Impact of Plastic Waste on Biodiversity and Human Health: A Comprehensive Summary

Lau Wei Sin

Ethan McDowell

Jemma Stubington

Laidlaw Scholars Leadership-in-Action Project 24/25

Acknowledgement

This literature review is conducted for use by The MerTerre Association and as part of the Central Leadership-in-Action Project 2025, funded by The Laidlaw Foundation and hosted collaboratively by makesense in Paris, France, and The MerTerre Association in Marseille, France. The author, Lau Wei Sin, would like to thank The University of Hong Kong and Horizons Office of The University of Hong Kong for providing the opportunity and support throughout this scholarship. Much appreciation goes to Emma Lempereur and Jade Thiebaut from the makesense Paris office, as well as Teo Juričev from The MerTerre Association, for their support throughout the project. The author is beyond grateful to her teammates, Ethan McDowell and Jemma Stubington, for all the collaborative work and essential moral support for the completion of the project.

Table of Contents

1. Introduction

In 2019, the UN identified climate change, pollution and biodiversity loss as the triple planetary crisis, describing the three urgent environmental issues that need to be resolved for a sustainable planet (What Is the Triple Planetary Crisis?, 2022). Between 1950 and 2017, it was estimated that 9.7 billion tonnes of plastic had been produced. Currently, approximately 438 million tons of plastic are produced each year (United Nations Environment Programme et al., 2021). It is a widely recognised fact that plastic pollution poses a significant and alarming threat to the environment, damaging all terrestrial, freshwater, and marine biodiversity.

Plastics are made of synthetic polymers of organic compounds, such as polyethylene (PE) and polyvinyl chloride (PVC), making them malleable in shape but also extremely durable, taking up to 500 years to decompose on their own. Through fragmentation and weathering of these plastics, microplastics and nanoplastics, smaller constituents of plastics, are formed and are now found at the peak of Mount Everest and even in the depths of the Mariana Trench (Peng et al., 2018). The detrimental effects of plastics and microplastics in marine and coastal ecosystems have been widely documented and often used to raise public awareness of plastic pollution. However, its impact on land, terrestrial and freshwater ecosystems is often undermined despite recent studies showing evidence that rivers located in heavily industrialised areas have a higher concentration of microplastics than that of the marine environment, underscoring the need for equal attention (De Souza Machado et al., 2017).

Unsurprisingly, human activity is the main driver of all three crises and, consequently, also the victims of our actions. A study in 2019 detected various shapes and types of microplastic and nanoplastic in human colon, placenta, skin, respiratory tract and human stool sample, suggesting several routes of human exposure to plastics, including direct ingestion and inhalation (Schwabl et al., 2019; Tekman et al., 2022). The ubiquitous presence of microplastics and nanoplastics in our living environment poses an alarming threat to human health, with harmful effects such as immune system disruption, increased risk of metabolic disorders, irreversible effects on reproductive health and potential threat to fetal development (Yong et al., 2020; Ullah et al., 2023; Dubey et al., 2022).

Through reviewing existing literature worldwide, this report will firstly introduce the issue of plastic pollution, formation of microplastics and nanoplastics and their routes of exposure to humans and different ecosystems. This report will then summarise the negative impacts of plastic on human health, such as accumulated toxicity, triggering of inflammatory immunological response and its threat to reproductive health and fetal development. Furthermore, the impact of plastic pollution waste on biodiversity will also be explored at the terrestrial, freshwater, marine and coastal environment levels.

2. Plastics, Microplastics and Nanoplastics

Plastics define a category of materials made of organic polymers, which are large, long-chain molecules formed from the repeated linking of the same or different smaller units, that can be moulded into different shapes while soft. 99% of all plastics are formed from non-renewable hydrocarbon sources such as oil and natural gas extracted from the earth's crust. Their strength, light weight and malleable characteristics of plastics make them extremely popular as a material as early as the 1950s. Common plastics found in our daily life include: polyethylene (PE), commonly used for making water bottles, toys and plastic bags, polypropylene (PP), commonly used for making food containers, bag liners and dishware, and polyvinyl chloride (PVC), commonly used in pipes.

In 2022, the world produced 430 million metric tons of plastics, of which two-thirds are short-lived plastic products that become waste after two to three uses (United Nations Environment Programme et al., 2023). The global plastic production is predicted to triple by the year 2060 if current trends continue. As ecological concerns about plastic pollution grow, recent studies by scientists have found microplastics being ubiquitous in all habitats on earth, from the deepest Mariana trench to the highest mountain, Mount Everest, in human excretory waste and human placenta (Peng et al., 2018; Gruber et al., 2020).

Microplastics are defined as small plastic fragments that are **smaller than 5 mm** in size, and nanoplastics are even smaller plastic fragments **smaller than 1 µm** in size (United Nations Environment Programme et al., 2021). Microplastics can take on several forms such as fragments or fibres and are primarily formed from two sources, microplastic beads that are intentionally added to commercial products, such as cosmetics, hand sanitizer, paint and other personal care products, and from fragmentation of bigger plastics through radiation, weathering, mechanical abrasion or other natural processes (United Nations Environment Programme et al., 2021).

Microplastics are introduced into ecosystems in many ways. Two major ways include the abrasion of rubber tyres on road surfaces, and secondly, from untreated sewage rich in fibres due to wear and tear of textiles through laundering. This sewage is then discharged into upstream water ecosystems like rivers and streams, which will eventually end up in the ocean, contaminating both freshwater and marine ecosystems. The remaining sludge from sewage treatment plants containing high concentrations of microplastics is also often utilised as soil fertiliser, contaminating terrestrial ecosystems (De Souza Machado et al., 2017). As a result, ingestion of microplastics by various marine and freshwater organisms is documented in various scientific literature, entering various food chains and eventually also consumed by humans (Wright et al., 2013).

Environmental exposure to plastics is considered non- or poorly reversible when fragmentation caused by weathering is involved (MacLeod et al., 2021). Plastic pollution entering ecosystems is likely to end up irreversibly accumulating at five locations: (1) remote coastal surface, (2) water column, (3) seabed, (4) terrestrial soil and (5) body or organisms. The low degradation rate of plastic in these environments, due to low sunlight exposure, low temperature, and the presence of additives such as stabilisers in plastics, is the main reason for the irreversible addition of plastics to ecosystems. These commonly present additives, such as phthalates and bisphenol A (BPA), in plastic are likely to leach toxic chemicals into the environment during weathering, threatening the health of both wildlife and humans.

Microplastics pose geophysical and biological threats to the global environment, impacting all organisms and ecosystems. Furthermore, scientists suggest that microplastic accumulation is likely to interact with other environmental stressors such as climate change, ocean acidification and invasive species, amplifying ecological threat (MacLeod et al., 2021).

3. Impact on Human Health

Though plastics pose little to no threat to human health, recent studies have heightened public health concerns over microplastics. Studies have shown evidence of microplastics presence in 8 out of 12 human organ systems, including significant levels in human excretory waste, breast milk and placenta, suggesting that the quantity taken in is quite high (Roslan et al., 2024; United Nations Environment Programme et al., 2023; Yong et al., 2020).

Everyday, humans are exposed to microplastics and nanoplastics through direct ingestion in food and water, direct inhalation of polluted air and dermal contact with personal care products containing microplastics. Though the detrimental effects of ingestion of microplastics by marine animals are well documented, their potential detrimental effects on human health are still not well studied. This section examines and summarises the effects of microplastics and nanoplastics on human health, focusing on cellular toxicity, inflammatory responses, genotoxicity, respiratory effects, reproductive and developmental toxicity and endocrine disruption.

Cellular Toxicity (Cytotoxicity)

Several studies have demonstrated that microplastics (MPs) and nanoplastics (NPs) **can be internalised by human cells**. For instance, polystyrene particles have been shown to undergo active uptake by white blood cells, while polyethylene terephthalate (PET), commonly found in single-use plastic bottles, can **cross the intestinal barrier** via Caco-2 cells, a model for human gut epithelium (Wu et al., 2019). Once inside cells, these particles induce cytotoxic effects by stimulating the **overproduction of pro-inflammatory cytokines**, which are signalling proteins that trigger immune responses against pathogens. Additionally, MPs and NPs **stimulate excessive reactive oxygen species (ROS) generation,** which are highly reactive molecules that are commonly used against invasive parasites. Intracellularly, ROS can **cause oxidative damage to the cell membrane, genetic material, and proteins**, contributing to **elevated oxidative stress and possibly causing cell death**.

