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# EVALUATING ECOLOGICAL IMPACTS AND ATMOSPHERIC FATE OF MICROPLASTICS: ECOLOGICAL PERSPECTIVES AND CHALLENGES

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## Abstract

Plastic pollution has emerged as a critical global issue, with the impacts of microplastics (MPs) on ecosystems becoming increasingly significant. These microscopic plastic particles pose severe threats to ecological systems and their atmospheric fate. The formation of MPs is a complex process influenced by a variety of sources. Their distribution is significantly affected by atmospheric dynamics, including wind and weather events, leading to their deposition on the Earth's surface through rain, snow, and dust. Consequently, MPs infiltrate both aquatic and terrestrial ecosystems, accumulating in water bodies, soil, and plant life, thereby posing potential risks to human health via trophic transfer. Understanding the fate of MPs in the atmosphere is crucial, yet information on this topic remains limited. This study aims to address this gap by investigating the ecological impacts of MPs and their atmospheric behavior. Additionally, it highlights the analysis methods used to detect the adverse effects of MP pollution on the environment and ecosystems. The study also discusses the misinformation arising from various analytical techniques, the environmental threats posed by both MP and non-MP substances due to misinformation, and the challenges in maintaining quality control during analysis.

By addressing these current limitations, this study provides a foundation for future research and policy development, emphasizing the need for accurate analysis methods and comprehensive understanding of MP pollution. This work not only underscores the urgent need to mitigate MP pollution but also sets the stage for developing effective strategies to address this pervasive environmental challenge.

*Key words:* ecological, environmental, health, microplastic, plastic pollution

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## 1. Introduction

Plastic pollution ranks among the top environmental issues globally and poses a significant threat to human habitats. The non-biodegradability of plastics and their massive production lead to a severe accumulation of plastic in water systems, soils, and oceans (Iroegbu et al., 2021), which causes spread through drainage systems (Tran-Nguyen et al., 2022), runoff from wastewater treatment plants (Li et al., 2023), and by the action of wind (Yang et al., 2023), current and waves (Issac and Kandasubramanian,

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2021), penetrating freshwater ecosystems and life forms (Li et al., 2023). MPs are microscopic-sized fragments formed when plastic materials are broken into small pieces by various means (Sharma and Chatterjee, 2017). In general, the main factors affecting the formation of MPs are known as photodegradation (Liu et al., 2022), mechanical abrasion (Song et al., 2017), chemical degradation (Zhang et al., 2021), and some industrial processes (Enfrin et al., 2019) and product production stages (Duis and Coors, 2016). MPs are generally spread from various environmental sources into water systems, soils, and air, damaging ecosystems and affecting biodiversity (He et al., 2018; Wang et al., 2021). There are also concerns about the potential impacts of MPs on human health (Al Mamun et al., 2023). MPs sizes are generally smaller than 5 millimeters (Dris et al., 2015; Kumar et al., 2023) but can go down to nanoscale sizes (Caputo et al., 2021). This size range facilitates the spread of MPs into environmental systems through water, soil, and air (de Souza Machado et al., 2018).

Therefore, MP pollution has become a global environmental problem today. In terms of their effects on ecosystems, MPs, with their non-digestible nature and ability to adsorb toxic chemicals, pose a serious concern that demonstrates their potential to harm the health of aquatic organisms and disrupt the balance of ecosystems (Harmon, 2018), resulting in accumulation in organisms' digestive systems and trigger toxic effects. The ingestion of MPs as food by aquatic organisms such as fish, marine mammals, and aquatic invertebrates can lead to their accumulation in the digestive systems and a decrease in food intake, adversely affecting organisms' growth, reproduction, and survival abilities (Hollman et al., 2013). The effects of MPs on hydrological (Nakayama and Osako, 2023) and phenolic (Li et al., 2023) variables may also have implications for ecosystem health, biodiversity, food security and human health (Gao et al., 2023). A study by Gao et al. (2023) examined the habitat suitability of waterfowl for hydrological and phenological variables under drought and non-drought conditions. The results showed that under different degrees of drought, habitat suitability of waterbird habitats decreased (Gao et al., 2023). Toxic chemicals adsorbed onto the surfaces of MPs can pass into the organisms' bodies and give rise to toxic effects. The release of toxic chemicals adsorbed onto the surfaces of MPs can also contribute to the increase in ecological impacts (Auta et al., 2017). Specific toxic chemicals (Verla et al., 2019), such as phthalates (Deng et al., 2021), bisphenols (Han et al., 2022), organophosphates (Onoja et al., 2022), biocides (Verdú et al., 2021), and brominated flame retardants (Cheng et al., 2020), can lead to severe adverse health effects, displaying persistent and bioaccumulative characteristics. MPs pose a significant threat to human health and the well-being of other living organisms due to their inhalable nature, contributing to a range of potential health issues. Reaching the lungs of microscopic particles can adversely affect the respiratory system and contribute to an increase in respiratory diseases (Ageel et al., 2022).

