THOMAS ADEWUMI UNIVERSITY, OKO, KWARA STATE
Science | Technology | Medicine

**Thomas Adewumi University Journal of Innovation, Science and Technology (TAU-JIST)**

***ISSN: 3043-503X***

***REVIEW ARTICLE***

# MICROPLASTICS IN THE ENVIRONMENT: IMPACT AND MITIGATION STRATEGIES

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**ARTICLE DETAILS**

***Article History:***

Received 02 July 2024
Accepted 05 October 2024
Available online 10 November 2024

## ABSTRACT

Microplastics are ubiquitous materials that present a profound and complex challenge with far-reaching impacts on both ecological systems and human health. Despite their microscopic size, they have a disproportionate impact, affecting marine and terrestrial environments, infiltrating food webs, and potentially harming human health. This review sheds light on the widespread presence and diverse origins of microplastics in the environment, emphasizing their role in bioaccumulation and their potential to act as carriers for toxic substances. This report also identified critical areas for intervention, including source reduction, improved waste management, and advanced bioremediation technologies. In conclusion, to curb microplastics pollution, the review recommends coordinated interdisciplinary efforts, improved detection technologies, and stricter regulatory frameworks.

**KEYWORDS**

Microplastics, Environment, Ecological impact, Waste management

## Introduction

Microplastics (MPs) are plastic particles smaller than 5 mm, which come from the degradation of plastics. They are ubiquitous in nature, and therefore impact both humans and animals. They have been detected in many marine species, drinking water and in numerous foods, such as salt, honey, etc. Exposure to microplastics can also occur through inhaled air (Roy et al., 2022). MPs act as carriers for persistent organic pollutants and heavy metals, transferring them from invertebrate organisms to higher trophic levels. Data from animal studies have shown that once absorbed, micro- and nanoplastics can distribute to the liver, spleen, heart, lungs, thymus, reproductive organs, kidneys and even the brain. In these organs, the additives and monomers in the microplastics' composition can interfere with important biological processes and can cause disruption of the endocrine system, immune system, and can have a negative impact on mobility, reproduction and

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| | **Website:** https://journals.tau.edu.ng/index.php/tau-jist | **DOI:** https://doi.org/10.5281/zenodo.14202531 |

development, as well as cause carcinogenesis (Mitrano et al., 2020).

As a result of the COVID-19 pandemic, there has been a remarkable increase in global use of face masks, which mainly contain polypropylene. The poor waste management of these materials has led to worsening microplastic pollution, and the long-term consequences can be extremely devastating if urgent action is not taken. Microplastics originate from both primary and secondary sources. Primary microplastics, such as microbeads found in cosmetics and cleaning products, and fiber fragments released during the washing of synthetic textiles, are intentionally produced or released. Secondary microplastics result from the breakdown of larger plastic debris through physical, chemical, and biological processes (Usman et al*.,* 2022; Roy et al*.,* 2022). Marine organisms, such as zooplankton, mussels, oysters, shrimp, and fish, are at risk of direct ingestion of microplastics or indirect exposure through the food web, resulting in potential ecological disruptions (Martín-Lara et al*.,* 2021).

The scale of plastic production and its persistence in the environment exacerbate the microplastic crisis. Common polymers, such as polyethylene (PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), and polyester, are prevalent in microplastic pollution. In 2015, the global plastic production exceeded 300 million tons, driven primarily by the manufacture of PE, PP, polyvinyl chloride (PVC), polyurethane (PUR), PS, and PET. These plastics are favored for their durability and resistance to degradation, yet their persistence leads to widespread accumulation in soils, rivers, lakes, and oceans (Witczak et al*.,* 2024). A 2014 study estimated that 0.48 to 1.27 million tons of plastic waste enter the ocean annually, and this figure is expected to double within a decade, with microplastics making up a significant portion of this debris (Ritchie et al*.,* 2023).

Beyond environmental harm, microplastics pose significant risks to human health. They have been detected in food items, drinking water, and even in human tissues such as the placenta and stool, raising concerns about bioaccumulation. Microplastics enter the human body through ingestion, inhalation, and dermal contact, with potential adverse effects, including inflammation, oxidative stress, and tissue damage. Moreover, the chemical additives in plastics, such as plasticizers and flame retardants, can leach out, exacerbating these health risks. Exposure to microplastics may lead to chronic conditions, including cardiovascular disease, cancer, autoimmune disorders and reproductive issues (male infertility and low sperm quality) (Damaj, Trad, Goevert & Wilkesmann 2024); O'Brien, Peirano & van den Berg 2023).

The persistence, small size, and global distribution of microplastics, combined with their ability to act as carriers for toxic chemicals, make them a particularly challenging environmental pollutant. While biodegradation of plastics, such as PE, PS, and PET, under specific conditions has shown promise, current remediation strategies are inadequate to fully address the scale of the issue. Effective control of microplastic pollution must prioritize source reduction, alongside the development of innovative and cost-effective remediation technologies (Curren et al., 2021; Conti et al., 2021).

Despite the growing body of research, significant knowledge gaps remain regarding the full impact of microplastics on both environmental and human health. Microplastics' high surface area and hydrophobicity allow them to adsorb other pollutants, potentially increasing their toxicity when ingested by organisms. This review aims to provide a comprehensive overview of microplastics, focusing on their sources, pathways into the environment, and impacts on human and ecological health. Additionally, it will discuss current approaches for the removal of microplastics from the environment and highlight the need for the development of more efficient mitigation strategies (Roy et al*.,* 2022). By synthesizing the latest research, this review seeks to inform policymakers, scientists, and stakeholders in their efforts to reduce microplastic pollution and its associated risks to both ecosystems and human well-being (Witczak et al*.,* 2024).

## Transport Mechanisms and Environmental Fate

Microplastics are widespread in both terrestrial and aquatic ecosystems, making them complex to manage (Petersen & Hubbart, 2021). There are different routes through which microplastics get into the environment (Ahmed et al., 2021). The microplastics in the environment are mostly found in water bodies, sediments, soils and animal biomass (Lau et al., 2020). Different transport mechanisms for microplastics exist in the environment (Peng et al., 2020). Their density, shape, polymer type, and dielectric constant determine their distribution and transport patterns (Rios Mendoza, Leon Vargas, & Balcer, 2021). Out of various microplastics, fibers are the most widely distributed from their sources, and they do not degrade easily (Koutnik et al., 2021).

Plastics generally have a long degradation time, leading to great accumulation in both land and aquatic ecosystems (Lau et al., 2020). The mismanagement of plastic wastes and their slow degradation make water bodies a primary accumulation point for plastics (Martínez et al., 2024). There exist a relationship between anthropogenic activities and the movement of microplastics from land to water (Kwon, Kang, Hong, & Shim, 2020). The aquatic ecosystem appears to be the worst hit by plastic pollution.

Microplastics mostly get into water bodies through mismanaged waste waters from homes and industries (Ramírez-Álvarez et al., 2020). They can also be moved by wind and runoffs from one place to the other (Mason et al., 2016). Rivers serve as important pathways of microplastics from the terrestrial environment to the oceans (Jambeck et al., 2015). These microplastics get vertically transported to the bottom of rivers and oceans, and they do not degrade easily (Martínez et al., 2024). This way, microplastics usually build up in estuarine sediments (Su et al., 2020). Mechanisms such as biofouling, aggregation, fragmentation, bioaccumulation, organism ingestion and current are responsible for the transport of microplastics within an ocean (Peng et al., 2020).

The amount and location of microplastics in oceans is usually determined by the current of the ocean (Jiang, Yang, Zhao & Wang, 2020). On an annual basis, macroplastics and microplastics of close to 10 million metric tons and 2 million metric tons respectively get into the oceans (Lau et al., 2020). Polyethylene and polypropylene are the predominant polymers found as sediments in oceans and other water bodies (Martínez et al., 2024).

Microplastics have also been found in the atmosphere in significant amount (Rios Mendoza, 2021), showing that they can be effectively transported by air (Martínez et al. 2024). Thus, microplastics can travel great distances before finally being deposited, making the environmental management of these particles more complex and challenging (Lau et al., 2020). Ultimately, the environmental fate of microplastics is largely determined by their physical properties and interaction with the environment (Rios Mendoza et al., 2021).

## Ecological Consequences of Microplastics

The consequences of microplastics pollution are multifaceted, affecting ecosystem structure, biodiversity, and functioning across various habitats (Bhuyan, 2022; Madiraju, Pamula, & Darsi*,* 2024). The presence of microplastics in ecosystems alters the physicochemical characteristics of the non-living environment, modifies the habitats where organisms reside and microbial properties. (He et al*.,* 2022; Wang, Zhang, Gao, & Wu, 2024). These particles interact with organisms both directly and indirectly, triggering a range of toxicological and ecological consequences. (Miller et al., 2020).

Microplastics could also affect essential biogeochemical processes such as carbon and nitrogen processes (Wang, Bai, Liu, Li, & Zhang 2023; Wang et al*.,* 2024). Microplastics have also been shown to disrupt energy flow within ecosystems by interfering with key processes. Such processes include the fixation and transfer of energy in primary producers, the acquisition, consumption, and distribution of energy in consumers, and energy metabolism in decomposers. Such disruptions can significantly impact overall ecosystem functioning and energy dynamics(López-Rojo et al., 2020).

## Impact on Marine Life and Food Webs

The marine habitat is the most extensively studied environment for microplastic contamination, because it is a major source of food for humans (Pironti et al., 2021). Studies have sought to establish the relationship between the presence of microplastics in the marine environment and their effects on both biotic and abiotic features (Bellas, Martínez-Armental, Martínez-Cámara, Besada, & Martínez-Gómez, 2016).

Microplastics have been identified as emerging pollutants with the potential to negatively affect aquatic ecosystems (Guilhermino, et al., 2018; Tang et al., 2021). Other water pollutants, including antibiotics, dyes, heavy metals, and chemicals, readily adhere to MPs, making them effective carriers of these pollutants into aquatic species (Ashrafy et al., 2023). Several studies have shown that microplastics adsorb and accumulate hazardous organic pollutants from aquatic environments, leading to concentrations of these pollutants in microplastics being hundreds or even thousands of times higher than in the surrounding water (Hirai et al., 2011; Zhao, et al., 2020).

Microplastics can enter marine food webs through ingestion, inhalation, entanglement, and trophic transfer (Setälä, Lehtiniemi, Coppock, & Cole, 2018). Investigations by researchers on the fate of microplastic upon ingestion by aquatic organisms revealed that it can be translocated within the tissues of different organ, may undergo egestion via pseudo-faeces or get accumulated in the specific tissue within the body (Thompson et al., 2004; Avio et al., 2015; Gola et al., 2021). These chemicals accumulate in the body from various sources. For instance, when a predator consumes a crustacean contaminated by microplastics, it becomes indirectly contaminated. If the predator consumes multiple contaminated shellfish, the chemicals accumulate in its digestive tract, a process known as bioaccumulation (Goodman, Hua, & Sang, 2022). Once microplastic get accumulated in the body tissue, it can cause multiple adverse effect on the health of the organism i.e., infertility, retardation in growth, internal or external injuries, blockage of body tracts. The bioaccumulated contaminant can cause potential health risk to the sea food consumers (van Raamsdonk et al., 2020). It has been reported that a consumer who regularly eats large quantities of seafood may ingest an estimated 11,000 plastic particles annually (Van Cauwenberghe, & Janssen, 2014, Ziani et al., 2023).