Prietl et al. (2013) showed that 20 nm nanoplastics (NP) of polystyrene (PS) can be easily taken up by human white blood cells, monocytes. PS NPs of size 20 nm to up to 1000 nm can exert cellular toxicity by stimulating the production of interleukin-8 (IL-8), a chemokine regulating phagocytosis. Exposure of PS NPs to monocytes significantly increased the bursting of ROS-containing granules in white blood cells, resulting in elevated oxidative stress. Other studies involving polystyrene (PS), polyethylene (PE) and polypropylene (PP) particles and their microparticles also demonstrated similar cytotoxicity trends. For example, polyethylene microplastics (3-16 µm) and polystyrene particles (10 µm) stimulated the production of ROS in human glioblastoma cell line (T98G) and human cervical adenocarcinoma cell line (HeLa) (Schirinzi et al., 2017). Other studies also demonstrated some degree of cytotoxicity triggered by microplastics on mononuclear white blood cells, human lung epithelial cells and nerve cell models (Yong et al., 2020).

Furthermore, although low levels of microplastics-associated cellular toxicity are found in non-immune cells, MPs are found to exert toxic effects through other means. For example, the mitochondrial membrane potential of gut epithelial cells (Caco-2) is disrupted by polystyrene nanoplastics, interfering with the function of the toxicant efflux pump, resulting in increased arsenic toxicity (Wu et al., 2019). Epithelial cells lining the lung surface (alveolar cells) are found to have lower viability and disrupted mitotic cell cycle when PS nanoparticles (25 and 70 nm) are present, interfering with the expression of proteins regulating induced cell death (Xu et al., 2019).

Inflammatory and Oxidative Stress Responses

Inflammation, usually indicated by elevated body temperature, redness and swelling, is part of the human's immune system response to injuries and pathogens to improve healing and removal of any invasive pathogens. However, prolonged (chronic) inflammation and sterile inflammation (inflammation without infection) can lead to cellular and tissue damage due to inflammatory cells and proteins attacking the body's cells. Chronic inflammation is associated with cardiovascular diseases, diabetes, autoimmune disease, and several types of cancer. *In vivo* and *in vitro* studies showed an association of microplastics with **elevated inflammatory indicators** in mouse and human cells. Human cells, particularly macrophages and human intestinal cells, exposed to microplastics and nanoplastics demonstrated **increased production of pro-inflammatory cytokines**, interleukin-6

(IL-6), interleukin-8 (IL-8), interleukin-1 (IL-1), tumour necrosis factor (TNF-α) and histamine (Pulvirenti et al., 2022; Hwang et al., 2019).

Hwang et al. (2019) showed that polypropylene (PP) particles, especially those smaller than 20 µm, are significantly toxic to human mononuclear white blood cells, including antibody-producing lymphocytes, natural killer cells and monocytes. PP microplastics induced a low-level increase in production of pro-inflammatory cytokines IL-6 and TNF-α in mononuclear white blood cells while also stimulating increased allergy-triggering histamine production in mast cells and basophils. These pro-inflammatory molecules, IL-6, TNF-α and histamine, together trigger local inflammatory responses by attracting other immune cells and increasing local blood flow.

Several studies demonstrated the activation of inflammatory pathways and upregulation of inflammatory gene transcription triggered by microplastics. Polystyrene nanoplastics induced significant upregulation of the NF-κB pathway as well as production of pro-inflammatory cytokines IL-8 and TNF-α, resulting in activation of TNF-α triggered cell death pathway (Xu et al., 2019). Exposure to microplastics isolated from the seawater significantly increased the levels of inflammatory markers NF-κB, MyD88 and NLRP3 in cells of oral cavity mucosa and increased the production of inflammatory cytokines IL-6, IL-1 and TNF-α (Caputi et al., 2022). NF-κB is a transcription factor for many pro-inflammatory cytokines and an activator of many downstream innate immune responses and inflammation.

Exposure of several human cell lines to microplastics and nanoplastics has shown elevated levels of ROS (reactive oxygen species) production (Yong et al., 2020). ROS, such as the hydroxide radical and hydrogen peroxide, are reactive and unstable chemicals composed of oxygen that can cause damage to cell membrane structures, DNA, RNA, and even cell death if accumulated. ROS production usually occurs during aerobic respiration or as a response to combat pathogen infection. However, ROS production without pathogen infection can also trigger an innate immune response, secreting proteins that attract localised immune cells, which can worsen local inflammation, potentially leading to cell damage and cell death. As a result, microplastics and nanoplastics are known to stress cells and the innate immune system.

Genotoxicity

Genotoxicity refers to chemicals that may damage genetic information within a cell, such as DNA and RNA, by generating mutations or breakage of genetic molecules, potentially leading to cancer. A study by Roursgaard et al. (2022) demonstrated that nanoplastics from real-life plastic food containers made of polypropylene (PP) and polyethylene terephthalate (PET) exhibited genotoxicity on two human cell lines, gastrointestinal epithelial cells model, Caco-2 and immortal liver cell line, HepG2. Exposure of these cell lines to nanoplastics caused a concentration-dependent increase in DNA strand breakage, which was independent of cytotoxicity, cell cycle disruption or ROS production. The study suggests a direct interaction of nanoplastics with genetic material or indirect effects mediated by other mechanisms. Genotoxicity and its potential carcinogenic effects of plastics raise concerns of health risk from environmental and dietary exposure to degraded plastics.

Respiratory Effects

Recent studies have detected a high abundance of microplastics in the air of various indoor environments, including private homes, schools, and offices in China, Iran, and the United Kingdom (Noorimotlagh et al., 2024). These airborne microplastics can be directly inhaled, posing potential risks to respiratory health. Additionally, a study by Torres-Agullo et al. (2021) has suggested possible microplastic accumulation in the human nasal cavity due to the prolonged use of microplastic-containing face masks during the COVID-19 pandemic, further highlighting the pervasive nature of microplastic exposure and its implications for respiratory function.

In vitro exposure of polystyrene (PS) nanoplastics to human respiratory epithelial cells suggested that nanoplastics disrupt the alveolar surface tension by depleting junction proteins. Disruption of epithelial function eases the entry of foreign substances, such as dust and allergens, into the interstitium and the bloodstream. Expression of proteins that reduce lung repair capacity was also raised after exposure to PS NPs. Entry of foreign substances into the bloodstream and reduced lung repair capacity could potentially lead to chronic lung diseases such as chronic obstructive pulmonary disease, increased vulnerability to allergic reactions, asthma and lung injury.

Microplastics and nanoplastics also exhibited cellular toxicity effects on human respiratory cells, causing significant morphological changes and inhibiting cell proliferation in alveolar cells. Polystyrene microplastics increased the expression of pro-apoptotic proteins, proteins that favour cell death, and reduced overall cell viability of alveolar epithelial cells (Lu et al., 2022). Similar to other human cell lines, microplastics also induced a localised inflammation response in respiratory epithelial cells. Microplastic exposure to epithelial cell inflammation increased the expression of pro-inflammatory cytokines TNF-α, IL-6, IL-1β and tumour growth factor beta (TGF-β). TGF-β is a cytokine regulating many cellular functions, including cell differentiation and tissue remodelling. Crucially, upregulation of TGF-β is evidenced to be associated with many lung diseases such as pulmonary fibrosis, emphysema, bronchial asthma, and lung cancer.

Lastly, a previous study by Lu et al. (2022) also showed that microplastics can combine with a common allergen, house dust mite, and amplify allergic reactions in asthmatic mice. Increased mucus secretion and allergy-induced airway inflammation, along with increased expression of allergy reaction causing protease MALT1, are observed in lung tissues of asthmatic mice co-exposed to house dust mite and microplastics compared to mice only exposed to house dust mite.

These findings suggest that through inducing cellular toxicity, inflammation and amplified allergic reactions, microplastics can have negative implications for the respiratory health of humans, especially those already with respiratory health diseases like asthma. These harmful effects, if prolonged exposure to microplastics, can potentially cause chronic lung diseases like COPD, asthma and lung injury.

Reproductive and Developmental Toxicity

The potential health impacts of plastics, particularly microplastics (MPs), on reproductive and developmental health have become a growing concern in recent years. Early studies reported compromised sperm quality in men and infertility issues in women among plastic industry workers, suggesting a possible link between plastic exposure and reproductive dysfunction (Jelnes, 1988; Hougaard et al., 2009). However, due to ethical limitations, direct research on the effects of plastics on human reproductive health remains scarce. Recent findings have heightened these concerns, revealing that MPs can cross the human placental barrier, posing a potential threat to fetal development (Ragusa et al., 2020). Furthermore, extensive research in model organisms, including rodents and aquatic species, has demonstrated that MPs contribute to reproductive toxicity (e.g., hormonal disruption, reduced fertility) and developmental defects (e.g., fetal growth restriction, transgenerational effects). These findings underscore the urgent need to investigate the mechanisms and long-term consequences of MP exposure in humans.

