UNDP Jt. Gr. Expert. Sci. Asp. Mar. Environ. Prot. Rep. Stud. GESAMP No. 90, 96 p., [Online]. Available: www.imo.org

“Shi C., Han X., Guo W., Wu Q., Yang X., Wang Y., Tang G., Wang S., Wang Z., Liu Y., et al. Disturbed Gut-Liver axis indicating oral exposure to polystyrene microplastic potentially increases the risk of insulin resistance. Environ. Int. 2022;164:107273. d”.

[K. Ziani et al., “Microplastics: A Real Global Threat for Environment and Food Safety: A State of the Art Review,” Nutrients, vol. 15, no. 3, 2023, doi: 10.3390/nu15030617.

“Boucher, J., & Friot, D. (2017). Primary microplastics in the oceans: A global evaluation of sources. Gland, Switzerland: IUCN.”.

A. A. Horton and S. J. Dixon, “Microplastics: An introduction to environmental transport processes,” Wiley Interdiscip. Rev. Water, vol. 5, no. 2, 2018, doi: 10.1002/WAT2.1268.

“Boucher, J., Friot, D., 2017. Primary Microplastics in the Oceans: a Global Evaluation of Sources. IUCN, Gland, Switzerland. https://doi.org/10.2305/IUCN.CH.2017.01.en.”.

“Auta, H., Emenike, C., Fauziah, S., 2017. Distribution and importance of microplastics in the marine environment: a review of the sources, fate, effects, and potential solutions. Environ. Int. 102, 165-176”.

A. A. Horton, A. Walton, D. J. Spurgeon, E. Lahive, and C. Svendsen, “Horton, A.A., Walton, A., Spurgeon, D.J., Lahive, E., Svendsen, C., 2017. Microplastics in freshwater and terrestrial environments: Evaluating the current understanding to identify the knowledge gaps and future research priorities. Sci. Total Environ. 586,” Sci. Total Environ., vol. 586, pp. 127–141, 2017, [Online]. Available: http://dx.doi.org/10.1016/j.scitotenv.2017.01.190

“Barnes, D.K., Galgani, F., Thompson, R.C., Barlaz, M., 2009. Accumulation and fragmentation of plastic debris in global environments. Philos. T. R. Soc. B 364, 1985-1998”.

A. Karami, A. Golieskardi, C. Keong Choo, V. Larat, T. S. Galloway, and B. Salamatinia, “The presence of microplastics in commercial salts from different1. Karami A, Golieskardi A, Keong Choo C, Larat V, Galloway TS, Salamatinia B. The presence of microplastics in commercial salts from different countries. Sci Rep. 2017;7(November 2016):1-9. ," Sci. Rep., vol. 7, no. November 2016, pp. 1–9, 2017, [Online]. Available: http://dx.doi.org/10.1038/srep46173

C. Wang, J. Zhao, and B. Xing, "Environmental source, fate, and toxicity of microplastics," J. Hazard. Mater., vol. 407, 2021, doi: 10.1016/j.jhazmat.2020.124357.

"Carr SA. 2017. Sources and dispersive modes of micro-fibers in the environment. Integr Environ Assess Manag 13:466-469".

"Sutton R, Mason SA, Stanek SK, Willis-Norton E, Wren IF, Box C. 2016. Microplastic contamination in the san francisco bay, california, USA. Mar Pollut Bull 109:230-235".

"Fendall, L.S., Sewell, M.A., 2009. Contributing to marine pollution by washing your face: microplastics in facial cleansers. Marine Pollution Bulletin 58, 1225– 1228.", [Online]. Available: https://www.researchgate.net/profile/Mary_Sewell/publication/222182425_Contributing_to_marine_pollution_by_washing_your_face_Microplastics_in_facial_cleansers/links/09e415090adf7c081d000000.pdf

"Napper IE, Thompson RC. 2016. Release of synthetic microplastic plastic fibres from domestic washing machines: Effects of fabric type and washing conditions. Mar Pollut Bull 112:39-45".

"Sillanpaa M, Sainio P. 2017. Release of polyester and cotton fibers from textiles in machine washings. Environ Sci Pollut Res Int 24:19313-19321.".

"De Falco F, Gullo MP, Gentile G, Di Pace E, Cocca M, Gelabert L, et al. 2018. Evaluation of microplastic release caused by textile washing processes of synthetic fabrics. Environ Pollut 236:916-925".

"De Falco F, Cocca M, Avella M, Thompson RC. 2020. Microfiber release to water, via laundering, and to air, via everyday use: A comparison between polyester clothing with differing textile parameters. Environ Sci Technol 54:3288-3296.".

Napper, "Napper, I.E., Bakir, A., Rowland, S.J., Thompson, R.C., 2015. Characterisation, quantity and sorptive properties of microplastics extracted from".