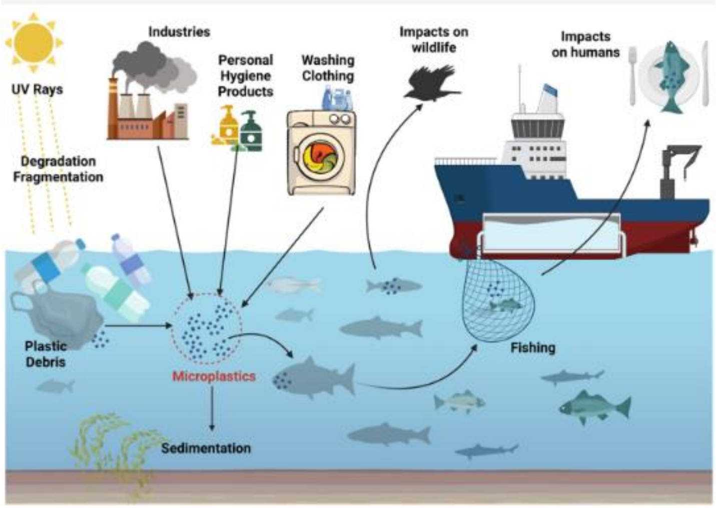


**Figure 1.** Microplastics in the marine environment. *Reprinted from* Ziani et al. (2023 Figure 1, p. 6)

## Effects on Terrestrial Organisms and Soil Health

While much of the focus and research has been on microplastic pollution in marine environments, the terrestrial environment also warrants significant attention, as microplastic not only contaminates the land but is also transferred to marine and other aquatic ecosystems (Surendran, Jayakumar, Raja, Gopinath, & Chellam, 2023). It is estimated that 75–90% of plastic debris found in the marine environment is of terrestrial origin (Duis & Coors, 2016). The origin of MPs is largely linked with anthropogenic products and activities including mulching, cosmetics, laundry and personal care, the textile industry (microfibers), car manufacturing (tire abrasion and tire wear particles), and plastic products, various aspects of agriculture practices, industry, and manufacturing (Ding et al., 2022; Periyasamy & Tehrani-Bagha, 2022; Rai et al., 2023) .

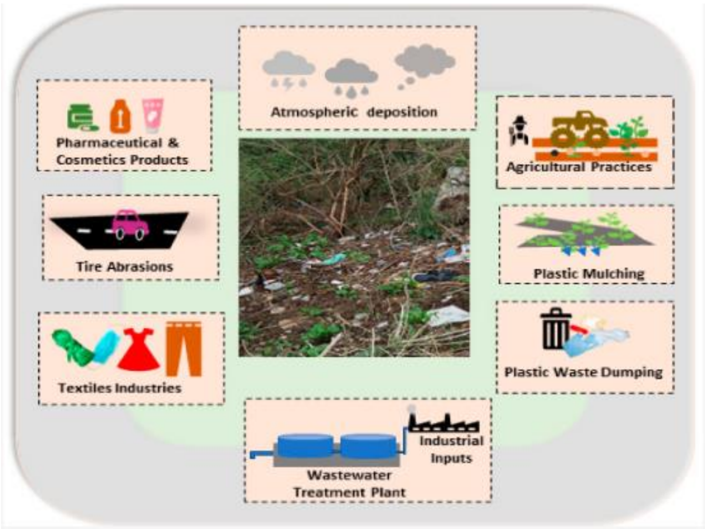

**Figure 2:** Potential sources of microplastics in soil *Adapted from* Rai et al. (2023).

Microplastic pollution in soil ecosystems can negatively affect soil health and disrupt overall ecosystem functioning (Li et al., 2023). These impacts have been reported in the agricultural soil physicochemical properties such as pH; bulk density and water holding capacity; porosity; soil aggregations; and hydraulic conductivity (Yu, Zhang, Tan, & Zhang, 2022; Rai et al., 2023). The impact of MPs is not limited to the physical and chemical properties of the soil; there is also significant effect on soil-dwelling organisms such as plants, invertebrates, and microorganisms (Sajjad et al., 2022). These changes ultimately disrupt nutrient cycling and alter microbial communities, which in turn lead to reduced soil fertility and lower soil quality, ultimately resulting in decreased plant yield (Li et al., 2023).

Studies have shown that microplastics negatively affect plant growth by hindering seed germination, restricting root growth, and impairing nutrient uptake, while also causing oxidative stress, cellular toxicity, and genetic damage (Jiang et al., 2019; Mondal, Kundu, Debnath, Mondal, & Sen, 2022). MPs can disrupt various aspects of plant physiology, including development, mineral uptake, photosynthetic processes, and metabolite production. Additionally, they can be taken up by roots and transported to other parts of the plant (Dhevagi, Keerthi Sahasa, Poornima, & Ramya, 2024; Mészáros et al., 2023).

## Bioaccumulation and Biomagnification in Wildlife

Research has demonstrated that microplastics can accumulate in organisms' bodies through the food chain (Lohmann, 2017; Saeedi, 2023) as they transfer from prey to predators, with the potential to impact entire ecosystems (Jeong, Lee, & Redwan, 2024). The ingestion of microplastics alters feeding behavior by affecting food intake and causing a false sense of satiation (Robson et al., 2020). This can result in malnutrition and an inadequate energy supply negatively impacting growth and/or metamorphosis as well as altering metabolic rates ultimately leading to increased mortality (Teampanpong, & Duengkae, 2024). Furthermore, animals exposed to microplastics are more susceptible to pathogens, oxidative stress disruptions, and increased mortality (Subaramaniyam et al., 2023).

## Human Health Implications of Microplastics and Nanoplastics

Physical contact with microplastics may occur through skin exposure, particularly for individuals frequently handling plastic materials (e.g., in textile or waste management industries). Over time, these interactions may lead to skin irritation or other localized effects, especially if the microplastics carry harmful chemicals or pollutants on their surface (Prata, da Costa, Lopes, Duarte, & Rocha-Santos, 2020). Ingestion is one of the most common forms of exposure, affecting both humans and animals. Humans can ingest microplastics directly through contaminated food and water or indirectly by consuming animals that have ingested microplastics themselves. Once ingested, microplastics can accumulate in the gastrointestinal tract, potentially causing physical damage, inflammation, and exposure to toxic additives and adsorbed environmental contaminants, which could lead to longer-term health impacts (Smith,Love, Rochman, & Neff, 2018). Inhalation exposure occurs as airborne microplastic particles become suspended in the air from clothing fibers, synthetic textiles, or degraded plastic materials. This form of exposure is especially prevalent indoors, where microplastic fibers from textiles and furnishings can accumulate in the air. Inhaled microplastics may deposit in the respiratory tract, leading to respiratory irritation, inflammation, and chronic conditions, particularly with prolonged exposure (Prata, 2018).

Microplastics appearing in remote locations can be explained by the plastic cycle (Horton and Dixon 2018), whereby a concerning amount of plastic waste escapes into the environment, polluting land, waterways, and oceans. Microplastics can enter the water cycle, becoming part of rain clouds. This contaminated rain can then fall on remote areas, such as mountains (Bank and Hansson 2019). Shockingly, microscopic plastic fragments have been found in salt meant for the dinner tables (Shokunbi, Jegede, & Shokunbi, 2023). These MPs can originate from various sources, such as marine pollution, industrial processes, and the breakdown of larger plastic items

(Peixoto et al. 2019). Similarly, Microplastics can be found in bottled drinking water, in beer, energy drinks and other soft drinks (Kosuth, Mason, & Wattenberg. 2018, Shruti, Pe´rez-Guevara, Elizalde-Martı´nez, and Kutralam-Muniasamy. 2020). This can occur from leaches from the caps of plastic bottles or from the plastics itself (Choudhary, Kurien & Srivastava, 2020). Water treatment processes may not effectively eliminate all microplastic particles, leading to environmental contamination of water bodies that are subsequently used in bottling (Cao et al., 2024). Microplastics can also accumulate in the flesh of fruits and vegetables when polluted water is used to wash them (Conti et al., 2020).

Microplastics are increasingly recognized for their potential impact on human health. They are a leading concern due to their accumulation and interaction with biological systems. Ingested microplastics may accumulate in the gastrointestinal (GI) tract, causing physical irritation or blockage in extreme cases. Studies have shown potential inflammatory responses in the gut lining, leading to conditions such as gut dysbiosis. Many plastics contain toxic additives like flame retardants, plasticizers, and heavy metals. When microplastics are ingested, these chemicals can leach into the body, causing systemic toxicity, including endocrine disruption, neurotoxicity, and even liver damage.

Phthalates are commonly used as plasticizers to provide flexibility to plastics. They are an additive, therefore not chemically bound (covalently bonded) to the polymer and so are more likely to be released and transfer to the environment. Upon ingestion, microplastics can translocate to the bloodstream, organs, and tissues, potentially causing physical and chemical toxicity. For example, recent studies have shown that ingested microplastics can cause inflammation in the gastrointestinal tract, alter gut microbiota, and even affect metabolic processes (Galloway et al., 2017). The release of toxic additives, such as phthalates and bisphenol A, during microplastic degradation is also associated with endocrine disruption, which can impact hormone regulation, particularly in reproductive and developmental health (Rochman, Hentschel & The, 2014). Phthalates also present potential risks to metabolic health, increase adipogenesis by activating peroxisome proliferator-activated receptors (PPARs), contributing to weight gain and metabolic disturbances and phthalates may impact respiratory health. BPA may influence cardiovascular health, with studies showing associations between BPA levels and hypertension as well as other cardiovascular risk factors (Chen et al., 2023). Styrene exposure, particularly through inhalation or ingestion of styrene-containing products, has raised health concerns, primarily due to its carcinogenic potential. The International Agency for Research on Cancer (IARC) classifies styrene as a possible human carcinogen (Group 2B), with research suggesting that prolonged exposure to styrene may elevate the risk of developing leukemia and lymphoma. Beyond its cancer-related risks, styrene exposure also poses threats to the nervous system. Short-term exposure can lead to symptoms such as headaches, dizziness, and fatigue, while long-term exposure has been linked to neurotoxic effects, including memory problems and behavioral changes (Moshiran, Karimi, Golbabaei, Sadeghi & Moshiran, 2021). Additionally, some studies have linked styrene exposure to respiratory issues and irritation of the eyes, nose, and throat, with long-term effects including chronic respiratory symptoms among workers with significant exposure (Agency for Toxic Substances and Disease Registry, 2010).

Airborne microplastics, found in both indoor and outdoor environments, can be inhaled and accumulate in lung tissues. Inhaled microplastics may deposit in the respiratory tract, causing irritation, inflammation, and potentially chronic respiratory conditions such as asthma or bronchitis. Some studies suggest that the inhalation of microplastics could contribute to respiratory diseases, including fibrosis or lung cancer. A study conducted by Prata (2018) highlighted that inhaled microplastics might lead to respiratory issues, such as inflammation and fibrosis, particularly among people with long-term exposure. Moreover, research on human cell cultures suggests that microplastics can induce oxidative stress, cellular damage, and even apoptosis (Gautam et al., 2022). These processes are implicated in chronic diseases, including cardiovascular and neurodegenerative diseases, thus linking microplastics to broader health risks. However, long-term studies are still required to fully understand the chronic impact of microplastics on human health. There have been many studies that show there are MPs in the atmosphere that can be readily inhaled (Liu, Wang, Wei, Song & Li. 2019, Zhang et al.,2020, Huang, Qing, Wang, Han & Wang, 2020).