In rodent and aquatic species, microplastic exposure primarily caused male reproductive dysfunction through decreasing sperm quality, hormonal disruption and blood testis barrier disruption (Dubey et al., 2022). Exposure of microplastics to zebrafish and earthworms has caused increased testicular apoptosis and sperm deformities, both of which will cause decreased male fertility. Studies in mice demonstrated significantly decreased testosterone levels, the main male reproductive hormone for the development of reproductive organs and muscle mass, as well as a decrease in sperm generating cells and a disrupted blood-testis barrier after chronic exposure to microplastics. Furthermore, oral administration of polystyrene and polypropylene nanoplastics to mice has proved to disrupt male reproductive functions of mice through causing decreased decrease in steroidogenic enzymes, morphological changes in sperm, decreased sperm count, motility and serum testosterone level. These findings in model organisms suggest microplastics-associated toxicity to the male reproductive system, though direct evidence is still needed to validate a direct causative relationship.

Similarly, microplastics-associated female reproductive toxicity is observed in many model organisms, including oysters, zebrafish, mice and rats. These studies indicated symptoms of ovarian dysfunction with irregular oocytes and disrupted follicle maturation and differentiation when exposed to polystyrene microplastics long-term (Dubey et al., 2022). A study done on female rats by Haddadi et al. (2022) showed that rats that are exposed to 5 µm polystyrene microplastics have a disrupted oestrous cycle compared to the control group. The inflammatory effect of microplastics also increased oxidative stress in ovarian tissues and epithelial cells of the uterus, which consequently activated pathways leading to increased expression of TGF-β, resulting in TGF-β-mediated fibrosis (tissue hardening) in the endometrial epithelial cells and uterus and ovarian fibrosis (Dubey et al., 2022). Animal models that are exposed to microplastics are found to have lower quality of oocytes, follicles and ovarian reserve, suggesting inflammatory effects of microplastics might have induced toxicity in the female reproductive system.

Developmental toxicity is when the environment, diet or chemicals cause alterations in an organism's natural growth and development. A study by Ragusa et al. (2020) recently revealed that microplastics are able to cross the blood-placental barrier, a tight and highly regulated barrier safeguarding the development of a baby inside a mother's womb, raising concerns about possible microplastics-associated developmental toxicity. Gruber et al. (2020) demonstrated that human plasma protein, namely albumin and immunoglobulin G (antibody molecule), facilitates the transfer of 80 nm polystyrene nanoplastics across the placental barrier. Due to ethical reasons, no studies on the effects of microplastics on human embryo development have been done. However, similarly, studies on animal models also suggested microplastics-associated developmental toxicity in several different species. For instance, PS microplastics are associated with lower bodyweight of offspring, transgenerational testicular toxicity, immune disruption, and increased risk of metabolic disorders in offspring of mice and reduced number of live births (Dubey et al., 2022).

Endocrine Disruption

Plastic pollution is often a concern as plastics can leach toxic chemicals into the environment, specifically, chemical additives that are added in the manufacturing process of plastics, such as bisphenol A (BPA), polybrominated diphenyl ethers (PBDE), phthalates, organotins, as well as possible heavy metals such as mercury, arsenic, copper and lead. Similarly, in the human body, bioaccumulation of microplastics in human body is irreversible, and chemical leaching of toxic additives is a threat to human health as well. Toxic chemical additives are known to disrupt endocrine glands in the human body and disrupt hormonal balance, leading to biological imbalances and complications that can come with it. Although more research needs to be done to fully understand the possible endocrine disruptive effects of additives in human health, commonly used animal models Table 1 summarises the possible harmful effects of chemical additives from microplastics on endocrine function and human health (Ullah et al., 2023).

Endocrine Gland	Function	Disruption
Thyroid gland	Responsible for normal brain function, growth, and neurological development of all animals. Hormones regulate growth, development, metabolism, and reproduction.	PBDEs, BPA, phthalates, and organotins act as thyroid-disrupting chemicals. Additives in plastics interfere with the biochemical pathways of T4 and T3 (thyroid hormones) and affect the production and metabolism of thyroid hormones. Additives can combine with thyroid hormones and inhibit the binding of thyroid hormone to its receptor. Exposure to phthalates interferes with gene expression of the hypothalamic-pituitary-thyroid (HPT) axis and is associated with hyperthyroidism in humans.
Hypothalamus	Controls homeostasis, connects the central nervous system to the endocrine system and secretes hormones that stimulate or inhibit release of hormones from the pituitary glands.	In rats, PBDEs and Phthalates dysregulate the regulatory hypothalamic-pituitary-thyroid (HPT) and hypothalamic-pituitary-gonadal (HPG) axis. Phthalates and TBT disrupt the level of hormone secretion (e.g., GnRH, LH, FSH). BPA and phthalates cause neuroendocrine disruptions, affecting stress responses and reproductive functions.
Pituitary gland	Essential role in major physiological functions such as growth, sexual development,	In rats, additives are found to affect the secretion levels of GnRH, LH, and FSH, and increase corticosterone and ACTH levels.

	metabolism, and stress responses and regulates neuroendocrine activity through regulatory axes (e.g. HPT and HPG)	Additives also dysregulate the regulatory axes, affecting the response of hormones (TRH) and exert carcinogenic toxicity to the reproductive system.

Table 1. Summary of the endocrine disruptive effects of additives in plastics

Smaller plastic particles, microplastics and nanoplastics have a higher tendency to undergo active uptake by cells and leach toxic chemicals at a higher rate because of their higher surface area. Hence, microplastics and nanoplastics are more likely to release more endocrine-disrupting toxic chemicals into tissues when irreversibly accumulated in the human body. Exposure and possible intake of microplastics and nanoplastics through foodware, polluted air and drinking water pose an alarming global threat to human health, highlighting the urgent need for regulatory measures to mitigate exposures.

4. Impact on Biodiversity

Biodiversity is a term to describe the variety of all the different living organisms that can be found in a particular habitat, including plants, animals, fungi and microorganisms. These living organisms live together in a habitat, maintaining a balance and supporting life, forming an ecosystem. Biodiversity is crucial to support life in an ecosystem, including for humans, providing us with food, clean water, medicine and shelter. However, human activities like deforestation, pollution, climate change and urbanisation are now putting pressure on these ecosystems and causing habitat loss. Many species of animals and plants are now threatened with extinction, leading to biodiversity loss.

With the ubiquitousness, low degradation rate and toxicity of plastics, plastic pollution is a great harm to biodiversity. It threatens all lives in an ecosystem, animal species, plants and even microorganisms, affecting their ability to survive and disturbing the balance within the ecosystem. Although the impact of plastic pollution on marine and coastal biodiversity is most widely documented, studies suggest its negative impact on terrestrial and freshwater biodiversity is equally, if not worse than that of marine biodiversity (De Souza Machado et al., 2017; Azevedo-Santos et al., 2021). This section of the report examines and summarises the sources and impact of plastic pollution across terrestrial, freshwater and marine and coastal biodiversity.

Impact on Terrestrial Biodiversity

The impact of plastic pollution on terrestrial biodiversity is often undermined compared to that of marine and coastal biodiversity. However, scientists suggest that microplastic pollution on land could be 4-23 times higher than in the marine environment, of which agricultural soil is the most microplastic-polluted (De Souza Machado et al., 2017; Food and Agriculture Organization of the United Nations [FAO], 2021). Plastic pollution and microplastics make their way to terrestrial soil through several ways:

(a) **Sludge from sewage treatment plants is often used as soil fertiliser.** Sewage water contains a high concentration of microplastics from personal care products and laundering of textiles, and 99% of microplastics and nanoplastics remain in the sludge during the water treatment process (De Souza Machado et al., 2017; Renault et al., 2024)

(b) **Atmospheric deposition of microplastics from landfills and urban centres.** Air pollution from microplastics and their atmospheric transfer are significant transport vectors of microplastics to land and ocean (Zhang et al., 2020).

(c) **Agriculture plastic pollution.** Poor practices, lack of regulations and wear and tear of agricultural plastic products such as soil films, mulches, water pipes, wraps, nettings and polymer for seed coating contribute to the addition of plastic pollution in agricultural soil (Food and Agriculture Organization of the United Nations [FAO], 2021).

Furthermore, plastic waste left on terrestrial soil is degraded into microplastics more easily than in marine environments. This is primarily due to terrestrial soil receiving direct and intense UV exposure and is facilitated by temperature-enhanced oxidation in the degradation process. Moreover, soil acts as a physical grinder, and microorganisms that are naturally present in soil microbiota also catalyse the degradation process. Consequently, plastics are degraded to microplastics more easily, causing chemical changes that result in the leaching of their toxic additives into soil.