"Boots B, Russell CW, Green DS. 2019. Effects of microplastics in soil ecosystems: Above and below ground. Environ Sci Technol 53:11496-11506".

"Corradini F, Meza P, Eguiluz R, Casado F, Huerta-Lwanga E, Geissen V. 2019. Evidence of microplastic accumulation in agricultural soils from sewage sludge disposal. Sci Total Environ 671:411-420".

"von Moos N, Burkhardt-Holm P, Kohler A. 2012. Uptake and effects of microplastics on cells and tissue of the blue mussel Mytilus edulis l. After an experimental exposure. Environ Sci Technol 46:11327–11335.".

"Jingyi Li, Huihui Liu, J. Paul Chen*, Microplastics in freshwater systems: A review on occurrence, environmental effects, and methods for microplastics detection. Water Research 137 (2018) 362e374 - Cerca con Google", [Online]. Available: https://www.google.com/search?rlz=1C1GCEU_itIT820IT820&ei=1Au1X6TfIpK7UKvHqoAF&q=Jingyi+Li%2C+Huihui+Liu%2C+J.+Paul+Chen*%2C+Microplastics+in+freshwater+systems%3A+A+review+on+occurrence%2C+environmental+effects%2C+and+methods+for+microplastics+detection.

C. Xu et al., "Are we underestimating the sources of microplastic pollution in terrestrial environment?," J. Hazard. Mater., vol. 400, 2020, doi: 10.1016/j.jhazmat.2020.123228.

"Law, K.L.; Morét-Ferguson, S.; Maximenko, N.A.; Proskurowski, G.; Peacock, E.E.; Hafner, J.; Reddy, C.M. Plastic Accumulation in the North Atlantic Subtropical Gyre. Science 2010, 329, 1185–1188. [CrossRef]".

"Rodríguez-Seijo, A.; Lourenço, J.; Rocha-Santos, T.A.P.; Da Costa, J.; Duarte, A.C.; Vala, H.; Pereira, R. Histopathological and molecular effects of microplastics in Eisenia andrei Bouché. Environ. Pollut. 2017, 220, 495–503. [CrossRef]".

"Cai, L., Wang, J., Peng, J., Tan, Z., Zhan, Z., Tan, X., Chen, Q., 2017. Characteristic ofmicroplastics in the atmospheric fallout from Dongguan city, China: preliminary re-search and first evidence. Environ.

Sci. Pollut. Res. 24, 24928–24935. https://doi.org/10.1007/s11356-017-0116-x.”.

F. Haque and C. Fan, “Fate and Impacts of Microplastics in the Environment: Hydrosphere, Pedosphere, and Atmosphere,” Environ. - MDPI, vol. 10, no. 5, 2023, doi: 10.3390/environments10050070.

“Plastic Resin Pellets as a Transport Medium for Toxic Chemicals in the Marine Environment Environ. Sci. Technol. 2001, 35, 318-324”, [Online]. Available: http://www.mindfully.org/Plastic/Pellets-Transport-Medium.htm

“Cole, M.; Lindeque, P.; Halsband, C.; Galloway, T.S. Microplastics as contaminants in the marine environment: A review. Mar. Pollut. Bull. 2011, 62, 2588–2597. [CrossRef]”.

“Galvão, A.; Aleixo, M.; De Pablo, H.; Lopes, C.; Raimundo, J. Microplastics in wastewater: Microfiber emissions from common household laundry. Environ. Sci. Pollut. Res. 2020, 27, 26643–26649. [CrossRef]”.

“Cheng, Y.; Wang, J.; Yi, X.; Li, L.; Liu, X.; Ru, S. Low microalgae availability increases the ingestion rates and potential effects of microplastics on marine copepod Pseudodiaptomus annandalei. Mar. Pollut. Bull. 2020, 152, 110919. [CrossRef]”.

“Zhang K. et al. Understanding plastic degradation and microplastic formation in the environment: A review //Environmental Pollution. – 2021. – T. 274. – C. 116554.”.

“Sruthy, S., Ramasamy, E., 2017. Microplastic pollution in Vembanad Lake, Kerala, India: the first report of microplastics in lake and estuarine sediments in India. Environ. Pollut. 222, 315e322. https://doi.org/10.1016/j.envpol.2016.12.038.”.

“Claessens, M., De Meester, S., Van Landuyt, L., De Clerck, K., Janssen, C.R., 2011. Occurrence and distribution of microplastics in marine sediments along the Belgian coast. Mar. Pollut. Bull. 62, 2199e2204. https://doi.org/10.1016/ j.marpolbul.2011.06.03”.