### Microplastics as Vectors for Harmful Chemicals and Pathogens

It is suggested that Microplastics could become the source or carrier of pesticides into other environments, such as water, and have the potential for environmental and human safety risks (Ziani et al., 2023).

Pesticides, such as carbendazim, dipterex, and malathion, can readily adhere to the surface of microplastics (Bao et al., 2024). This adsorption process is influenced by factors like the chemical properties of the pesticide, the surface characteristics of the microplastic, and environmental conditions. The adsorption of pesticides onto microplastics can have severe environmental and human health implications such as persistence leading to their bioaccumulation in organisms at higher trophic levels, including humans. These exposures may pose risks to human health, particularly affecting vulnerable populations like children and the elderly. Microplastics with adsorbed pesticides can enter terrestrial ecosystems through various mechanisms, such as wind and water (Hoang et al., 2024). These contaminants can impact soil quality, plant growth, and biodiversity. Additionally, antibiotics can adsorb to microplastics in contaminated waters and result in them being transported long distances. Although experimental evidence on the ecotoxicological effects of antibiotic-sorbed microplastics remains limited, the potential risk is clear (Stapleton, Ansari & Hai, 2023).

Microplastics also adsorb and concentrate persistent organic pollutants (POPs) like polychlorinated biphenyls (PCBs), dioxins, and pesticides from their surrounding environment (Wang, Lin, Dong, Chen, & Liu, 2021). Once ingested by humans, these chemicals can be released into the body, posing risks such as endocrine disruption, carcinogenic effects, and neurotoxicity. Heavy metals, such as cadmium, lead, and mercury, can also bind to microplastics. These metals are toxic at low concentrations and can accumulate in human tissues, causing kidney damage, neurodevelopmental issues, and immune suppression.

Weathering occur in plastics due to degradation from sunlight, temperature changes, and physical forces, they become rougher and more fragmented, forming ideal surfaces for microbial colonization. This colonized plastic surface is known as the plastisphere (Zettler, Mincer & Amaral-Zettler, 2013). The plastisphere is composed of a wide variety of microorganisms, including bacteria, fungi, and algae, which may have both ecological and health implications. The plastisphere is an ecological niche that creates a unique microbial community on plastic surfaces. Unlike natural particles in marine systems, plastic particles are resistant to breakdown and can travel great distances in the ocean, introducing microbes to new ecosystems. The plastisphere's microbial inhabitants often differ from those on natural substrates, potentially due to the plastic's unique chemical composition and its tendency to adsorb organic pollutants and metals from surrounding water. These distinct conditions foster the growth of certain microorganisms that may not be as prevalent on natural surfaces. A growing body of research has revealed that the plastisphere can act as a reservoir for antibiotic resistance genes (ARGs), creating significant risks for both environmental and human health (Arias-Andres, Klümper, Rojas-Jimenez & Grossart, 2018). If antibiotic-resistant bacteria from marine systems enter human populations—through seafood consumption, water exposure, or other pathways—they could contribute to the global issue of antibiotic resistance, which limits our ability to treat bacterial infections effectively. Research indicates that the plastisphere can serve as a reservoir for antibiotic resistance genes (ARGs), posing potential risks to human and environmental health (Arias-Andres, Klümper, Rojas-Jimenez & Grossart, 2018). ARGs are genes within bacterial communities that provide resistance to antibiotics, allowing bacteria to survive and proliferate despite antibiotic exposure. The presence of ARGs on plastisphere-associated microbes may facilitate the spread of antibiotic resistance in aquatic ecosystems. Sources of ARGs in the plastisphere likely include wastewater discharges, agricultural runoff, and other human activities that introduce antibiotics and resistant bacteria into marine environments (Oberbeckmann, Kreikemeyer & Labrenz, 2015). Microplastics can provide a beneficial surface for antimicrobial resistant bacteria to form a biofilm and facilitate horizontal gene transfer, which they would otherwise be unable to do in water alone and this could lead to the enrichment of superbugs (Blackburn & Green, 2021).

Unlike free-floating bacteria, those attached to microplastics benefit from the stability and concentrated surface area that these particles provide, enhancing their capacity to survive and proliferate (Arias-Andres et al., 2018). Research indicates that the rough surfaces of microplastics allow for diverse microbial communities to develop biofilms, creating an environment conducive to gene exchange that might not be possible in the open water column (Zettler, Mincer and Amaral-Zettler, 2013).

Within these biofilms, bacteria can efficiently transfer antibiotic resistance genes (ARGs) through horizontal gene transfer (HGT) mechanisms, including conjugation, transduction, and transformation, which accelerates the spread of antibiotic resistance. This process raises significant public health concerns, as it supports the development of "superbugs"—bacteria with multiple resistance genes that are increasingly difficult to treat with standard antibiotics (Kirstein et al., 2016). Additionally, the widespread presence and movement of microplastics enable these bacteria-laden particles to disperse throughout aquatic ecosystems, potentially introducing ARGs to new environments and worsening the antibiotic resistance crisis (Ziani et al., 2023)

## Mitigation Strategies: Prevention and Policy

Microplastics are rapidly garnering the attention of researchers and policymakers worldwide (Munhoz, Harkes, Beriot, Larreta, & Basurko, 2022). This has led to the development of different policies and strategies to combat the growing microplastics scourge. These strategies include, banning plastic microbeads from cosmetics, promoting the use of biodegradable materials, improving the recycling of plastics, efficient separation of plastics at wastewater treatment plants, and developing clean-up and bioremediation technologies (Wu, Yang, & Criddle, 2017). The global microplastics mitigation strategies are divided into upstream (pre-consumption) and downstream (post-consumption) (Lau et al., 2020). The pre-consumption strategies are aimed at demand reduction, while collection and recycling are the main focus of the post-consumption strategies. The upstream strategies are largely driven by sensitization and awareness campaigns coupled with right intergovernmental policies.

Although microplastics regulation did not gain traction until the early 2000s (Munhoz et al., 2022), there are now a number of international agreements and policies that have been put in place to mitigate the environmental impact of microplastics. For example, the Basel Convention has been amended to include clauses regulating trade in microplastics (Lau et al., 2020). The Brazil Conference of the United Nations (UN) on Sustainable Development held in 2012 drew tremendous attention to the microplastics menace (Critchell et al., 2019). Since then, the UN has continued to provide guidelines for mitigation of the microplastics challenge (Pettipas, Bernier, & Walker, 2016).

Consequently, international bodies like the International Coral Reef Initiative, the European Chemicals Agency and the Secretariat of the Antarctic Treaty approved microbeads plastic reduction (Jemec Kokalj, Kuehnel, Puntar, Žgajnar Gotvajn, & Kalčičková, 2022). Also, the International Convention for the Prevention of Pollution from Ships made it unlawful for plastic wastes to be dumped into the sea (Martínez et al., 2024). In addition, countries like Canada have classified microplastics as toxins (Munhoz et al., 2022; Pettipas, Bernier, & Walker, 2016). Many countries have also outlawed the use of some plastic products such as single-use plastics and even microbeads in cosmetics production (Lau et al., 2020). The US, UK, the Netherlands, France, Taiwan, South Korea, and Sweden have all outlawed the use of microplastics in wash-off cosmetic products (Al-Salem, Uddin, & Al-Yamani, 2020; Karbalaei, Hanachi, Walker, & Cole, 2018).

In Greenland, the government has implemented a central waste management system that enforces the transfer of wastes from smaller areas to major urban centres for incineration (Martínez et al., 2024). According to Lau et al. (2020), "Implementing recycling and waste management systems at scale could reduce plastic pollution by 45% in aquatic and terrestrial systems by 2040". To achieve this, more efforts are required in terms of infrastructural provisions and policy enactment and implementation. In addition, enhanced public awareness on the dangers of microplastics pollution has the potential of significantly reducing the demand for plastic products like single-use plastics, leading to reduced microplastic pollution (Lau et al., 2020).

### Innovative Solutions for Microplastic Reduction

Efforts to combat microplastic pollution, which accumulates in aquatic systems, soils, and the atmosphere, have inspired a range of innovative strategies focused on reducing its environmental presence and impact.

### Development of Biodegradable Plastics

The term "bioplastic" is often used interchangeably with "biodegradable," though not all bioplastics are, in fact, biodegradable. There are three broad groups of bioplastics: those that are both bio-based and biodegradable, those that are only bio-based but not biodegradable and those that are only biodegradable.

Bioplastics (bio-based polymers) are perceived to be better alternative to conventional (petroleum-based) plastics (Atiwesh, Mikhael, Parrish, Banoub, & Lee, 2021). They are designed to degrade within months or years (Thakur et al., 2018). These plastics, derived from renewable sources like starch, cellulose, and polylactic acid (PLA), break down into organic compounds (Shafqat et al., 2020; Rajeshkumar et al., 2021). However, the successful widespread adoption of biodegradable plastics depends on developing improved materials that degrade efficiently in a broader range of environments, including marine settings where many microplastics end up (Moshood et al., 2022).

It should also be noted that the impact of bioplastics on the environment is still unclear due to the lack of sufficient data (Islam et al., 2024).

### Bioremediation Approaches (Microorganisms and Enzymes for Plastic Degradation)

Studies have indicated that bacteria, bacterial consortia, biofilm formation, and fungi can biodegrade various polymers (Syranidou et al., 2017; Yan, Wei, Cui, Bornscheuer, & Liu, 2021; Lokesh et al., 2023). Depending on factors such as the organisms involved, the molecular weight of the plastic, the type of polymer, and environmental conditions (Pischedda, Tosin, & Degli-Innocenti, 2019; Chamas et al., 2020) , waste plastics can be broken down into methane, carbon dioxide, biomass, water, and inorganic compounds.

Certain bacteria and fungi, such as *Ideonella sakaiensis* and *Aspergillus tubingensis*, have demonstrated the ability to degrade common plastics, like PET and polyurethane, into simpler compounds (Temporiti, Nicola, Nielsen, & Tosi, 2022; Srikanth, Sandeep, Sucharitha, & Sudhakar, 2022). Researchers are exploring ways to enhance the natural degradation capabilities of these microorganisms through genetic engineering and optimizing conditions for faster degradation rates (Jaiswal, Sharma, & Shukla, 2020). Enzyme-based degradation, involving specific enzymes like PETase and MHETase, (Maity, Maity, Bera, & Roy, 2021; Amobonye, Bhagwat, Singh, & Pillai, 2021) has also shown promise for breaking down plastics more efficiently, particularly when combined with other methods such as heat treatment or chemical processing to expedite breakdown. These biological methods offer a low-energy, eco-friendly alternative to traditional plastic disposal methods, potentially enabling large-scale microplastic reduction in various environments (Iheanacho et al., 2024).

### Technological Innovations (e.g., Filtration Systems, Plastic Alternatives)

Technological solutions, including advanced filtration systems and plastic alternatives, are increasingly crucial in addressing microplastic contamination. Filtration technologies, such as specialized filters in washing machines, capture microfibers from synthetic textiles, a major source of microplastic pollution. Industrial wastewater treatment plants are also being upgraded with high-efficiency filters capable of trapping even the smallest plastic particles. Additionally, innovations in materials science are yielding plastic alternatives derived from algae, mycelium, and other biodegradable materials, which perform similar functions to traditional plastics but avoid generating harmful microplastics. Such innovations, while still being optimized for scalability and cost-effectiveness, represent promising avenues for reducing the production of microplastics at the source (Kankanige & Babel, 2020).