Microplastics impact terrestrial biodiversity in several ways. Firstly, the presence of microplastics **affects the geochemistry of soils**. Soil incubation experiment with microplastics by Wang et al. (2022) showed that the commonly used polymer for plastic bottles, high-density polyethylene (HDPE), and biodegradable plastics (polylactic acid, PLA) can increase the pH of soil by 10% when incubated together for 100 days. The experiment also tested that **nitrate content is significantly reduced** in the presence of microplastics, with a 99% decrease when 10% of PLA is present. Loss of nitrate content is alarming as it is a key nutrient needed by plants for the synthesis of amino acids and proteins, which is key to the growth and development of plants.

A major concern of plastic pollution is the leaching of toxic chemicals from them. Physical breakdown of plastics is synergetic with chemical degradation that releases the toxic additives of plastics, as mentioned in the earlier section (see endocrine disruption). In areas with heavy traffic and industrialisation, topsoils can contain up to 7% of microplastics by weight (De Souza Machado et al., 2017). Nonvolatile organochlorines from polyvinyl chloride (PVC) can alter the chloride content in soil, which can affect the water uptake of plants in the area. Similarly, in the human body, leaching of bisphenol A (BPA) and phthalates can also **exhibit toxic reproductive and endocrine-disruptive effects in animals living in the habitat** (De Souza Machado et al., 2020).

Studies conducted to investigate the effects of microplastics on soil microfauna are usually focused on invertebrates like earthworms, nematodes, mites and enchytraeids. Results showed that agricultural soil and soil used by humans that are polluted by microplastics and plastic additives have a significant effect on soil animal communities. Microplastics and microfibers interact with soil organisms in a manner that is dependent on the developmental stage and size of an organism, as studies have shown different impacts across larvae and adult stages of the same species. Due to the presence of many other interfering factors, knowledge gaps of the direct impact of microplastics on these soil organisms exist. However, just like marine animals, microplastics are **mistakenly ingested by microfauna** at the bottom of the food chain and can **accumulate in the food web** in terrestrial ecosystems. 94% of terrestrial birds, which are predators of these soil microfauna, with diverse foraging behaviour in China, have microplastics in their digestive tract after death (Zhao, Zhu, & Li, 2016, as cited in De Souza Machado et al., 2017). When microplastics are ingested by these organisms, microplastic particles can damage their gut system, trigger an immune response and cause oxidative stress, harming the overall wellbeing and causing mortality.

In fact, two earthworm species, Lumbricus terrestris and Eisenia fetida, showed **increased mortality and reduced growth** when living in microplastic-polluted soil in a study conducted by Lwanga et al. (2016, as cited in De Souza Machado et al., 2020). Furthermore, microplastics have also been shown to **affect the burrowing behaviour** of these earthworms, with a higher number of burrows and thicker burrow walls created in microplastic-contaminated soil. The activity of these earthworms has the potential to carry microplastics further down in terrestrial soil, where the degradation rate is lower in a sunlight-deprived and anaerobic environment. The potential effect of vertical transport of microplastics is still unknown, but it contributes to the irreversible accumulation of microplastics in our environment.

Soil microbiota refers to the population of microorganisms living in the soil and plays an important role in regulating many functions, such as nutrient cycling (including nitrogen fixing), plant growth, and disease suppression. Changes in the environment can **affect soil microbiota**, which will heavily influence soil fertility. One such example is the addition of microplastics to soils, which can affect the decomposition of organic matter, microbial enzymatic activities, and levels of nutrients present (Liu et al., 2017). More specifically, microplastics can affect the microbial biodiversity by altering the population distribution of different microorganisms present in the soil and affect symbiotic relationships in the microbial community (De Souza Machado et al., 2020).

Lastly, there is a growing interest in the Trojan horse effect of microplastics; the hydrophobic surfaces of microplastics within water treatment plants tend to be colonised by pathogenic and opportunistic organisms (Carriera et al., 2023). When the sludge is used as soil fertiliser, these microplastic particles enter terrestrial ecosystems and act as a potential pathogen vector. A study conducted on these pathogen communities on microplastic surfaces showed higher levels of antibiotic-resistance genes (Arias-Andres M et al, 2018, as cited in De Souza Machado et al., 2020). If released into the environment, these microplastic particles can contribute to the spreading of contagious disease and the antimicrobial resistance (AMR) crisis.

In conclusion, the addition of microplastics to terrestrial soils can have negative impacts on terrestrial biodiversity. Through affecting the geochemistry and biophysical environment of the soil, microplastics can potentially alter the behaviour of terrestrial animals and harm the growth and development of plants by the leaching of toxic additives and changes in soil content. Microplastics also affect terrestrial biodiversity by affecting the natural soil microbiota, interfering with important functions such as nutrient cycling, plant growth, and possibly aiding with the spread of antibiotic resistance genes through pathogens colonised microplastic surfaces.

Impact on Freshwater Biodiversity

Although freshwater ecosystems account for a far smaller percentage of Earth's water volume compared to their marine counterparts, freshwater ecosystems are home to more than 20% of all vertebrate species, underscoring the significantly high level of biodiversity (Ottoni et al., 2023). Freshwater ecosystems provide a variety of habitats, consisting of rivers, streams, waterfalls, lakes and swamps, providing a variety of different conditions and habitats to many freshwater organisms.

As reported by Lechner & Ramler (2015), a production plant neighbouring the Danube River (Austria) could emit 94.5 t/year of industrial microplastics. Rivers in heavily industrialised areas could contain much higher concentrations of microplastics than the marine environment. In addition, treated effluent from water treatment plants often contains a high concentration of microplastics in the form of microfibre but is released to upstream streams and rivers, directly entering the freshwater ecosystem. Yet, plastic pollution in freshwater ecosystems is receiving far less attention than marine ecosystems.

Plastic pollution generally affects freshwater organisms in a similar manner to the marine environment: **ingestion by and entanglements of animals, disruption of food webs, and toxicity effects**. A study by Azevedo-Santos et al. (2021) reported evidence of plastic ingestion by 206 freshwater species, including both invertebrates and vertebrates. **Ingestion of plastic** by most groups included in the study, crustaceans, fish, molluscs, amphibians, Cnidarians and mammals, is shown to be sublethal and lethal for two species of crustaceans and a mammal. Amongst freshwater species, fish are the most affected population by the ingestion of plastics, resulting in inflammatory reactions in the guts, intestinal-related injuries, gut distension and odd swimming behaviour. In addition, the study also highlighted the possibility of **plastics adhering to the gills of fishes**, affecting their respiratory functions and possibly leading to fatality. Risks of ingestion of plastics and entanglement are real, especially by fishing nets and lines, significantly threatening the lives of other freshwater animals, amphibians and freshwater birds in the same way. Many vulnerable species have "near threatened" status, and plastic pollution is catalysing their disappearance from the earth.

At the subspecies level, Danio rerio, commonly known as zebrafish, is a freshwater species that is commonly used as a model animal organism in laboratories. Many studies have associated exposure to microplastics with negative biological impacts in larvae of and adult zebrafish, highlighting the reproductive and developmental toxicity of microplastics. For example, PS and PE microplastics can cause liver inflammation and lipid accumulation, affect lipid and energy metabolism, delay and inhibit hatching, accumulate in the guts, liver and gills, and reduce gut microbiota biodiversity (Hodkovicova et al., 2022). Moreover, exposure of nanoplastics to larvae of zebrafish caused accumulation in the gastrointestinal tract, liver, blood, heart, pancreas and brain in adult zebrafish after hatching. In adult fish, microplastics and their leached chemicals are shown to be associated with elevated inflammation levels, oxidative stress, neurotoxicity, significant accumulation in the guts and liver, metabolism and endocrine disruption, abnormal swimming activity and alterations in gene expression altering crucial biological processes (Hodkovicova et al., 2022).

Plastics are formed from organic polymers, and they can act as a good source of carbon because of their high carbon content. A study by Sheridan et al. (2022) showed that plastics are more bioavailable than natural organic matter present in lakes. Consequently, plastic pollution has been shown to increase bacterial growth in freshwater lakes located in Scandinavian regions. Microplastic provides carbon source for algae, microorganisms at the bottom of freshwater food chains, and stimulate their growth, leading to more biomass at the bottom of the food chain. This could result in a ripple effect that supports the growth of organisms at a higher trophic level feeding on algae. However, microplastics also accumulate in the food chain irretrievably, which could one day exceed a safe concentration threshold and be lethal to freshwater organisms. Microplastics exposure could also accelerate nutrient pollution, eutrophication from the uncontrolled growth of algae (Zhang et al., 2019). Eutrophication would deplete the oxygen concentration and prevent sunlight, killing aquatic animals and plants, leading to freshwater biodiversity loss.