“raveena, S. M.; Laohaprapanon, S. Quality Assessment forMethodological Aspects of Microplastics Analysis in Bottled Water -A Critical Review. Food Control 2021, 130, 108285”.

“Rillig, M. C.; Lehmann, A. Microplastic in TerrestrialEcosystems. Science 2020, 368 (6498), 1430−1431.”.

“hou, J.; Jia, R.; Brown, R. W.; Yang, Y.; Zeng, Z.; Jones, D. L.;Zang, H. The Long-Term Uncertainty of Biodegradable Mulch FilmResidues and Associated Microplastics Pollution on Plant-Soil Health.J. Hazard. Mater. 2023, 442, 130055”.

“Du, F.; Cai, H.; Zhang, Q.; Chen, Q.; Shi, H. Microplastics inTake-out Food Containers. J. Hazard. Mater. 2020, 399, 122969.”.

“Su, Y.; Hu, X.; Tang, H.; Lu, K.; Li, H.; Liu, S.; Xing, B.; Ji, R.Steam Disinfection Releases Micro(Nano)Plastics from Silicone-Rubber Baby Teats as Examined by Optical Photothermal InfraredMicrospectroscopy. Nat. Nanotechnol. 2022, 17 (1), 76−85.”.

“i, Q. L.; Yuan, M.; Chen, Y.; Jin, X. J.; Shangguan, J. F.; Cui, J.L.; Chang, S. X.; Guo, M. R.; Wang, Y. The Neglected PotentialSource of Microplastics from Daily Necessities: A Study on ProtectiveMobile Phone Cases. J. Hazard. Mater. 2023, 441, 129911.”.

“anerjee, A.; Shelver, W. L. Micro- and Nanoplastic InducedCellular Toxicity in Mammals: A Review. Sci. Total Environ. 2021,755, 142518.”.

“Kang, H. M.; Byeon, E.; Jeong, H.; Kim, M. S.; Chen, Q. Q.;Lee, J. S. Different Effects of Nano- and Microplastics on OxidativeStatus and Gut Microbiota in the Marine Medaka OryziasMelastigma. J. Hazard. Mater. 2021, 405, 124207.”.

“Deng, Y.; Chen, H.; Huang, Y.; Wang, Q.; Chen, W.; Chen, D.Polystyrene Microplastics Affect the Reproductive Performance ofMale Mice and Lipid Homeostasis in Their Offspring. Environ. Sci.Technol. Lett. 2022, 9 (9), 752−757”.

“Park EJ, Han JS, Park EJ, Seong E, Lee GH, Kim DW, et al. Repeated-oral dose toxicity of polyethylene microplastics and the possible implications on reproduction and development of the next generation. Toxicol Lett. 2020;324:75–85.”.

“Jin, H.; Yang, C.; Jiang, C.; Li, L.; Pan, M.; Li, D.; Han, X.;Ding, J. Evaluation of Neurotoxicity in BALB/C Mice FollowingChronic Exposure to Polystyrene Microplastics. Environ. HealthPerspect.

2022, 130 (10), 107002”.

“Liu H, Yang X, Liu G, Liang C, Xue S, Chen H, Ritsema CJ, Geissen V (2017) Response of soil dissolved organic matter to microplastic addition in Chinese loess soil. Chemosphere 185:907–917”.

“Awet TT, Kohl Y, Meier F, Straskraba S, Grün A-L, Ruf T, Jost C, Drexel R, Tunc E, Emmerling C (2018) Efects of polystyrene nanoparticles on the microbiota and functional diversity of enzymes in soil. Environ Sci Eur 30:11”.

“He L, Wu D, Rong H, Li M, Tong M, Kim H (2018) Infuence of nano-and microplastic particles on the transport and deposition behaviors of bacteria in quartz sand. Environ Sci Technol 52:11555–11563”.

“Arias-Andres M, Klümper U, Rojas-Jimenez K, Grossart H-P (2018) Microplastic pollution increases gene exchange in aquatic ecosystems. Environ Pollut 237:253–261”.

“Sun M, Ye M, Jiao W, Feng Y, Yu P, Liu M, Jiao J, He X, Liu K, Zhao Y (2018) Changes in tetracycline partitioning and bacteria/phagecomediated ARGs in microplastic-contaminated greenhouse soil facilitated by sophorolipid. J Hazard Mater 345:131–139”.

F. Zhu, C. Zhu, C. Wang, and C. Gu, “**微塑料在土壤系**统中的发生与生态影响:**土壤系**统中微塑料的发生与生态影响:综述 Occurrence and Ecological Impacts of Microplastics in Soil Systems : A Review,” Bull. Environ. Contam. Toxicol., no. May, 2019, [Online]. Available: https://doi.org/10.1007/s00128-019-02623-z

“Brennecke D, Duarte B, Paiva F, Cacador I, Canning-Clode J (2016) Microplastics as vector for heavy metal contamination from the marine environment. Estuar Coast Mar Sci 178:189–195. https://doi.org/10.1016/j.ecss.2015. 12.003”.