### Environmental Clean-Up Initiatives (e.g., Ocean Clean-Up Technologies)

Environmental clean-up initiatives play an essential role in actively removing microplastics already present in the environment. Technologies such as the Ocean Cleanup project's interception devices are designed to capture plastic waste in rivers before it reaches the ocean, significantly reducing marine pollution. For open-ocean clean-up, trawling devices equipped with fine mesh nets are being used to trap microplastics while allowing marine life to escape. Research is also focusing on designing autonomous robots and floating barriers capable of capturing and collecting microplastics from both surface and subsurface layers of water bodies. While these technologies are effective in localized clean-up efforts, they often face challenges such as high operational costs and environmental impact concerns. Nonetheless, they remain valuable tools in tackling microplastic pollution in affected ecosystems (van Giezen, & Wiegmans, 2020).

### Future Directions and Research Gaps in Microplastic Research

Research on microplastics has largely focused on their presence and potential harm, but there are several gaps regarding their long-term ecological impacts. While microplastics are known to be ingested by marine life, studies on their long-term effects on food webs and ecosystems are sketchy. Future studies as done by Miller, Motti, Hamann & Kroon (2023) are needed to assess how microplastics move through trophic levels and whether they bioaccumulate or biomagnify, especially in key species like fish, plankton, and marine mammals. Most research has concentrated on aquatic environments, but microplastics in terrestrial ecosystems (e.g., soil) and agricultural systems (e.g., crops exposed to microplastic-laden fertilizers) require more attention. Microplastics in soil could affect plant growth, soil microbiomes, and the health of terrestrial organisms (Singh & Bhagwat, 2022). Long-term studies on chronic exposure to low levels of microplastics in humans and animals are essential. Most studies focus on acute exposure, but chronic exposure may lead to cumulative effects, such as cancer, reproductive toxicity, and neurotoxicity, which need to be systematically studied. The release of chemical additives and absorbed pollutants from microplastics in ecosystems needs more research. The interaction between microplastics, natural toxins, and pollutants could create synergistic toxic effects on wildlife and ecosystems, a subject that is still underexplored. To address the extensive ecological impacts of plastic pollution, especially microplastics, it is essential to adopt comprehensive strategies that incorporate interdisciplinary approaches and transcend traditional disciplinary boundaries. Collaborative efforts among researchers, policymakers, and industries are critical for addressing the pervasive environmental consequences of plastic waste. Researchers must underscore the urgency of targeted initiatives and the development of holistic strategies to mitigate the extensive effects of microplastics on ecosystems. These efforts should prioritize sustained interdisciplinary collaboration, fostering innovative solutions to ensure the long-term health and sustainability of global ecosystems amid this escalating environmental crisis (Perera, Dissanayake & Jayasinghe, 2024).

### Challenges in Microplastic Detection and Monitoring

Visual classification is frequently used to detect microplastics in environmental samples; however, this method is often unreliable and has limited accuracy. Thus, the analytical methods for microplastics need to be standardized as soon as possible. Meanwhile, new methods for analyzing nanoplastics are urgently needed (Lv, et al., 2019).

### Challenges Associated with the Detection and Monitoring of Microplastics

1. ***Size Detection Limits***: Microplastics vary widely in size, from millimeters to nanometers, and current detection techniques often fail to effectively identify and measure smaller particles, especially

at the nanoscale. Detecting and quantifying these tiny particles is particularly challenging, as many nanoplastics fall below the detection threshold of standard instruments, creating significant monitoring gaps (Lamichhane et al., 2023). Enhanced, more sensitive methods are needed to detect nanoplastics across environments, as their minute size allows them to penetrate biological tissues and environmental systems more readily.

2. ***Diverse Composition***: Microplastics are composed of diverse polymers and often carry additional chemicals or contaminants absorbed from the environment, making identification complex. Determining the specific polymer types and associated chemical additives remains challenging. Techniques such as Raman and FTIR spectroscopy are commonly used to characterize plastic types, but these methods are time-intensive and may have difficulty identifying extremely small or heavily degraded particles. Additionally, different plastics often require distinct analytical approaches, including Fourier-transform infrared (FTIR) spectroscopy, Raman spectroscopy, and scanning electron microscopy, each with unique limitations (Ivleva, 2021).
3. ***Lack of Standardized Methods***: Currently, there are no universally accepted or harmonized procedures for sampling, isolating, or quantifying microplastics. Studies frequently apply different concentration units and methodologies, complicating cross-study comparisons (Frias & Nash, 2019). This lack of standardization hinders consistent quantification and assessment of microplastic pollution. A major research gap remains in establishing standardized protocols for sample collection, processing, and identification, as studies use various techniques (e.g., filtration, spectroscopy), making it challenging to compare results. Although researchers have developed methods to isolate and remove microplastics across ecological domains, no harmonized approach exists. Key factors such as sampling site, laboratory contamination risks, separation efficiency, and documentation practices act as confounders (Bellasi., Binda., Pozzi, Boldrocchi, & Bettinetti, 2021). Inconsistent extraction methods and the absence of a uniform procedure are major sources of error in microplastic quantification (Zobkov & Esiukova, 2017). Variability in critical parameters, including sampling depth and position, repeat extractions, and settling times, depends on location and environmental conditions (Besley, Vijver, Behrens & Bosker, 2017). Methods designed for aquatic environments are not necessarily applicable to soil and sludge microplastics (Liu et al., 2019). Additionally, research is needed to develop methods for removing organic content without damaging microplastics (Prata, da Costa, Girão, Lopes, Duarte, & Rocha-Santos, 2019).
4. ***Environmental and Biological Matrices***: Detecting microplastics in complex environmental samples (such as soil, marine water, wastewater, and sediments) and biological tissues (like fish and human organs) presents significant challenges. Effective methods are essential for extracting, identifying, and quantifying microplastics from these diverse matrices without contamination. Natural particles and debris in environmental samples often interfere with microplastic detection, especially when visual methods are used, as these can easily be mistaken for microplastics, leading to inaccurate measurements that may overestimate or underestimate microplastic concentrations (Araujo, Nolasco, Ribeiro, & Ribeiro-Claro, 2018).
5. ***Resource Intensiveness***: Microplastic detection is resource-intensive, often requiring specialized equipment and laborious procedures to isolate and identify particles accurately, especially at smaller sizes (Hidalgo-Ruz, Gutow, Thompson & Thiel 2012). High costs and technical demands make it challenging to conduct large-scale or long-term monitoring.

These challenges underscore the need for improved and standardized detection methods to reliably monitor microplastics in various environments.

Based on the bibliometric analysis done by Jin, Liu and Yu (2022), overcoming the challenges is essential to unlocking the full potential of microplastic detection technology and safeguarding our environment. Significant challenges persist in the concentration and detection of microplastics in water and air samples. The development of advanced detection techniques requires novel strategies tailored to the specific characteristics of these environmental matrices. Detecting microplastics requires a delicate balance of sensitivity and specificity. Thermal cracking coupled with GC-MS offers a potential solution, but optimizing sample preparation will be crucial to unlocking its full potential. Establishing a standardized protocol for microplastic detection is crucial, as current detection methods lack consistency, even in terms of concentration units used. Developing a uniform set of criteria would enable comparability across studies, improving the reliability of results and facilitating cross-study analyses. The integration of artificial intelligence (AI) with environmental science to improve microplastic detection is highly necessary. Image processing, Fourier transform infrared spectroscopy (FTIR), Raman spectroscopy, and hyperspectral imaging (HSI) are AI-driven image processing techniques that will automate the identification and quantification of MPs, significantly reducing the need for manual analysis. Furthermore, improved AI algorithms that will efficiently integrate data from these methods, enabling real-time monitoring, traceability prediction, and pollution hotspot identification should be developed (Jin, Kong, Li & Shen, 2024).

## Need for Comprehensive Studies on Long-Term Ecological Impacts

There is an urgent need for comprehensive studies to evaluate the long-term ecological impacts of microplastics and associated pollutants. Current research often focuses on short-term effects or localized studies, which may not capture the broader ecological consequences of microplastic contamination. Understanding the cumulative effects over extended periods is crucial, as microplastics can persist in the environment for years, potentially leading to chronic exposure for various organisms. Long-term studies can help assess how microplastics affect ecosystem health, including biodiversity, species interactions, and ecosystem services. This knowledge is essential for managing and mitigating the risks posed by microplastic pollution. Investigating bioaccumulation and biomagnification of microplastics and their associated pollutants accumulate in food webs is vital. Comprehensive studies can provide insights into bioaccumulation and biomagnification processes, which could have significant implications for higher trophic levels, including humans. Extended research is needed to understand how chronic exposure to microplastics affects both marine and terrestrial organisms. This includes studying sublethal effects, reproductive health, and potential long-term changes in behavior and physiology. Microplastics can disrupt vital ecosystem services, such as water filtration, nutrient cycling, and habitat structure. Comprehensive studies can quantify these impacts and inform policies aimed at protecting ecosystem functions. Understanding how ecosystems and organisms adapt to microplastic pollution over time is critical. Research can help identify resilient species and communities, providing valuable information for conservation strategies.

## Policy Development and Interdisciplinary Collaboration for Mitigation

To mitigate the impact of microplastics, coordinated efforts are required between scientific research, policy development, and public awareness. Developing international regulations to limit the production, use, and disposal of plastic materials is essential. Microplastics, especially those from sources like microbeads in personal care products, synthetic fibers from textiles, and plastic packaging, need tighter regulation to reduce environmental contamination. Several countries have already banned microbeads in personal care products (Habib et al., 2022) but more comprehensive policies are needed for plastic packaging, single-use plastics, and waste management to reduce the overall plastic burden. There is a need to develop sustainable plastic alternatives (e.g., biodegradable plastics, bio-based polymers) that reduce the accumulation of microplastics in the environment. Encouraging research and development into these alternatives, alongside promoting circular economy practices like recycling and reuse, will be critical in reducing the environmental load of plastics. Public education campaigns on reducing plastic use, improving waste disposal practices, and the risks of microplastics can help decrease plastic pollution at the source (Hettiarachchi & Meegoda, 2023). Consumers can be encouraged to shift towards reusable products and support policies that regulate plastic production and waste management. Tackling the microplastic issue requires collaboration across multiple disciplines, including environmental science, toxicology, chemistry, public health, and policy-making (Pardeshi et al., 2024). Integrating research from various fields will provide a more comprehensive understanding of the full extent of microplastic pollution and its impacts on both ecosystems and human health. Since microplastic pollution is a global issue, international cooperation is crucial for developing effective mitigation strategies. Global treaties, such as those that regulate carbon emissions, could be extended to encompass plastic pollution, with nations working together to reduce the use of plastics, improve waste management systems, and clean up contaminated environments.

## Conclusion

Microplastics present a profound and complex challenge with far-reaching impacts on both ecological systems and human health. Despite their microscopic size, they have a disproportionate impact, affecting marine and terrestrial environments, infiltrating food webs, and potentially harming human health through ingestion and exposure to harmful chemicals. This review highlights the pervasive presence and varied sources of microplastics in the environment, illustrating their role in bioaccumulation and potential as vectors for toxic substances. Addressing this issue requires interdisciplinary collaboration and global cooperation to create treaties, reduce plastic usage, and improve waste management worldwide.

The current body of research highlights critical areas for intervention, including source reduction, improved waste management, and advanced bioremediation technologies. Consequently, addressing microplastic pollution demands coordinated interdisciplinary efforts, improved detection technologies, and stricter regulatory frameworks to curb plastic production and facilitate cleaner ecosystems. Future research should prioritize comprehensive studies on the ecological and health impacts of microplastics, with particular attention to developing sustainable plastic alternatives and enhancing public awareness. By fostering collaborative innovation across scientific, industrial, and policy domains, society can more effectively mitigate the escalating crisis of microplastic pollution and its persistent threat to the environment, biodiversity and human well-being.