Impact on Marine and Coastal Biodiversity

The first record of plastic pollution dates back to 1972, when scientists began encountering small pieces of plastic in the Sargasso Sea (Rochman, 2020). To date, the interaction between plastic debris and marine life has been reported in 851 studies from 1,511 locations worldwide (Tekman et al., 2022). An estimate of 2150 species of animals in the ocean have encountered plastic pollution, and studies have reported negative effects on 90% the species studied.

In 2024 alone, The Ocean Clean Up removed 11.5 million kilograms (KG) of trash from oceans and rivers, a number that exceeded the total amount collected in the 6 years prior (The Ocean Cleanup, 2024). However, the addition of plastics to the environment is still considered irreversible due to the impossibility of removing microplastics and nanoplastics that are already ubiquitous in our environment. This is more true given the large surface area of the ocean and the continuous degradation of plastics into microplastics. According to a report by Tekman et al. (2022) for the World Wildlife Fund, "Even if all plastic pollution inputs into the ocean were to stop today, this process of degradation means the mass of microplastics in oceans and beaches will more than double between 2020 and 2050."

Plastic pollution will only increase and never decrease in the future. Furthermore, it is now a global consensus that microplastics work synergistically with other environmental stressors, such as global warming, ocean acidification, ocean noise pollution, eutrophication and invasive species, that turn the marine environment into one that is unlivable for its inhabitants. Microplastics, together with other environmental stressors, combine and produce a "cocktail effect" that threatens species to extinction and ultimately, loss of biodiversity.

In 2020, Everaert et al. (2020) conducted a study on 23 marine species to assess the potential harmful effects of floating microplastics on the marine ecosystem and proposed **a median unacceptable level (threshold level) of microplastic concentration of 1.21×10^5 MP m^{-3}**. To date, microplastic concentration in certain spots of the Mediterranean, the East China Sea, the Yellow Sea and the Arctic sea ice has already exceeded this threshold level (Tekman et al., 2022). Exceeding this "safe" threshold could threaten the loss of biodiversity, through risks such as altering the population of species, losing genetic diversity and causing changes in naturally occurring evolutionary trajectories (Chapman et al., 2016, as cited in Everaert et al., 2020).

Plastic pollution enters the ocean from the land, primarily from human activity such as fishing, agricultural activities, dumping of waste, wastewater and littering and causes negative effects through physical and chemical interactions. Once entered the water, plastic debris is suspended in the ocean by waves and turbulence and eventually taken up by organic matter or sinks to the ocean sea bed, making it one of the habitats with the highest concentration of microplastic particles (MacLeod et al., 2021). Moreover, the seabed receives no sunlight and is usually at a low temperature, a condition where plastics cannot undergo further degradation but only accumulate.

The impact of plastic pollution on marine biodiversity is widely studied and documented. This section of the report aims to summarise the impact of plastic pollution on marine biodiversity through physical and chemical interactions and their impact on ecosystems and biodiversity while focusing on sourcing information from recent studies.

Impact Through Physical Interaction

The main negative effects of plastics on marine biodiversity through physical interactions are:

(a) **Entanglement of marine animals**: Fishing plastic waste, such as fishing lines and nets and plastic bags, often cause entanglement in marine animals, resulting in restricted movement, wounding and even death. Entanglement could also happen to coral reefs and deep-sea sponge colonies. It is predicted that a third of coral reefs in the Asia Pacific region are entangled with 11 billion items of plastic (Briggs, 2018).

(b) **Ingestion of plastics**: Uptake of plastic debris can firstly cause blockages and injuries, or accumulate in the gastrointestinal tract of animals and affect food intake and egestion functions of marine animals, leading to fatality. Secondly, wild fishes with microplastic particles found within them show elevated levels of lipid peroxidation in the brain, gills and dorsal muscle, underscoring cellular uptake of MP and MP-associated inflammatory effects and oxidative damage from reactive oxygen species (ROS) (Barboza et al., 2019). Thirdly, evidence of MP-induced neurotoxicity is also discovered; fish with microplastics have a two-fold increase in acetylcholinesterase, signifying the increase in neurotransmitter production and overstimulation of post-synaptic receptors, which could be a result of membrane oxidative damage of transport vesicles that are essential for signal transmission in the nervous system. Similarly, for other organisms, microplastics also exhibited reproductive and developmental toxicity, affecting the growth and development of marine animals exposed to microplastics. The consequence of the ingestion of plastics is the entry of microplastics into food chains, which humans are likely part of, and thereby also ingesting microplastics.

(c) **Colonisation of plastic debris:** Marine organisms such as microbes, algae, and animals colonise floating plastic debris that enters the environment and, due to currents, end up in different locations in the ocean. Drifting of plastic debris and organisms colonising it "disperses" the organism and brings it to somewhere it does not belong. Oftentimes, this could lead to the introduction of invasive species in a new environment, which could outcompete native species, depleting their resources and forcing them to extinction.

(d) **Contact or coverage by plastic:** The most direct impact of marine organisms due to coverage by plastic is oxygen deficiency and blockage of sunlight. For example, plastic debris covered mangrove roots led to suffocation, leaf loss and death of mangrove trees (Van Bijsterveldt et al., 2020). Plastics are endangering mangrove forests, which are important coastal ecosystems that stabilise shorelines, prevent land erosion and are home to thousands of species.

Impact Through Chemical Interaction

As part of the manufacturing process of plastics, additives are often added to plastics to obtain desirable functions. For example, bisphenol A (BPA) hardens plastics, and phthalates make plastics more flexible. Flame retardants like polybrominated diphenyl ethers (PBDE) are added to prevent the burning of plastics, while heavy metals, like tin and mercury, are added to serve as antimicrobial agents and biocides. Although harmful additives such as polychlorinated biphenyls are banned under the Stockholm Convention on Persistent Organic Pollutants, many harmful additives that can leach easily from plastic products persist in the global environment, and many of them exhibit endocrine-disrupting effects. Table 2 summarises the potential harmful effects on aquatic animals from chemicals that can be leached from plastics.

Leached Chemical	Potential Harmful Effects on Aquatic Animals
Bisphenol A (BPA)	● Endocrine disruptor ● Excessive oestrogenic activity ● Disrupt thyroid functions ● Mutagenic (potentially carcinogenic) ● Pro-inflammatory
Phthalates	● Endocrine disruptor ● Reproductive and developmental toxicities ● Affects movement and feeding behaviour
Flame retardant (Polybrominated diphenyl ethers, PBDE)	● Carcinogen ● Endocrine disruptor ● Neurotoxicity ● Reproductive toxicity
Metals	● Growth retardation ● Liver lesion ● Kidney damage ● Infertility (Mazed et al., 2022)
Petroleum hydrocarbons	● Endocrine disruptor ● Reproductive toxicity
Polychlorinated biphenyls	● Endocrine disruptor ● Neurotoxicity ● Carcinogenic effects ● Persist in the global environment for a long time ● Bioaccumulation in predators like sharks and killer whales
Polycyclic aromatic	● Can induce liver damage

hydrocarbons	● Associated with biochemical and physiological disorders ● Endocrine disruptors ● Carcinogenic ● Can cause cardiovascular diseases

Table 2. Summary of the potential harmful effects of additives in plastics on aquatic animals

Other Impacts

(a) Deep Sea Impacts

The ocean seafloor is one of the major accumulation zones for microplastics, as microplastics tend to sink and accumulate with minimal to no degradation activity. Microplastics are found even in the ocean's deepest point, the Mariana Trench (Chiba et al. 2018, as cited in Tekman et al., 2022). Particularly high concentrations of microplastics are found in the seabed of the South China Sea, the Mediterranean Sea and the Arctic Ocean due to high marine traffic and fishing activities. Studies have shown that accumulated microplastics on the ocean seafloor can affect the naturally occurring nutrient cycling process in various ways. Microplastics are a new source of carbon in the ocean and could hinder the ability of the ocean to remove carbon dioxide from the atmosphere (MacLeod et al., 2021). Instead, carbon dioxide remains in the atmosphere and contributes to global warming. Additionally, microorganisms that colonise the surfaces of plastic debris form a layer called "biofilm", which can firstly affect the buoyancy and fate of plastic debris in the ocean, but also affect nutrient cycling. Biofilms on microplastics are found to affect nitrogen and phosphorus cycling in aquatic systems, affecting the delivery of nutrients to the deep-sea environments and hence altering the deep-sea habitat.

(b) Ecosystems at Risk

A review on the impact of plastic pollution on Mediterranean reefs revealed that 78 coral species are affected by plastic pollution, and several of them are listed as endangered species. Above all, most coral reefs are affected through entanglement by abandoned, lost or discarded fishing gear (Angiolillo & Fortibuoni, 2020). Coral reefs, also known as the rainforests of the ocean, are habitats to about 25% of marine life and are a form of natural protection of shorelines from waves, storms and erosion. However, coral reefs are now facing many environmental stressors such as global warming, pollution from tourism, ocean acidification, and much more, which cause coral reef bleaching and prevent their ability to form an exoskeleton.