“Can-Guven E (2021) Microplastics as emerging atmospheric pollutants: a review and bibliometric analysis. Air Qual Atmos Health 14(2):203–215. https://doi.org/10.1007/s11869-020-00926-3”.

“Chai MW, Li RL, Li B, Wu HL, Yu LY (2023) Responses of mangrove (Kandelia obovata) growth, photosynthesis, and rhizosphere soil properties to microplastic pollution. Mar Pollut Bull 189. https://doi.org/10.1016/j. marpolbul.2023.114827”.

“Chen YX, Ling Y, Li XY, Hu JN, Cao CJ, He DF (2020) Size-dependent cellular internalization and efects of polystyrene microplastics in microalgae P. Helgolandica var. tsingtaoensis and S. Quadricauda. J Hazard Mater 399. https://doi.org/10.1016/j.jhazmat.”.

“Chen M, Bi M, Nie W, Chen Y (2022c) New insight into ammonium removal in riverbanks under the exposure of microplastics. J Hazard Mater 440. https://doi.org/10.1016/j.jhazmat.2022.129725”.

“Chen M, Liu S, Bi M, Yang X, Deng R, Chen Y (2022d) Aging behavior of microplastics afected DOM in riparian sediments: from the characteristics to bioavailability. J Hazard Mater 431. https://doi.org/10.1016/j.jhazmat. 2022.128522”.

K. Li, L. Du, C. Qin, N. Bolan, H. Wang, and H. Wang, “Microplastic pollution as an environmental risk exacerbating the greenhouse effect and climate change: a review,” Carbon Res., vol. 3, no. 1, 2024, doi: 10.1007/s44246-023-00097-7.

“de Souza Machado AA, Lau CW, Kloas W, Bergmann J, Bachelier JB, Faltin E, et al. Microplastics Can Change Soil Properties and Affect Plant Performance. Environ Sci Technol. 2019; 53:6044–52. https:// doi.org/10.1021/acs.est.9b01339 PMID: 31021077”.

“Smolders E, Degryse F. Fate and Effect of Zinc from Tire Debris in Soil. Environ Sci Technol. 2002; 36:3706–10. https://doi.org/10.1021/es025567p PMID: 12322741”.

“Barreto C, Rillig M, Lindo Z. Addition of polyester in soil affects litter decomposition rates but not microarthropod communities. Soil Org. 2020;92109–119–109–119. https://doi.org/10.25674/so92iss2pp109”.

M. C. Rillig, E. Leifheit, and J. Lehmann, “Microplastic effects on carbon cycling processes in soils,” PLoS Biol., vol. 19, no. 3, 2021, doi: 10.1371/JOURNAL.PBIO.3001130.

“Synthetic fibers in atmospheric fallout_ A source of microplastics in the environment_ _ Elsevier Enhanced Reader”.

“Lee, Jeo. ‘Economic Valuation of Marine Litter and Microplastic Pollution in the Marine Environment: An

Initial Assessment of the Case of the United Kingdom.’ Centre for Financial & Management Studies, July 2015, https://doi.org/126-142. SOAS University o”.

“Prüst, Minne, et al. ‘The Plastic Brain: Neurotoxicity of Micro- and Nanoplastics.’ Particle and Fibre Toxicology, vol. 17, no. 1, June 2020, https://doi.org/10.1186/s12989-020-00358-y”.

“Raffaele Marfella, et al. ‘Microplastics and Nanoplastics in Atheromas and Cardiovascular Events.’ The New England Journal of Medicine, vol. 390, no. 10, Massachusetts Medical Society, Mar. 2024, pp. 900–10, https://doi.org/10.1056/nejmoa2309822”.

“Prüst, Minne, et al. ‘The Plastic Brain: Neurotoxicity of Micro- and Nanoplastics.’ Particle and Fibre Toxicology, vol. 17, no. 1, June 2020, https://doi.org/10.1186/s12989-020-00358-y.”.

“Gao, Wei, et al. ‘Assessment of Quality Control Measures in the Monitoring of Microplastic: A Critical Review.’ Environmental Pollutants & Bioavailability, vol. 35, no. 1, Taylor & Francis, Apr. 2023, https://doi.org/10.1080/26395940.2023.2203349”.

“Browne, Mark Anthony, et al. ‘Accumulation of Microplastic on Shorelines Woldwide: Sources and Sinks.’ Environmental Science & Technology, vol. 45, no. 21, Nov. 2011, pp. 9175–79”.