## References


Agency for Toxic Substances and Disease Registry (US). (2010, November 3). *Toxicological profile for styrene: Health effects*. Atlanta, GA: Agency for Toxic Substances and Disease Registry. Available from https://www.ncbi.nlm.nih.gov/books/NBK601965/

Ahmadi Moshiran, V., Karimi, A., Golbabaei, F., Sadeghi, M., & Sajedian, A. A. (2021). Comparative Assessment of Carcinogenic Risk of Styrene Vapors Using Two Semi-Quantitative Methods in a Petrochemical Industry. *Archives of Occupational Health*, *5*(1), 929-936.

Ahmed, M. B., Rahman, M. S., Alom, J., Hasan, M. S., Johir, M. A. H., Mondal, M. I. H., Lee, D.-Y., Park, J., Zhou, J. L., & Yoon, M.-H. (2021). Microplastic particles in the aquatic environment: A systematic review. *Science of the Total Environment*, *775*, 145793. https://doi.org/10.1016/j.scitotenv.2021.145793

Al-Salem, S.M., Uddin, S., & Al-Yamani, F (2020). An Assessment of Microplastics Threat to the Marine Environment: A Short Review in Context of the Arabian/Persian Gulf. *Mar. Environ. Res.*, *159*, 104961.

Amobonye, A., Bhagwat, P., Singh, S., & Pillai, S. (2021). Plastic biodegradation: Frontline microbes and their enzymes. *Science of The Total Environment*, *759*, 143536. https://doi.org/10.1016/j.scitotenv.2020.143536

Araujo, C. F., Nolasco, M. M., Ribeiro, A. M. P., & Ribeiro-Claro, P. J. A. (2018). Identification of microplastics using Raman spectroscopy: Latest developments and future prospects. *Water Research*, 142, 426-440.

Arias-Andres, M., Klümper, U., Rojas-Jimenez, K., & Grossart, H.-P. (2018). Microplastic pollution increases gene exchange in aquatic ecosystems. *Environmental Pollution*, 237, 253-261.

Arias-Andres, M., Klümper, U., Rojas-Jimenez, K., & Grossart, H.-P. (2018). Microplastic pollution increases gene exchange in aquatic ecosystems. *Environmental Pollution*, 237, 253-261.

Ashrafy, A., Liza, A. A., Islam, M. N., Billah, M. M., Arafat, S. T., Rahman, M. M., & Rahman, S. M. (2023). Microplastics pollution: A brief review of its source and abundance in different aquatic ecosystems. *Journal of Hazardous Materials Advances*, *9*, 100215. https://doi.org/10.1016/j.hazadv.2022.100215

Avio, C.G., Gorbi, S., Milan, M., Benedetti, M., Fattorini, D., D'Errico, G., Pauletto, M., Bargelloni, L., & Regoli, F., (2015). Pollutants bioavailability and toxicological risk from microplastics to marine mussels. *Environmental Pollution, 198*, 211–222. https://doi.org/ 10.1016/j.envpol.2014.12.021

Baj J, Dring JC, Czeczelewski M, Kozyra P, Forma A, Flieger J, Kowalska B, Buszewicz G, Teresiński G. (2022). Derivatives of Plastics as Potential Carcinogenic Factors: The Current State of Knowledge. *Cancers*. 14(19):4637. https://doi.org/10.3390/cancers14194637

Bank, M. S., & Hansson, S. V. (2019). The plastic cycle: A novel and holistic paradigm for the Anthropocene. *Environmental Science & Technology, 53*(12), 7177–7179. https://doi.org/10.1021/acs.est.9b02942

Bao, X., Gu, Y., Chen, L., Wang, Z., Pan, H., Huang, S., ... & Chen, X. (2024). Microplastics derived from plastic mulch films and their carrier function effect on the environmental risk of pesticides. *Science of The Total Environment*, 171472.

Bellas, J., Martínez-Armental, J., Martínez-Cámara, A., Besada, V., & Martínez-Gómez, C. (2016). Ingestion of microplastics by demersal fish from the Spanish Atlantic and Mediterranean coasts. *Marine Pollution Bulletin, 109*, 55–60.

Bellasi, A., Binda, G., Pozzi, A., Boldrocchi, G., & Bettinetti, R. (2021). The extraction of microplastics from sediments: An overview of existing methods and the proposal of a new and green alternative. *Chemosphere*, *278*, 130357.

Bhuyan, M. S. (2022). Effects of microplastics on fish and in human health. *Frontiers in Environmental Science, 10*, Article 827289. https://doi.org/10.3389/fenvs.2022.827289

Binda, G., Spanu, D., Monticelli, D., Pozzi, A., Bellasi, A., Bettinetti, R., ... & Nizzetto, L. (2021). Unfolding the interaction between microplastics and (trace) elements in water: A critical review. *Water Research*, *204*, 117637.

Blackburn, K., & Green, D. (2021). The potential effects of microplastics on human health: What is known and what is unknown. *Ambio*, *Royal Swedish Academy of Sciences*. https://doi.org/10.1007/s13280-021-01589-9

Campanale, C., Massarelli, C., Savino, I., Locaputo, V., & Uricchio, V. F. (2020). A Detailed Review Study on Potential Effects of Microplastics and Additives of Concern on Human Health. *International Journal of Environmental Research and Public Health*, 17(4), 1212.

Cao, N.-D.-T., Vo, D.-H. T., Pham, M.-D.-T., Nguyen, V.-T., Nguyen, T.-B., Le, L.-T., Mukhtar, H., Nguyen, H.-V., Visvanathan, C., & Bui, X.-T. (2024). Microplastics contamination in water supply system and treatment processes. *Science of The Total Environment, 926*, 171793. https://doi.org/10.1016/j.scitotenv.2024.171793

Chamas, A., Moon, H., Zheng, J., Qiu, Y., Tabassum, T., Jang, J. H., Abu-Omar, M., Scott, S. L., & Suh, S. (2020). Degradation rates of plastics in the environment. *ACS Sustainable Chemistry & Engineering, 8*(9), 3494-3511. https://doi.org/10.1021/acssuschemeng.9b06635

Chen, M., Yang, Y., Baral, K., Fu, Y., Meng, Y., Zhang, Y., & Zhao, M. (2023). Relationship between bisphenol A and the cardiovascular disease metabolic risk factors in American adults: A population-based study. *Chemosphere*, *324*, 138289.

Choudhary, D., Kurien, C., & Srivastava, A. K. (2020). Microplastic contamination and life cycle assessment of bottled drinking water. In N. A. Siddiqui, S. M. Tauseef, & R. Dobhal (Eds.), *Advances in water pollution monitoring and control* (pp. 41–48). Singapore: Springer.

Conti, G. O., Ferrante, M., Banni, M., Favara, C., Nicolosi, I., Cristaldi, A., Fiore, M., & Zuccarello, P. (2020). Micro- and nanoplastics in edible fruit and vegetables: The first diet risk assessment for the general population. *Environmental Research, 187*, 109677. https://doi.org/10.1016/j.envres.2020.109677

Conti, I., Simioni, C., Varano, G., Brenna, C., Costanzi, E., & Neri, L. M. (2021). Legislation to limit the environmental plastic and microplastic pollution and their influence on human exposure. *Environmental Pollution, 288*, 117708. https://doi.org/10.1016/j.envpol.2021.117708

Critchell, K., Bauer-Civiello, A., Benham, C., Berry, K., Eagle, L., Hamann, M., Hussey, K., & Ridgway, T. (2019). Plastic pollution in the coastal environment: Current challenges and future solutions. In E. Wolanski, J. W. Day, M. Elliott, & R. Ramachandran (Eds.), *Coasts and estuaries* (pp. 595–609). Elsevier.

Curren, E., Kuwahara, V. S., Yoshida, T., & Leong, S. C. Y. (2021). Marine microplastics in the ASEAN region: A review of the current state of knowledge. *Environmental Pollution, 288*, 117776. https://doi.org/10.1016/j.envpol.2021.117776

Damaj S, Trad F, Goevert D, & Wilkesmann J. (2024). Bridging the gaps between microplastics and human health. *Microplastics, 3*(1), 46-66. doi:10.3390/microplastics3010004.

Debraj, D., & Lavanya, M. (2023). Microplastics everywhere: A review on existing methods of extraction. *Science of The Total Environment, 893*, 164878. https://doi.org/10.1016/j.scitotenv.2023.164878

Ding, J., Lv, M., Zhu, D., Leifheit, E. F., Chen, Q. L., Wang, Y. Q., & Zhu, Y. G. (2022). Tire wear particles: An emerging threat to soil health. *Critical Reviews in Environmental Science and Technology, 53*(2), 239–257. https://doi.org/10.1080/10643389.2022.2047581

Duis, K., & Coors, A. (2016). Microplastics in the aquatic and terrestrial environment: Sources (with a specific focus on personal care products), fate, and effects. *Environmental Sciences Europe, 28*(2). https://doi.org/10.1186/s12302-015-0069-y

Frias, J. P. G. L., & Nash, R. (2019). Microplastics: Finding a consensus on the definition. *Marine Pollution Bulletin*, 138, 145-147.

Frias, J. P., & Nash, R. (2019). Microplastics: Finding a consensus on the definition. *Marine pollution bulletin*, *138*, 145-147.

Galloway, T. S. (2015). Micro- and nano-plastics and human health. In M. Bergmann, L. Gutow, & M. Klages (Eds.), *Marine anthropogenic litter* (pp. 343–366). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-16510-3_13

Galloway, T. S., Cole, M., & Lewis, C. (2017). Interactions of microplastic debris throughout the marine ecosystem. *Nature Ecology & Evolution*, 1(5), 1-8.

Galloway, T. S., Cole, M., & Lewis, C. (2017). Interactions of microplastic debris throughout the marine ecosystem. *Nature ecology & evolution*, *1*(5), 0116.

Gautam, R., Jo, J., Acharya, M., Maharjan, A., Lee, D., K.C., P. B., Kim, C., Kim, K., Kim, H., & Heo, Y. (2022). Evaluation of potential toxicity of polyethylene microplastics on human derived cell lines. *Science of The Total Environment, 838*(Part 2), 156089. https://doi.org/10.1016/j.scitotenv.2022.156089

Gigault, J., Halle, A. T., Baudrimont, M., Pascal, P. Y., Gauffre, F., Phi, T. L., & Ter Halle, A. (2018). Current opinion: What is a nanoplastic? *Environmental Pollution*, 235, 1030-1034.

Gola D., Tyagi P. K., Arya A., Chauhan N., Agarwal M., Singh S. K., & Gola S. (2021). The impact of microplastics on marine environment: A review. *Environmental Nanotechnology, Monitoring & Management, 16,* 100552. https://doi.org/10.1016/j.enmm.2021.100552

Goodman, K. E., Hua, T., & Sang, Q. X. A. (2022). Effects of polystyrene microplastics on human kidney and liver cell morphology, cellular proliferation, and metabolism. *ACS Omega, 7*(38), 34136–34153. https://doi.org/10.1021/acsomega.2c03453

Guilhermino, L., Vieira, L. R., Ribeiro, D., Tavares, A. S., Cardoso, V., Alves, A., & Almeida, J. M. (2018). Uptake and effects of the antimicrobial florfenicol, microplastics, and their mixtures on the freshwater exotic invasive bivalve Corbicula fluminea. *Science of The Total Environment, 622*, 1131–1142.