Studies in multiple coral reef sites worldwide, such as in the southwestern Indian Ocean, Hawaii, and Ecuador, have shown that plastic pollution has led to higher occurrence of damaged branches, tissue abrasion and death of corals (Tekman et al., 2022). Corals may directly ingest microplastic particles or be indirectly affected as microplastic is shown to affect the crucial symbiotic relationship between corals and algae (Tang et al., 2015, as cited in Tekman et al., 2022). Microplastic exposure to coral reefs causes cell death and disturbance in the symbiotic relationship with algae affects the exoskeleton formation of coral reefs and consequently affects their survival.

Overall Impact on Marine Biodiversity

In marine ecosystems, plastic pollution can directly impact and cause harm to marine organisms through physical interactions or indirectly through the leaching of toxic additives. Furthermore, microplastics also affect the marine ecosystem's functions, like carbon sequestration and its nutrient cycle. Plastic pollution can cause the dispersion of marine animals and microorganisms, resulting in invasive species, affecting the ecosystem's natural structure. Important ecosystems such as coral reefs and mangrove forests are also at risk of smothering and entanglement by plastic debris. Persistent addition of plastic pollution in the marine environment will affect marine populations, harm genetic diversity and interfere with evolutionary paths, ultimately resulting in biodiversity loss.

5. Conclusion and Summary

Plastic pollution has become a global threat to biodiversity and human health, affecting terrestrial, freshwater and marine ecosystems. The findings of this report are summarised below:

1. Human health:
    a. **Tendency for cellular uptake and cellular toxicity (cytotoxicity).** Microplastics can be internalised by humans, and experimental models suggest the possibility of microplastics crossing the intestinal barrier. Once inside cells, microplastics stimulate the production of proteins that can promote cell death.
    b. **Inflammation and Oxidative Stress.** Exposure to microplastics is associated with upregulation of inflammatory gene transcription, elevated production of pro-inflammatory proteins and reactive oxygen species. Pro-inflammatory proteins can trigger local inflammatory responses and possibly result in chronic inflammation, which is associated with cardiovascular diseases, diabetes, autoimmune disease, and several types of cancer. Reactive oxygen species can cause oxidative damage to membrane structures and genetic materials like DNA and RNA, and promote cell death.
    c. **Genotoxicity.** Nanoplastics could have direct interaction with genetic material, and cellular exposure to nanoplastics has been shown to increase the frequency of DNA strand breakage.
    d. **Respiratory Effects.** Microplastics and nanoplastics can be inhaled directly and cause local inflammation on the surface of the lungs, disrupt the body's natural barrier and enter the bloodstream, resulting in chronic lung diseases. Microplastic particles can combine with common allergens and amplify allergic reactions in asthmatic mice through stimulating the production of histamine and pose a threatening risk to asthmatic humans.
    e. **Reproductive and Developmental Toxicity.** Exposure of model organisms to microplastics has been shown to reduce fertility in both genders through reducing the

quality of germ cells in a transgenerational manner and has a significant endocrine-disruptive effect on reproductive hormones. Microplastics can also cross the human blood-placental barrier and exhibit developmental toxicity, increasing the mortality rate and development of many model organisms.

f. **Endocrine-disruptive effects.** Leaching of additives in plastics has significant endocrine-disruptive effects, affecting the functions of the thyroid glands, hypothalamus and pituitary gland. Toxic additives can significantly affect the physiological functions, such as metabolism, reproduction, development and hormone regulation of animals.

2. Biodiversity:

   a. **Terrestrial:** Plastic pollution affects terrestrial biodiversity through altering soil geochemistry, ecotoxicity, ingestion by terrestrial animals and disrupting the soil microbiome. Microplastics can disrupt the nitrogen cycle, be ingested by soil microfauna and accumulate in the food web and disrupt the soil microbiota and influence soil health. Moreover, plastics can also be directly ingested by terrestrial organisms and negatively impact their health through endocrine-disruptive effects.

   b. **Freshwater:** Plastic pollution in freshwater biodiversity is undermined, but its impact is similar and comparable to that of marine ecosystems. Plastics can be ingested and cause entanglements of freshwater animals, disrupt food webs and have ecotoxicological effects in freshwater ecosystems. Microplastics can act as a source of carbon and cause eutrophication through algal blooms.

   c. **Marine:** Microplastic concentration in the Yellow Sea, Mediterranean Sea, the East China Sea and the Arctic sea ice has exceeded a safe threshold and could result in affected individual populations, loss of genetic diversity and change evolutionary trajectories. Plastic pollution negatively impacts marine biodiversity through physical interactions (ingestion, entanglement, colonisation, and smothering) and chemical interactions (toxicity by additives), and puts many important ecosystems, such as coral reefs and coastal mangrove forests, at high risk of suffocation and death. Plastic pollution also affects carbon sequestration, the nutrient cycle to deep-sea habitats and introduces invasive species.

Plastic pollution is a global crisis that will only grow and combine with existing environmental stressors like climate change and habitat degradation to create a "cocktail effect" to harm ecosystems. This synergy accelerates habitat destruction and species extinction, driving the irreversible loss of biodiversity. Once dismissed as a distant marine issue, plastic pollution now infiltrates human biology, with microplastics detected in organs, blood, and excretory waste. As both the cause and victims of this crisis, humans must confront the reality that plastic pollution threatens all life, from the smallest soil organisms to predators like ourselves.

References

Angiolillo, M., & Fortibuoni, T. (2020). Impacts of marine litter on Mediterranean reef systems: From shallow to deep waters. *Frontiers in Marine Science*, *7*. https://doi.org/10.3389/fmars.2020.581966

Azevedo-Santos, V. M., Brito, M. F. G., Manoel, P. S., Perroca, J. F., Rodrigues-Filho, J. L., Paschoal, L. R. P., Gonçalves, G. R. L., Wolf, M. R., Blettler, M. C. M., Andrade, M. C., Nobile, A. B., Lima, F. P., Ruocco, A. M. C., Silva, C. V., Perbiche-Neves, G., Portinho, J. L., Giarrizzo, T., Arcifa, M. S., & Pelicice, F. M. (2021). Plastic pollution: A focus on freshwater biodiversity. *AMBIO*, *50*(7), 1313–1324. https://doi.org/10.1007/s13280-020-01496-5

Barboza, L. G. A., Lopes, C., Oliveira, P., Bessa, F., Otero, V., Henriques, B., Raimundo, J., Caetano, M., Vale, C., & Guilhermino, L. (2019). Microplastics in wild fish from North East Atlantic Ocean and its potential for causing neurotoxic effects, lipid oxidative damage, and human health risks associated with ingestion exposure. *The Science of the Total Environment*, *717*, 134625. https://doi.org/10.1016/j.scitotenv.2019.134625

Briggs, B. H. (2018, January 26). *A third of coral reefs "entangled with plastic."* https://www.bbc.com/news/science-environment-42821004

Caputi, S., Diomede, F., Lanuti, P., Marconi, G. D., Di Carlo, P., Sinjari, B., & Trubiani, O. (2022). Microplastics Affect the Inflammation Pathway in Human Gingival Fibroblasts: A Study in the Adriatic Sea. *International Journal of Environmental Research and Public Health*, *19*(13), 7782. https://doi.org/10.3390/ijerph19137782

Carriera, F., Di Fiore, C., & Avino, P. (2023). Trojan horse effects of microplastics: A mini-review about their role as a vector of organic and inorganic compounds in several matrices. *AIMS Environmental Science*, *10*(5), 732–742. https://doi.org/10.3934/environsci.2023040

De Souza Machado, A. A., Horton, A. A., Davis, T., & Maaß, S. (2020). Microplastics and their effects on soil function as a Life-Supporting system. In *The handbook of environmental chemistry* (pp. 199–222). https://doi.org/10.1007/698_2020_450

De Souza Machado, A. A., Kloas, W., Zarfl, C., Hempel, S., & Rillig, M. C. (2017). Microplastics as an emerging threat to terrestrial ecosystems. *Global Change Biology*, *24*(4), 1405–1416. https://doi.org/10.1111/gcb.14020

Dubey, I., Khan, S., & Kushwaha, S. (2022). Developmental and reproductive toxic effects of exposure to microplastics: A review of associated signaling pathways. *Frontiers in Toxicology*, *4*. https://doi.org/10.3389/ftox.2022.901798

Everaert, G., De Rijcke, M., Lonneville, B., Janssen, C., Backhaus, T., Mees, J., Van Sebille, E., Koelmans, A., Catarino, A., & Vandegehuchte, M. (2020). Risks of floating microplastic in the global ocean. *Environmental Pollution*, *267*, 115499. https://doi.org/10.1016/j.envpol.2020.115499

Food and Agriculture Organization of the United Nations [FAO]. (2021). Assessment of agricultural plastics and their sustainability: A call for action. In *FAO eBooks*. https://doi.org/10.4060/cb7856en

Gruber, M. M., Hirschmugl, B., Berger, N., Holter, M., Radulović, S., Leitinger, G., Liesinger, L., Berghold, A., Roblegg, E., Birner-Gruenberger, R., Bjelic-Radisic, V., & Wadsack, C. (2020). Plasma proteins facilitates placental transfer of polystyrene particles. *Journal of Nanobiotechnology*, *18*(1). https://doi.org/10.1186/s12951-020-00676-5

Haddadi, A., Kessabi, K., Boughammoura, S., Rhouma, M. B., Mlouka, R., Banni, M., & Messaoudi, I. (2022). Exposure to microplastics leads to a defective ovarian function and change in cytoskeleton protein expression in rat. *Environmental Science and Pollution Research*, *29*(23), 34594–34606. https://doi.org/10.1007/s11356-021-18218-3

Hodkovicova, N., Hollerova, A., Svobodova, Z., Faldyna, M., & Faggio, C. (2022). Effects of plastic particles on aquatic invertebrates and fish – A review. *Environmental Toxicology and Pharmacology*, *96*, 104013. https://doi.org/10.1016/j.etap.2022.104013

Hougaard, K. S., Hannerz, H., Feveile, H., & Bonde, J. P. (2009). Increased incidence of infertility treatment among women working in the plastics industry. *Reproductive Toxicology*, *27*(2), 186–189. https://doi.org/10.1016/j.reprotox.2009.01.003

Hwang, J., Choi, D., Han, S., Choi, J., & Hong, J. (2019). An assessment of the toxicity of polypropylene microplastics in human derived cells. *The Science of the Total Environment*, *684*, 657–669. https://doi.org/10.1016/j.scitotenv.2019.05.071

Jelnes, J. E. (1988). Semen quality in workers producing reinforced plastic. *Reproductive Toxicology*, *2*(3–4), 209–212. https://doi.org/10.1016/0890-6238(88)90024-x

Lechner, A., & Ramler, D. (2015). The discharge of certain amounts of industrial microplastic from a production plant into the River Danube is permitted by the Austrian legislation. *Environmental Pollution*, *200*, 159–160. https://doi.org/10.1016/j.envpol.2015.02.019

Liu, H., Yang, X., Liu, G., Liang, C., Xue, S., Chen, H., Ritsema, C. J., & Geissen, V. (2017). Response of soil dissolved organic matter to microplastic addition in Chinese loess soil. *Chemosphere*, *185*, 907–917. https://doi.org/10.1016/j.chemosphere.2017.07.064

Lu, K., Zhan, D., Fang, Y., Li, L., Chen, G., Chen, S., & Wang, L. (2022). Microplastics, potential threat to patients with lung diseases. *Frontiers in Toxicology*, *4*. https://doi.org/10.3389/ftox.2022.958414

MacLeod, M., Arp, H. P. H., Tekman, M. B., & Jahnke, A. (2021). The global threat from plastic pollution. *Science*, *373*(6550), 61–65. https://doi.org/10.1126/science.abg5433

Mazed, M. A., Rahman, M. A., & Ahmed, S. I. (2022). A review on effects of heavy metals on aquatic animals and public health significance. *Veterinary Sciences Research and Reviews*, *8*(2). https://doi.org/10.17582/journal.vsrr/2022/8.2.96.104

Noorimotlagh, Z., Hopke, P. K., & Mirzaee, S. A. (2024). A systematic review of airborne microplastics emissions as emerging contaminants in outdoor and indoor air environments. *Emerging Contaminants*, *10*(4), 100372. https://doi.org/10.1016/j.emcon.2024.100372

Ottoni, F. P., South, J., Azevedo-Santos, V. M., Henschel, E., & De Bragança, P. H. N. (2023). Editorial: Freshwater biodiversity crisis: Multidisciplinary approaches as tools for conservation. *Frontiers in Environmental Science*, *11*. https://doi.org/10.3389/fenvs.2023.1155608

Peng, X., Chen, M., Chen, S., Dasgupta, S., Xu, H., Ta, K., Du, M., Li, J., Guo, Z., & Bai, S. (2018). Microplastics contaminate the deepest part of the world's ocean. *Geochemical Perspectives Letters*, 1–5. https://doi.org/10.7185/geochemlet.1829

Prietl, B., Meindl, C., Roblegg, E., Pieber, T. R., Lanzer, G., & Fröhlich, E. (2013). Nano-sized and micro-sized polystyrene particles affect phagocyte function. *Cell Biology and Toxicology*, *30*(1), 1–16. https://doi.org/10.1007/s10565-013-9265-y

Pulvirenti, E., Ferrante, M., Barbera, N., Favara, C., Aquilia, E., Palella, M., Cristaldi, A., Conti, G. O., & Fiore, M. (2022). Effects of Nano and Microplastics on the Inflammatory Process: In Vitro and In Vivo Studies Systematic Review. *Frontiers in Bioscience-Landmark*, *27*(10). https://doi.org/10.31083/j.fbl2710287

Ragusa, A., Svelato, A., Santacroce, C., Catalano, P., Notarstefano, V., Carnevali, O., Papa, F., Rongioletti, M. C. A., Baiocco, F., Draghi, S., D'Amore, E., Rinaldo, D., Matta, M., & Giorgini, E. (2020). Plasticenta: First evidence of microplastics in human placenta. *Environment International*, *146*, 106274. https://doi.org/10.1016/j.envint.2020.106274

Renault, D., Wiegand, C., Balzani, P., Richard, C. M., Haubrock, P. J., Colinet, H., Davranche, M., Pierson-Wickmann, A., & Derocles, S. A. (2024). The Plasticene era: Current uncertainties in estimates of the hazards posed by tiny plastic particles on soils and terrestrial invertebrates. *The Science of the Total Environment*, *927*, 172252. https://doi.org/10.1016/j.scitotenv.2024.172252

Rochman, C. (2020). The Story of Plastic Pollution: From the Distant Ocean Gyres to the Global Policy Stage. *Oceanography*, *33*(3), 60–70. https://doi.org/10.5670/oceanog.2020.308

Roslan, N. S., Lee, Y. Y., Ibrahim, Y. S., Anuar, S. T., Yusof, K. M. K. K., Lai, L. A., & Brentnall, T. (2024). Detection of microplastics in human tissues and organs: A scoping review. *Journal of Global Health*, *14*. https://doi.org/10.7189/jogh.14.04179

Roursgaard, M., Rothmann, M. H., Schulte, J., Karadimou, I., Marinelli, E., & Møller, P. (2022). Genotoxicity of Particles From Grinded Plastic Items in Caco-2 and HepG2 Cells. *Frontiers in Public Health*, *10*. https://doi.org/10.3389/fpubh.2022.906430

Schirinzi, G. F., Pérez-Pomeda, I., Sanchís, J., Rossini, C., Farré, M., & Barceló, D. (2017). Cytotoxic effects of commonly used nanomaterials and microplastics on cerebral and epithelial human cells. *Environmental Research*, *159*, 579–587. https://doi.org/10.1016/j.envres.2017.08.043

Schwabl, P., Köppel, S., Königshofer, P., Bucsics, T., Trauner, M., Reiberger, T., & Liebmann, B. (2019). Detection of Various Microplastics in Human Stool. *Annals of Internal Medicine*, *171*(7), 453–457. https://doi.org/10.7326/m19-0618

Sheridan, E. A., Fonvielle, J. A., Cottingham, S., Zhang, Y., Dittmar, T., Aldridge, D. C., & Tanentzap, A. J. (2022). Plastic pollution fosters more microbial growth in lakes than natural organic matter. *Nature Communications*, *13*(1). https://doi.org/10.1038/s41467-022-31691-9

Tekman, M. B., Walther, B. A., Peter, C., Gutow, L., Bergmann, M., & Alfred Wegener Institute Helmholtz-Centre for Polar- and Marine Research. (2022). Impacts of plastic pollution in the oceans on marine species, biodiversity and ecosystems. In WWF Germany, *WWF Germany*. WWF Germany, Berlin. https://doi.org/10.5281/zenodo.5898684

The Ocean Cleanup. (2024, December 19). *2024: A record-breaking year for The Ocean Cleanup*. Retrieved August 8, 2025, from https://theoceancleanup.com/updates/2024-a-record-breaking-year-for-the-ocean-cleanup/