Habib, R. Z., Aldhanhani, J. A., Ali, A. H., Ghebremedhin, F., Elkashlan, M., Mesfun, M., ... & Thiemann, T. (2022). Trends of microplastic abundance in personal care products in the United Arab Emirates over the period of 3 years (2018–2020). *Environmental Science and Pollution Research*, *29*(59), 89614-89624.

Hartmann, N. B., Hüffer, T., Thompson, R. C., Hassellöv, M., Verschoor, A., Daugaard, A. E., ... & Wagner, M. (2019). Are we speaking the same language? Recommendations for a definition and categorization framework for plastic debris. *Environmental Science & Technology*, 53(3), 1039-1047.

He, S., Wei, Y., Yang, C., & He, Z. (2022). Interactions of microplastics and soil pollutants in soil-plant systems. *Environmental Pollution, 315*, Article 120357. https://doi.org/10.1016/j.envpol.2022.120357

Hettiarachchi, H., & Meegoda, J. N. (2023). Microplastic pollution prevention: the need for robust policy interventions to close the loopholes in current waste management practices. *International journal of environmental research and public health*, *20*(14), 6434.

Hidalgo-Ruz, V., Gutow, L., Thompson, R. C., & Thiel, M. (2012). Microplastics in the marine environment: a review of the methods used for identification and quantification. *Environmental science & technology*, *46*(6), 3060-3075.

Hidalgo-Ruz, V., Gutow, L., Thompson, R. C., & Thiel, M. (2012). Microplastics in the marine environment: A review of the methods used for identification and quantification. *Environmental Science & Technology*, 46(6), 3060-3075.

Hirai, H., Takada, H., Ogata, Y., Yamashita, R., Mizukawa, K., Saha, M., Kwan, C., Moore, C., Gray, H., & Laursen, D. (2011). Organic micropollutants in marine plastic debris from the open ocean and remote and urban beaches. *Marine Pollution Bulletin, 62*(8), 1683–1692.

Hoang, V.-H., Nguyen, M.-K., Hoang, T.-D., Ha, M. C., Huyen, N. T. T., Bui, V. K. H., Pham, M.-T., Nguyen, C.-M., Chang, S. W., & Nguyen, D. D. (2024). Sources, environmental fate, and impacts of microplastic contamination in agricultural soils: A comprehensive review. *Science of The Total Environment, 950*, 175276.

Horton, A.A., and S.J. Dixon (2018). Microplastics: An introduction to environmental transport processes. WIREs Water 5: https://doi. org/10.1002/wat2.1268. https://doi.org/10.1016/j.watres.2023.119790

Huang, Y., Qing, X., Wang, W., Han, G., & Wang, J. (2020). Minireview on current studies of airborne microplastics: Analytical methods, occurrence, sources, fate, and potential risk to human beings. *TrAC Trends in Analytical Chemistry, 125*, 115821. https://doi.org/10.1016/j.trac.2020.115821

Huang, Y., X. Qing, W. Wang, G. Han, and J. Wang. (2020). Minireview on current studies of airborne microplastics: Analytical methods, occurrence, sources, fate and potential risk to human beings. TrAC, Trends in Analytical Chemistry 125: https://doi.org/10.1016/J.TRAC.2020.115821

Hussain, N., Gogoi, S., Bora, A., & Rout, P. (2020). Toxicological effects of microplastics and their associated chemicals on animals and humans: A review. *Environmental Science and Pollution Research*, 27(26), 31141-31152.

Iheanacho, B. C., Ajoge, H. N., Ismail, U., Zoum, F. A., Ifeanyi-Nze, F. O., Okunbi, F. O., Edeh, C. F., Chimezie, N. N., Udoh, E. A., Nworie, J. O., Oseni, T. O., Mark, M. U., Akpowu, G. A., Kolapo, D. A., Odibo, A. O., Edun, O. J., Zogini, U. C., & Egwuonwu, C. O. (2024). A Comprehensive Study on the Production and Characterization of Eco-Friendly Biodegradable Plastic Films from Dent Corn Starch. *Archives of Advanced Engineering Science, 1-10*. https://doi.org/10.47852/bonviewAAES42022946

Islam, M., Xayachak, T., Haque, N., Lau, D., Bhuiyan, M., & Pramanik, B. K. (2024). Impact of bioplastics on environment from its production to end-of-life. *Process Safety and Environmental Protection, 188*, 151-166. https://doi.org/10.1016/j.psep.2024.05.113

Ivleva, N. P. (2021). Chemical analysis of microplastics and nanoplastics: challenges, advanced methods, and perspectives. *Chemical reviews*, *121*(19), 11886-11936.

Jaiswal, S., Sharma, B., & Shukla, P. (2020). Integrated approaches in microbial degradation of plastics. *Environmental Technology & Innovation, 17*, 100567. https://doi.org/10.1016/j.eti.2019.100567

Jambeck, J., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A. L., … Law, K. L. (2015). Plastic waste inputs from land into the ocean. *Science*, *347*(6223), 768–771.

Jemec Kokalj, A., Kuehnel, D., Puntar, B., Žgajnar Gotvajn, A., & Kalčičková, G. (2019). An exploratory ecotoxicity study of primary microplastics versus aged in natural waters and wastewaters. *Environmental Pollution, 254*, 112980.

Jeong, E., Lee, J.-Y., & Redwan, M. (2024). Animal exposure to microplastics and health effects: A review. *Emerging Contaminants, 10*(4), 100369. https://doi.org/10.1016/j.emcon.2024.100369

Jiang, X., Chen, H., Liao, Y., Ye, Z., Li, M., & Klobučar, G. (2019) Ecotoxicity and genotoxicity of polystyrene microplastics on higher plant Vicia faba. *Environental Pollution, 250*, 831–838 https://doi.org/10.1016/j.envpol.2019.04.055

Jiang, Y., Yang, F., Zhao, Y., Wang, J., (2020). Greenland Sea Gyre increases microplastic pollution in the surface waters of the Nordic Seas. *Science of the Total Environment, 712*, 136484. https://doi.org/10.1016/j.scitotenv.2019.136484

Jin, H., Kong, F., Li, X., & Shen, J. (2024). Artificial intelligence in microplastic detection and pollution control. *Environmental Research, 262*(Part 1), 119812. https://doi.org/10.1016/j.envres.2024.119812

Jin, M., Liu, J., & Yu, J. (2022). Current development and future challenges in microplastic detection techniques: A bibliometrics-based analysis and review. *Science Progress, 105*(4). https://doi.org/10.1177/00368504221132151

Junaid, M., Abbas, Z., Siddiqui, J. A., Liu, S., Tabraiz, S., Yue, Q., & Wang, J. (2023). Ecotoxicological impacts associated with the interplay between micro (nano) plastics and pesticides in aquatic and terrestrial environments. *TrAC Trends in Analytical Chemistry*, *165*, 117133

Karbalaei, S., Hanachi, P., Walker, T.R., & Cole, M (2018). Occurrence, Sources, Human Health Impacts and Mitigation of Microplastic Pollution. *Environ. Sci. Pollut. Res., 25*, 36046–36063.

Kirstein, I. V., Kirmizi, S., Wichels, A., Garin-Fernandez, A., Erler, R., Löder, M., & Gerdts, G. (2016). Dangerous hitchhikers? Evidence for potentially pathogenic *Vibrio* spp. on microplastic particles. *Marine Environmental Research, 120*, 1-8. https://doi.org/10.1016/j.marenvres.2016.07.004

Kosuth, M., Mason, S. A., & Wattenberg, E. V. (2018). Anthropogenic contamination of tap water, beer, and sea salt. *PLoS ONE, 13*, e0194970. https://doi.org/10.1371/journal.pone.0194970

Koutnik, V.S., Leonard, J., Alkidim, S., DePrima, F.J., Ravi, S., Hoek, E.M.V., Mohanty, S.K. (2021). Distribution of microplastics in soil and freshwater environments: Global analysis and framework for transport modeling. *Environmental pollution (1987) 274*, 116552. https://doi.org/10.1016/j.envpol.2021.116552

Kwon, O.Y., Kang, J.-H., Hong, S.H., & Shim, W.J. (2020). Spatial distribution of microplastic in the surface waters along the coast of Korea. *Marine pollution bulletin, 155*, 110729. https://doi.org/10.1016/j.marpolbul.2019.110729

Lamichhane, G., Acharya, A., Marahatha, R., Modi, B., Paudel, R., Adhikari, A., & Parajuli, N. (2023). Microplastics in environment: global concern, challenges, and controlling measures. *International Journal of Environmental Science and Technology*, *20*(4), 4673-4694.

Lau, W. W. Y., Shiran, Y., Bailey, R. M., Cook, E., Stuchtey, M. R., Koskella, J., Velis, C. A., Godfrey, L., Boucher, J., Murphy, M. B., Thompson, R. C., Jankowska, E., Castillo, A. C., Pilditch, T. D., Dixon, B., Koerselman, L., Kosior, E., Favoino, E., Gutberlet, J., ... Palardy, J. E. (2020). Evaluating scenarios toward zero plastic pollution. *Science*, *369*(6510), 1455–1461. https://doi.org/10.1126/science.aba9475

Li, J., Liu, L., Zhang, Y., Fu, W., Liu, X., Wang, Q., Mohsin, T., & Huang, L. (2023). Microplastic stress in plants: Effects on plant growth and their remediations. *Frontiers in Plant Science, 14*. https://doi.org/10.3389/fpls.2023.1226484

Li, Z., Yang, Y., Chen, X., He, Y., Bolan, N., Rinklebe, J., Lam, S. S., Peng, W., & Sonne, C. (2023). A discussion of microplastics in soil and risks for ecosystems and food chains. *Chemosphere, 313*, 137637. https://doi.org/10.1016/j.chemosphere.2022.137637

Liu, K., Wang, X., Fang, T., Xu, P., Zhu, L., & Li, D. (2019). Source and potential risk assessment of suspended atmospheric microplastics in Shanghai. *Science of the Total Environment*, 675, 138-147.

Liu, K., Wang, X., Fang, T., Xu, P., Zhu, L., & Li, D. (2019). Source and potential risk assessment of suspended atmospheric microplastics in Shanghai. *Science of the Total Environment, 675*, 462–471. https://doi.org/10.1016/j.scitotenv.2019.04.080

Liu, K., Wang, X., Wei, N., Song, Z., & Li, D. (2019). Accurate quantification and transport estimation of suspended atmospheric microplastics in megacities: Implications for human health. *Environment International, 132*, 105127. https://doi.org/10.1016/j.envint.2019.105127

Lohmann, R. (2017). Microplastics are not important for the cycling and bioaccumulation of organic pollutants in the oceans—but should microplastics be considered POPs themselves? *Integrated Environmental Assessment and Management, 13*, 460–465.