Torres-Agullo, A., Karanasiou, A., Moreno, T., & Lacorte, S. (2021). Overview on the occurrence of microplastics in air and implications from the use of face masks during the COVID-19 pandemic. *The Science of the Total Environment*, *800*, 149555. https://doi.org/10.1016/j.scitotenv.2021.149555

Ullah, S., Ahmad, S., Guo, X., Ullah, S., Ullah, S., Nabi, G., & Wanghe, K. (2023). A review of the endocrine disrupting effects of micro and nano plastic and their associated chemicals in mammals. *Frontiers in Endocrinology*, *13*. https://doi.org/10.3389/fendo.2022.1084236

United Nations Environment Programme, Milà I Canals, L., Cairns, A., Lefort, P., Meso, A., Raine, A. D., Smagadi, A., Stone, S., Tonda, E., Shiran, Y., De La Fuente, J., Koskella, J., Bove, A. T., Boon, E., Fletcher, S., March, A., Roberts, K., & Bassi, A. (2023). *Turning off the Tap: How the world can end plastic pollution and create a circular economy*. United Nations Environment Programme.

https://wedocs.unep.org/bitstream/handle/20.500.11822/42277/Plastic_pollution.pdf?sequence=3

United Nations Environment Programme, Secretariats of the Basel, Rotterdam and Stockholm Conventions (BRS) and GRID-Arendal, Tsakona, M., Baker, E., Rucevska, I., Maes, T., Appelquist, L. R., Macmillan-Lawler, M., Harris, P., Raubenheimer, K., Langeard, R., Savelli-Soderberg, H., Woodall, K. O., Dittkrist, J., Zwimpfer, T. A., Aidis, R., Mafuta, C., & Schoolmeester, T. (2021). *Drowning in Plastics - Marine Litter and Plastic Waste Vital Graphics*. https://wedocs.unep.org/xmlui/bitstream/handle/20.500.11822/36964/VITGRAPH.pdf

Van Bijsterveldt, C. E., Van Wesenbeeck, B. K., Ramadhani, S., Raven, O. V., Van Gool, F. E., Pribadi, R., & Bouma, T. J. (2020). Does plastic waste kill mangroves? A field experiment to assess the impact of macro plastics on mangrove growth, stress response and survival. *The Science of the Total Environment*, *756*, 143826. https://doi.org/10.1016/j.scitotenv.2020.143826

Wang, Q., Feng, X., Liu, Y., Cui, W., Sun, Y., Zhang, S., & Wang, F. (2022). Effects of microplastics and carbon nanotubes on soil geochemical properties and bacterial communities. *Journal of Hazardous Materials*, *433*, 128826. https://doi.org/10.1016/j.jhazmat.2022.128826

What is the Triple Planetary Crisis? (2022, April 13). UNFCCC. Retrieved July 28, 2025, from https://unfccc.int/news/what-is-the-triple-planetary-crisis

Wright, S. L., Thompson, R. C., & Galloway, T. S. (2013). The physical impacts of microplastics on marine organisms: A review. *Environmental Pollution*, *178*, 483–492. https://doi.org/10.1016/j.envpol.2013.02.031

Wu, B., Wu, X., Liu, S., Wang, Z., & Chen, L. (2019). Size-dependent effects of polystyrene microplastics on cytotoxicity and efflux pump inhibition in human Caco-2 cells. *Chemosphere*, *221*, 333–341. https://doi.org/10.1016/j.chemosphere.2019.01.056

Xu, M., Halimu, G., Zhang, Q., Song, Y., Fu, X., Li, Y., Li, Y., & Zhang, H. (2019). Internalization and toxicity: A preliminary study of effects of nanoplastic particles on human lung epithelial cell. *The Science of the Total Environment*, *694*, 133794. https://doi.org/10.1016/j.scitotenv.2019.133794

Yong, C., Valiyaveettil, S., & Tang, B. (2020). Toxicity of microplastics and nanoplastics in mammalian systems. *International Journal of Environmental Research and Public Health*, *17*(5), 1509. https://doi.org/10.3390/ijerph17051509

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., Liang, J., Zeng, G., Tang, W., Lu, Y., Luo, Y., Xing, W., Tang, N., Ye, S., Li, X., & Huang, W. (2019). How climate change and eutrophication interact with microplastic pollution and sediment resuspension in shallow lakes: A review. *The Science of the Total Environment*, *705*, 135979. https://doi.org/10.1016/j.scitotenv.2019.135979

Appendix 1 - Main Sources Used

Impact on Human Health:

1. Effect on Mammalian Cells

   Yong, C., Valiyaveettil, S., & Tang, B. (2020). Toxicity of microplastics and nanoplastics in mammalian systems. International Journal of Environmental Research and Public Health, 17(5), 1509. https://doi.org/10.3390/ijerph17051509

2. Respiratory Effects

   Lu, K., Zhan, D., Fang, Y., Li, L., Chen, G., Chen, S., & Wang, L. (2022). Microplastics, potential threat to patients with lung diseases. Frontiers in Toxicology, 4. https://doi.org/10.3389/ftox.2022.958414

3. Reproductive and Developmental Toxicity

   Dubey, I., Khan, S., & Kushwaha, S. (2022). Developmental and reproductive toxic effects of exposure to microplastics: A review of associated signaling pathways. Frontiers in Toxicology, 4. https://doi.org/10.3389/ftox.2022.901798

4. Placental Transfer

   Gruber, M. M., Hirschmugl, B., Berger, N., Holter, M., Radulović, S., Leitinger, G., Liesinger, L., Berghold, A., Roblegg, E., Birner-Gruenberger, R., Bjelic-Radisic, V., & Wadsack, C. (2020). Plasma proteins facilitates placental transfer of polystyrene particles. Journal of Nanobiotechnology, 18(1). https://doi.org/10.1186/s12951-020-00676-5

Impact of Plastic Pollution on Biodiversity:

1. The global threat from plastic pollution

   MacLeod, M., Arp, H. P. H., Tekman, M. B., & Jahnke, A. (2021). The global threat from plastic pollution. Science, 373(6550), 61–65. https://doi.org/10.1126/science.abg5433

Impact on Terrestrial Biodiversity:

1. Microplastics as an emerging threat to terrestrial ecosystems

   De Souza Machado, A. A., Kloas, W., Zarfl, C., Hempel, S., & Rillig, M. C. (2017). Microplastics as an emerging threat to terrestrial ecosystems. Global Change Biology, 24(4), 1405–1416. https://doi.org/10.1111/gcb.14020

2. Agriculture Plastic Pollution

   Food and Agriculture Organization of the United Nations [FAO]. (2021). Assessment of agricultural plastics and their sustainability: A call for action. In FAO eBooks. https://doi.org/10.4060/cb7856en

Impact on Freswater Biodiversity:

1. Plastic pollution: A focus on freshwater biodiversity

   Azevedo-Santos, V. M., Brito, M. F. G., Manoel, P. S., Perroca, J. F., Rodrigues-Filho, J. L., Paschoal, L. R. P., Gonçalves, G. R. L., Wolf, M. R., Blettler, M. C. M., Andrade, M. C., Nobile, A. B., Lima, F. P., Ruocco, A. M. C., Silva, C. V., Perbiche-Neves, G., Portinho, J. L., Giarrizzo, T., Arcifa, M. S., & Pelicice, F. M. (2021). Plastic pollution: A focus on freshwater biodiversity. AMBIO, 50(7), 1313–1324. https://doi.org/10.1007/s13280-020-01496-5

2. Effects of plastic particles on aquatic invertebrates and fish – A review

   Hodkovicova, N., Hollerova, A., Svobodova, Z., Faldyna, M., & Faggio, C. (2022). Effects of plastic particles on aquatic invertebrates and fish – A review. *Environmental Toxicology and Pharmacology*, *96*, 104013. https://doi.org/10.1016/j.etap.2022.104013

Impact on Marine Biodiversity:

1. Impacts of plastic pollution in the oceans on marine species, biodiversity and ecosystems.

   Tekman, M. B., Walther, B. A., Peter, C., Gutow, L., Bergmann, M., & Alfred Wegener Institute Helmholtz-Centre for Polar- and Marine Research. (2022). Impacts of plastic pollution in the oceans on marine species, biodiversity and ecosystems. In WWF Germany, WWF Germany. WWF Germany, Berlin. https://doi.org/10.5281/zenodo.5898684

2. Risks of floating microplastic in the global ocean.

   Everaert, G., De Rijcke, M., Lonneville, B., Janssen, C., Backhaus, T., Mees, J., Van Sebille, E., Koelmans, A., Catarino, A., & Vandegehuchte, M. (2020). Risks of floating microplastic in the global ocean. Environmental Pollution, 267, 115499. https://doi.org/10.1016/j.envpol.2020.115499