Lokesh, P., Shobika, R., Omer, S. N., Reddy, M., Saravanan, P., Rajeshkannan, R., Saravanan, V., & Venkatkumar, S. (2023). Bioremediation of plastics using microbial tools: A strategy for controlling plastic pollution. *Sustainable Chemistry for the Environment, 3*, 100027. https://doi.org/10.1016/j.scenv.2023.100027

López-Rojo, N., Pérez, J., Alonso, A., Correa-Araneda, F., & Boyero, L. (2020). Microplastics have lethal and sublethal effects on stream invertebrates and affect stream ecosystem functioning. *Environmental Pollution, 259*, Article 113898. https://doi.org/10.1016/j.envpol.2019.113898

Lv, L., Yan, X., Feng, L., Jiang, S., Lu, Z., Xie, H., Sun, S., Chen, J., & Lusher, A. L., Hollman, P. C. H., & Mendoza, A. (2017). Microplastics in fisheries and aquaculture: Status of knowledge on their occurrence and implications for aquatic organisms and food safety. *FAO Fisheries and Aquaculture Technical Paper, 615*. https://doi.org/10.1002/wer.1281

Madiraju, V. H., Pamula, A. S. P., & Darsi, B. P. (2024). Theoretical review on microplastic pollution: A multifaceted threat to marine ecosystems, human health, and environment. *IgMin Research, 2*(6), 460–468. https://doi.org/10.61927/igmin203

Maity, W., Maity, S., Bera, S., & Roy, A. (2021). Emerging roles of PETase and MHETase in the biodegradation of plastic wastes. *Applied Biochemistry and Biotechnology, 193*(8), 2699-2716. https://doi.org/10.1007/s12010-021-03562-4

Martínez, K. P., Andersen, T. J., da Silva, V., Strand, J., & Posth, N. R. (2024). Microplastics deposition in Arctic sediments of Greenland increases significantly after 1950. *Communications Earth & Environment, 5*, 584. https://doi.org/10.1038/s43247-024-01768-y

Martín-Lara, M. A., Godoy, V., Quesada, L., Lozano, E. J., & Calero, M. (2021). Environmental status of marine plastic pollution in Spain. *Marine Pollution Bulletin, 170*, 112677. https://doi.org/10.1016/j.marpolbul.2021.112677

Mason, S.A., Garneau, D., Sutton, R., Chu, Y., Ehmann, K., Barnes, J., Fink, P., Papazissimos, D., & Rogers, D.L. (2016). Microplastic pollution is widely detected in US municipal wastewater treatment plant effluent. *Environ. Pollut. 218*, 1045–1054.

Mészáros, E., Bodor, A., Kovács, E., Papp, S., Kovács, K., Perei, K., & Feigl, G. (2023). Impacts of plastics on plant development: Recent advances and future research directions. *Plants, 12*(18), 3282. https://doi.org/10.3390/plants12183282

Michaela E. Miller, Cherie A. Motti, Mark Hamann, Frederieke J. Kroon (2023). Assessment of microplastic bioconcentration, bioaccumulation and biomagnification in a simple coral reef food web, Science of The Total Environment, Volume 858, Part 1, 159615, https://doi.org/10.1016/j.scitotenv.2022.159615

Miller, M. E., Hamann, M., & Kroon, F. J. (2020). Bioaccumulation and biomagnification of microplastics in marine organisms: A review and meta-analysis of current data. *PLOS ONE, 15*(10), Article e0240792. https://doi.org/10.1371/journal.pone.0240792

Mitrano, D. M., & Wohlleben, W. (2020). Microplastic regulation should be more precise to incentivize both innovation and environmental safety. *Nature Communications, 11*, 5324. https://doi.org/10.1038/s41467-020-19069-1

Mondal, N. K., Kundu, S., Debnath, P., Mondal, A., & Sen, K. (2022). Effects of polyethylene terephthalate microplastic on germination, biochemistry, and phytotoxicity of Cicer arietinum L. and cytotoxicity study on Allium cepa L. *Environmental Toxicology and Pharmacology, 94*, 103908. https://doi.org/10.1016/j.etap.2022.103908

Moshood, T. D., Nawanir, G., Mahmud, F., Mohamad, F., Ahmad, M. H., & AbdulGhani, A. (2022). Sustainability of biodegradable plastics: New problem or solution to solve the global plastic pollution? *Current Research in Green and Sustainable Chemistry, 5*, 100273. https://doi.org/10.1016/j.crgsc.2022.100273

Munhoz, D. R., Harkes, P., Beriot, N., Larreta, J., & Basurko, O. C. (2022). Microplastics: A review of policies and responses. *Microplastics, 2*(1), 1–26. https://doi.org/10.3390/microplastics2010001

Napper, I. E., & Thompson, R. C. (2016). Release of synthetic microplastic plastic fibres from domestic washing machines: Effects of fabric type and washing conditions. *Marine Pollution Bulletin*, 112(1-2), 39-45.

National Toxicology Program. (2021). Styrene. In *15th Report on Carcinogens [Internet]*. National Toxicology Program.

Nguyen, M.-K., Rakib, M. R. J., Lin, C., Hung, N. T. Q., Le, V.-G., Nguyen, H.-L., Malafaia, G., & Idris, A. M. (2023). A comprehensive review on ecological effects of microplastic pollution: An interaction with pollutants in the ecosystems and future perspectives. *TrAC Trends in Analytical Chemistry, 168*, 117294. https://doi.org/10.1016/j.trac.2023.117294

Oberbeckmann, S., Kreikemeyer, B., & Labrenz, M. (2015). Environmental factors support the formation of specific bacterial assemblages on microplastics. *Frontiers in Microbiology*, 6, 1177.

O'Brien L, Peirano I, & van den Berg M. (2023). Health risks of microplastics in the human body: bioaccumulation and toxicity of common additives. *J Public Health Res., 32*.

Pardeshi, S., Dhodapkar, R., Namdeo, S. K., Koley, M., Balakrishnan, B., Dorairajan, U., & Jain, S. (2024). *Science Diplomacy, 6*(1).

Peixoto, D., C. Pinheiro, J. Amorim, L. Oliva-Teles, L. Guilhermino, and M. Vieira. (2019). Microplastic pollution in commercial salt for human consumption: A review. Estuarine, Coastal and Shelf Science 219: 161–168. https://doi.org/10.1016/J.ECSS.2019.02

Peng, G., Bellerby, R., Zhang, F., Sun, X., & Li, D. (2020). The ocean's ultimate trashcan: Hadal trenches as major depositories for plastic pollution. *Water research (Oxford)*, *168*, 115121. https://doi.org/10.1016/j.watres.2019.115121

Perera, H. A. T. N., Dissanayake, O. D. I. P., & Jayasingh, G. Y. (2024). Long-term ecological consequences of microplastics: A comprehensive review of ecosystem dynamics and adaptation mechanisms. In *Proceedings of the 1st International Conference on Plastics & Environmental Sustainability 2024* of the Centre for Environmental Studies & Sustainable Development, The Open University of Sri Lanka.

Periyasamy, A. P., & Tehrani-Bagha, A. (2022). A review on microplastic emission from textile materials and its reduction techniques. *Polymer Degradation and Stability*, *199*, 109901. https://doi.org/10.1016/j.polymdegradstab.2022.109901

Petersen, F., & Hubbart, J.A. (2021). The occurrence and transport of microplastics: The state of the science. *The Science of the total environment*, *758*, 143936. https://doi.org/10.1016/j.scitotenv.2020.143936

Pettipas, S., Bernier, M., & Walker, T. R. (2016). A Canadian policy framework to mitigate plastic marine pollution. *Marine Policy, 68*, 117–122.

Pettipas, S., Bernier, M., & Walker, T.R. (2016). A Canadian Policy Framework to Mitigate Plastic Marine Pollution. *Mar. Policy, 68*, 117–122.

Pironti, C., Ricciardi, M., Motta, O., Miele, Y., Proto, A., & Montano, L. (2021). Microplastics in the environment: Intake through the food web, human exposure, and toxicological effects. *Toxics, 9*(9), 224. https://doi.org/10.3390/toxics9090224

Pischedda, A., Tosin, M., & Degli-Innocenti, F. (2019). Biodegradation of plastics in soil: The effect of temperature. *Polymer Degradation and Stability*, *170*, 109017. https://doi.org/10.1016/j.polymdegradstab.2019.109017

Prata, J. C. (2018). Airborne microplastics: Consequences to human health? *Environmental Pollution*, 234, 115-126.

Prata, J. C., da Costa, J. P., Girão, A. V., Lopes, I., Duarte, A. C., & Rocha-Santos, T. (2019). Identifying a quick and efficient method of removing organic matter without damaging microplastic samples. *Science of the total environment*, *686*, 131-139.

Prata, J. C., da Costa, J. P., Lopes, I., Duarte, A. C., & Rocha-Santos, T. (2020). Environmental exposure to microplastics: An overview on possible human health effects. *Science of The Total Environment*, 702, 134455.

Rai, M., Pant, G., Pant, K., Aloo, B. N., Kumar, G., Singh, H. B., & Tripathi, V. (2023). Microplastic pollution in terrestrial ecosystems and its interaction with other soil pollutants: A potential threat to soil ecosystem sustainability. *Resources*, *12*(6), 67. https://doi.org/10.3390/resources12060067

Rajeshkumar, G., Seshadri, S. A., Devnani, G. L., Sanjay, M. R., Siengchin, S., Maran, J. P., Al-Dhabi, N. A., Karuppiah, P., Mariadhas, V. A., Sivarajasekar, N., & Anuf, A. R. (2021). Environment friendly, renewable and sustainable poly lactic acid (PLA) based natural fiber reinforced composites – A comprehensive review. *Journal of Cleaner Production*, *310*, 127483. https://doi.org/10.1016/j.jclepro.2021.127483

Ramírez-Álvarez, N., Rios Mendoza, L.M., Macías-Zamora, J.V., Oregel-Vázquez, L., Alvarez-Aguilar, A., Hernández-Guzmán, F.A., Sánchez-Osorio, J.L., Moore, C.J., Silva-Jiménez, H., & Navarro-Olache, L.F. (2020). Microplastics: Sources and distribution in surface waters and sediments of Todos Santos Bay, Mexico. *The Science of the total environment, 703*, 134838. https://doi.org/10.1016/j.scitotenv.2019.134838

Rios Mendoza, L.M., Leon Vargas, D., & Balcer, M. (2021). Microplastics occurrence and fate in the environment, *Current Opinion in Green and Sustainable Chemistry*, 32, 100523. https://doi.org/10.1016/j.cogsc.2021.100523.

Rist, S., Baun, A., & Hartmann, N. B. (2018). Ingestion of microplastics by marine organisms and its consequences. *Environmental Science & Technology*, 52(18), 9967-9974.

Ritchie, H., Samborska, V., & Roser, M. (2023). Plastic pollution. Our World in Data. Retrieved from https://ourworldindata.org/plastic-pollution

Robson, G. S., Andrades, R., Demetrio, G. R., Kuwai, G. M., Sobral, M. F., Vieira, J. de S., & Machovsky-Capuska, G. E. (2020). Exploring plastic-induced satiety in foraging green turtles. *Environmental Pollution*, *265*(Part B), 114918. https://doi.org/10.1016/j.envpol.2020.114918

Rochman, C. M., Browne, M. A., Halpern, B. S., Hentschel, B. T., & Kaye, S. (2013). Policy: Classify plastic waste as hazardous. *Science*, 339(6125), 186-187.

Rochman, C. M., Hentschel, B. T., & Teh, S. J. (2014). Long-term sorption of metals is similar among plastic types: Implications for plastic debris in aquatic environments. *PLoS ONE, 9*(1), e85433. https://doi.org/10.1371/journal.pone.0085433

Rochman, C. M., Hoh, E., Hentschel, B. T., & Kaye, S. (2013). Long-term field measurement of sorption of organic contaminants to five types of plastic pellets: implications for plastic marine debris. *Environmental Science & Technology*, 47(3), 1646-1654.

Roy, P., Mohanty, A. K., & Misra, M. (2022). Microplastics in ecosystems: Their implications and mitigation pathways. *Environmental Science Advances*, *1*, 9–29. https://doi.org/10.1039/D1VA00012H

Saeedi, M. (2023). How microplastics interact with the food chain: A short overview of fate and impacts. *Journal of Food Science* *and Technology, 61*(3), 1–11. https://doi.org/10.1007/s13197-023-05720-4

Sajjad, M., Huang, Q., Khan, S., Khan, M. A., Liu, Y., Wang, J., Lian, F., Wang, Q., & Guo, G. (2022). Microplastics in the soil environment: A critical review. *Environmental Technology & Innovation, 27*, 102408. https://doi.org/10.1016/j.eti.2022.102408

Setälä, O., Lehtiniemi, M., Coppock, R., & Cole, M. (2018). Microplastics in marine food webs. In E. Y. Zeng (Ed.), *Microplastic contamination in aquatic environments* (pp. 339-363). Elsevier. https://doi.org/10.1016/B978-0-12-813747-5.00011-4

Shafqat, A., Tahir, A., Mahmood, A., Tabinda, A. B., Yasar, A., & Pugazhendhi, A. (2020). A review on environmental significance carbon footprints of starch-based bio-plastic: A substitute of conventional plastics. *Biocatalysis and Agricultural Biotechnology, 27*, 101540. https://doi.org/10.1016/j.bcab.2020.101540

Shim, W. J., Hong, S. H., & Eo, S. E. (2017). Identification methods in microplastic analysis: A review. *Analytical Methods*, 9(9), 1384-1391.

Shokunbi, O. S., Jegede, D. O., & Shokunbi, O. S. (2023). A study of the microplastic contamination of commercial table salts: A case study in Nigeria. *Environmental Health Engineering and Management, 10*(2), 217-224. http://ehemj.com/article-1-1132-en.html

Shruti, V. C., Pérez-Guevara, F., Elizalde-Martínez, I., & Kutralam-Muniasamy, G. (2020). First study of its kind on the microplastic contamination of soft drinks, cold tea, and energy drinks—Future research and environmental considerations. *Science of the Total Environment, 726*, 138580. https://doi.org/10.1016/j.scitotenv.2020.138580

Singh, S., & Bhagwat, A. (2022). Microplastics: A potential threat to groundwater resources. *Groundwater for Sustainable Development, 19*, 100852. https://doi.org/10.1016/j.gsd.2022.100852

Smith, M., Love, D. C., Rochman, C. M., & Neff, R. A. (2018). Microplastics in seafood and the implications for human health. *Current Environmental Health Reports*, 5(3), 375-386.

Srikanth, M., Sandeep, T. S. R. S., Sucharitha, K., & Sudhakar G. (2022). Biodegradation of plastic polymers by fungi: A brief review. *Bioresource Technology Reports, 9*, 42. https://doi.org/10.1186/s40643-022-00532-4

Stapleton, M. J., Ansari, A. J., & Hai, F. I. (2023). Antibiotic sorption onto microplastics in water: A critical review of the factors, mechanisms and implications. *Water Research, 233*, 119790. https://doi.org/10.1016/j.watres.2023.119790

Su, L., Sharp, S.M., Pettigrove, V.J., Craig, N.J., Nan, B., Du, F., & Shi, H. (2020). Superimposed microplastic pollution in a coastal metropolis. *Water research (Oxford), 168*, 115140. https://doi.org/10.1016/j.watres.2019.115140

Surendran, U., Jayakumar, M., Raja, P., Gopinath, G., & Chellam, P. V. (2023). Microplastics in terrestrial ecosystems: Sources and migration in soil environments. *Chemosphere, 318*, 137946. https://doi.org/10.1016/j.chemosphere.2023.137946

Syranidou, E., Karkanorachaki, K., Amorotti, F., Franchini, M., Repouskou, E., Kaliva, M., Vamvakaki, M., Kolvenbach, B., Fava, F., & Corvini, P. F. (2017). Biodegradation of weathered polystyrene films in seawater microcosms. *Scientific Reports, 7*, 17991.

Tang, Y., Liu, Y., Chen, Y., Zhang, W., Zhao, J., He, S., Yang, C., Zhang, T., Tang, C., Zhang, C., & Yang, Z. (2021). A review: Research progress on microplastic pollutants in aquatic environments. *Science of The Total Environment, 766*, 142572. https://doi.org/10.1016/j.scitotenv.2020.142572

Teampanpong, J., & Duengkae, P. (2024). Terrestrial wildlife as indicators of microplastic pollution in western Thailand. *PeerJ, 12*, e17384. https://doi.org/10.7717/peerj.17384

Temporiti, M. E. E., Nicola, L., Nielsen, E., & Tosi, S. (2022). Fungal enzymes involved in plastics biodegradation. *Microorganisms, 10*(6), 1180. https://doi.org/10.3390/microorganisms10061180

Teuten, E. L., Saquing, J. M., Knappe, D. R. U., & Jickells, T. D. (2009). Transport and release of chemicals from plastics to the environment and to wildlife. *Philosophical Transactions of the Royal Society B: Biological Sciences, 364*(1526), 2027-2045. https://doi.org/10.1016/j.scitotenv.2024.175276

Thakur, S., Chaudhary, J., Sharma, B., Verma, A., Tamulevicius, S., & Thakur, V. K. (2018). Sustainability of bioplastics: Opportunities and challenges. *Current Opinion in Green and Sustainable Chemistry, 13*, 68–75. https://doi.org/10.1016/j.cogsc.2018.04.013

Thompson, R.C., Olson, Y., Mitchell, R.P., Davis, A., Rowland, S.J., John, A.W.G., McGonigle, D., & Russell, A.E., (2004). Lost at Sea: Where Is All the Plastic? *Science (80- .) 304*, 838. https://doi.org/10.1126/science.1094559 .

Usman, S., Abdull Razis, A. F., Shaari, K., Azmai, M. N. A., Saad, M. Z., Mat Isa, N., & Nazarudin, M. F. (2022). The burden of microplastics pollution and contending policies and regulations. *International Journal of Environmental Research and Public Health, 19*, 6773. https://doi.org/10.3390/ijerph19116773

Van Cauwenberghe, L., & Janssen, C. R. (2014). Microplastics in bivalves cultured for human consumption. *Environmental Pollution, 193*, 65–70.

van Giezen, A., & Wiegmans, B. (2020). Spoilt - Ocean cleanup: Alternative logistics chains to accommodate plastic waste recycling: An economic evaluation. *Transportation Research Interdisciplinary Perspectives, 5*, 100115. https://doi.org/10.1016/j.trip.2020.100115

van Raamsdonk, L. W. D., van der Zande, M., Koelmans, A. A., Hoogenboom, R. L. A. P., Peters, R. J. B., Groot, M. J., Peijnenburg, A. A. C. M., & Weesepoel, Y. J. A. (2020). Current insights into monitoring, bioaccumulation, and potential health effects of microplastics present in the food chain. *Foods, 9*(1), 72. https://doi.org/10.3390/foods9010072

Wang, L.-C., Lin, J. C.-T., Dong, C.-D., Chen, C.-W., & Liu, T.-K. (2021). The sorption of persistent organic pollutants in microplastics from the coastal environment. *Journal of Hazardous Materials, 420*, 126658. https://doi.org/10.1016/j.jhazmat.2021.126658

Wang, W., Zhang, Z., Gao, J., & Wu, H. (2024). The impacts of microplastics on the cycling of carbon and nitrogen in terrestrial soil ecosystems: Progress and prospects. *Science of The Total Environment, 915*, Article 169977. https://doi.org/10.1016/j.scitotenv.2024.169977

Wang, Y., Bai, J., Liu, Z., Li, W., & Zhang, X. (2023). Consequences of microplastics on global ecosystem structure and function. *Reviews of Environmental Contamination and Toxicology (formerly Residue Reviews), 261*, Article 22. https://doi.org/10.1007/s44169-023-00047-9

Witczak, A., Przedpełska, L., Pokorska-Niewiada, K., & Cybulski, J. (2024). Microplastics as a threat to aquatic ecosystems and human health. *Toxics, 12*(8), 571. https://doi.org/10.3390/toxics12080571

Wright, S. L., & Kelly, F. J. (2017). Plastic and human health: A micro issue? *Environmental Science & Technology*, *51*(12), 6634-6647.

Wu, W-M., Yang, J., & Criddle, C.S. (2017). Microplastics pollution and reduction strategies. *Front. Environ. Sci. Eng.*, *11*(1), 6–9. https://doi.org/10.1007/s11783-017-0897-7

Xin Bao, Yuntong Gu, Long Chen, Zijian Wang, Hui Pan, Shiran Huang, Zhiyuan Meng, Xiaojun Chen (2024). Microplastics derived from plastic mulch films and their carrier function effect on the environmental risk of pesticides. *Science of The Total Environment, 924*, 171472.

Yan, F., Wei, R., Cui, Q., Bornscheuer, U. T., & Liu, Y. J. (2021). Thermophilic whole-cell degradation of polyethylene terephthalate using engineered Clostridium thermocellum. *Microbial Biotechnology, 14*(2), 374-385.

Yu, H., Zhang, Y., Tan, W., & Zhang, Z. (2022). Microplastics as an emerging environmental pollutant in agricultural soils: Effects on ecosystems and human health. *Frontiers in Environmental Science, 10*, 855292. https://doi.org/10.3389/fenvs.2022.855292

Zettler, E. R., Mincer, T. J., & Amaral-Zettler, L. A. (2013). Life in the "plastisphere": Microbial communities on plastic marine debris. *Environmental Science & Technology*, *47*(13), 7137-7146.

Zhang, Y., Kang, S., Allen, S., Allen, D., Gao, T., & Sillanpää, M. (2020). Atmospheric microplastics: A review on current status and perspectives. *Earth-Science Reviews, 203*, 103118. https://doi.org/10.1016/j.earscirev.2020.103118

Zhang, Y., Wang, D., & Wang, X. (2020). Microplastics induce gut microbiota dysbiosis and intestinal inflammation in mice. *Environmental Pollution*, *263*, 114514.

Zhao, H.-J., Xu, J.-K., Yan, Z.-H., Ren, H.-Q., & Zhang, Y. (2020). Microplastics enhance the developmental toxicity of synthetic phenolic antioxidants by disturbing thyroid function and metabolism in developing zebrafish. *Environment International, 140*, 105750. https://doi.org/10.1016/j.envint.2020.105750

Zhou, J., Jia, R., Brown, R. W., Yang, Y., Zeng, Z., Jones, D. L., & Zang, H. (2023). The long-term uncertainty of biodegradable mulch film residues and associated microplastics pollution on plant-soil health. *Journal of Hazardous Materials, 442*, 130055. https://doi.org/10.1016/j.jhazmat.2022.130055

Ziani K, Ioniță-Mîndrican C-B, Mititelu M, Neacşu SM, Negrei C, Moroşan E, Drăgănescu D, Preda O-T. (2023). Microplastics: A Real Global Threat for Environment and Food Safety: A State of the Art Review. *Nutrients*, *15*(3):617. https://doi.org/10.3390/nu15030617

Ziani, K., Ioniță-Mîndrican, C.-B., Mititelu, M., Neacşu, S. M., Negrei, C., Moroşan, E., Drăgănescu, D., & Preda, O.-T. (2023). Microplastics: A real global threat for environment and food safety: A state of the art review. *Nutrients, 15*(3), 617. https://doi.org/10.3390/nu15030617

Zobkov, M., & Esiukova, E. (2017). Microplastics in Baltic bottom sediments: quantification procedures and first results. *Marine pollution bulletin*, *114*(2), 724-732.