In the realm of environmental impact, MPs, engendered through plastic waste breakdown, textile fibers, or industrial processes, undergo release into the atmosphere. Propelled over substantial distances by winds traverse diverse regions and ecosystems, imparting a far-reaching influence on environmental dynamics (Horton and Dixon, 2018), causing them to return to soil or water sources through precipitation due to their presence in the atmosphere (Zhou et al., 2021). Studies conducted in this context show that MPs in the atmosphere can also negatively affect soil and aquatic ecosystems. In recent years, MPs' ecological effects and atmospheric fate have received significant attention, and researchers are conducting several studies to develop a further understanding on this subject. Yao et al. (2022) state that MPs are present in the atmosphere in large quantities and significantly affect the digestive and reproductive systems and metabolism of organisms exposed to them. Additionally, it has been noted that MPs can cause various health risks, including oxidative stress and inflammatory damage to human health. Prata et al. (2020) expressed the potential of MPs in the atmosphere to penetrate deep into the body through the respiratory system, leading to neurotoxicity, cancer, respiratory problems, cytotoxicity, and other adverse effects. Mattsson et al. (2015) estimated that approximately 10% of the plastic released into the environment enters the oceans each year, and it is believed that about 7% of ocean pollution occurs through atmospheric transfer. Recent studies by Ahmad et al. (2023); Haque and Fan (2023); López et al. (2023) have drawn attention to the sources and environmental fate of atmospheric MPs alongside these findings. Gavrilescu (2021) stated that MPs can affect the photosynthetic abilities of vegetation, limit light uptake and nutrient absorption, reduce soil fertility and degrade the quality of agricultural products, reducing plants' growth and development potential, affect soil fertility and reduce the quality of agricultural products, which is a significant concern for ecosystem health and food security.

The potential for MPs to accumulate in soil and plants could also significantly impact human health. Some studies show that MPs can trigger respiratory diseases and have toxic effects ( Al Mamun et al., 2023; Lu et al., 2022;Prata et al., 2020). According to Al Mamun et al. (2023), plants can absorb MPs from the soil and reach humans along the food chain during growth. This suggests that MPs are a potential source of exposure for humans. Also, MPs can be suspended in the air and taken into the body by breathing. As a result, it is possible for MP particles to reach the lungs and spread from there to other organs. Some studies show that MPs can trigger respiratory diseases and damage the lungs. Amato-Lourenço et al. (2021) have demonstrated the negative effects of airborne MPs on human respiratory systems by detecting the presence of MPs in lung tissues. López et al. (2023) evaluated the toxic effects of MP particles in humans and found that normal human lung epithelial cells exhibited adverse effects such as inflammation and oxidative stress after exposure to MPs. The release of toxic chemicals adsorbed on the inner surfaces of MPs can increase the potentially harmful effects of MPs (Prata et al., 2020). A study conducted by Forte et al. (2016) demonstrated that NPs exhibit a pronounced ability to upregulate interleukin genes in human gastric adenocarcinoma cells. The genes that encode cytokines involved in the development of gastric diseases exert an influence on cell viability, inflammation, and cellular morphology.

In a study conducted by Jeong et al. (2016) utilizing in vitro experimentation, the researchers investigated the activation of defense mechanisms in response to MP exposure. The study showed a significant size-dependent activation of related enzymes and mitogen-activated protein kinases (MAPKs). Furthermore, the accumulation of MPs in the digestive systems of fish was found to regulate genes and enzymatic activities associated with reactive oxygen species (ROS). Notably, the presence of MPs led to the increased expression of diverse genes, such as superoxide dismutase 3 (SOD 3), caspase 3 (Casp3), tumor protein p53 (Tp53), and chemokine (C-X-C motif) receptor 5 (CXCR5), which play crucial roles in processes related to oxidative stress, apoptosis, and immune response, respectively. In this context, MPs' ecological effects and atmospheric fate are of great importance in terms of environmental sciences and public health (Patil et al., 2021).

Therefore, learning more about MP sources, release mechanisms, effects and solutions is critical to supporting environmental protection and sustainability efforts. This study aims to evaluate the ecological effects and atmospheric fate of MPs and discuss the important results by targeting the fate of MPs in the atmosphere and their effects on ecosystems, the fight against plastic pollution and the development of environmental protection strategies. The study will also help better understand the impacts of MPs on ecosystems and living organisms and provide effective solutions.

## 2. Transport mechanisms of MPs in the atmosphere

The transport of MPs in the atmosphere occurs through various mechanisms such as wind, atmospheric deposition, and precipitation ( Ahmad et al., 2023; Habibi et al., 2022;Huang et al., 2021). The wind plays a crucial role in the dispersion of MP particles in the atmosphere and poses significant environmental and human health risks (Fig. 1).

High-speed winds can carry MPs to greater distances and facilitate their dispersion. Strong winds can lift MP particles and keep them suspended in the air, allowing them to spread over a wider area. Wind speed and direction cause MPs to move away from their sources and reach different regions, causing MPs to be transported from coastal areas to the oceans and terrestrial regions to the poles (Zylstra, 2013; Haque and Fan, 2023). Significantly, a continuous and regular wind flow contributes to the widespread distribution of MPs in a specific direction and greater distances (Haque and Fan, 2023). The transport of MPs by wind enhances environmental interaction and pollution. Due to their small and lightweight nature, MPs can easily be transported by air currents, spreading to distant locations. These particles can remain suspended in the air in open areas, disseminating to different geographic regions and increasing their potential to spread in the environment (Camarero et al., 2017; Allen et al., 2019; Zhang et al., 2019; Wright et al., 2020). MPs originating from industrial centers and densely populated areas, especially in coastal regions, can be transported inland by the influence of the wind (Ambrosini et al., 2019). MP particles in the atmosphere can contribute to atmospheric deposition by combining with other atmospheric particles, which occurs through the interaction of MPs with environmental dust, pollen, water vapour, and other particles (Yao et al., 2022).

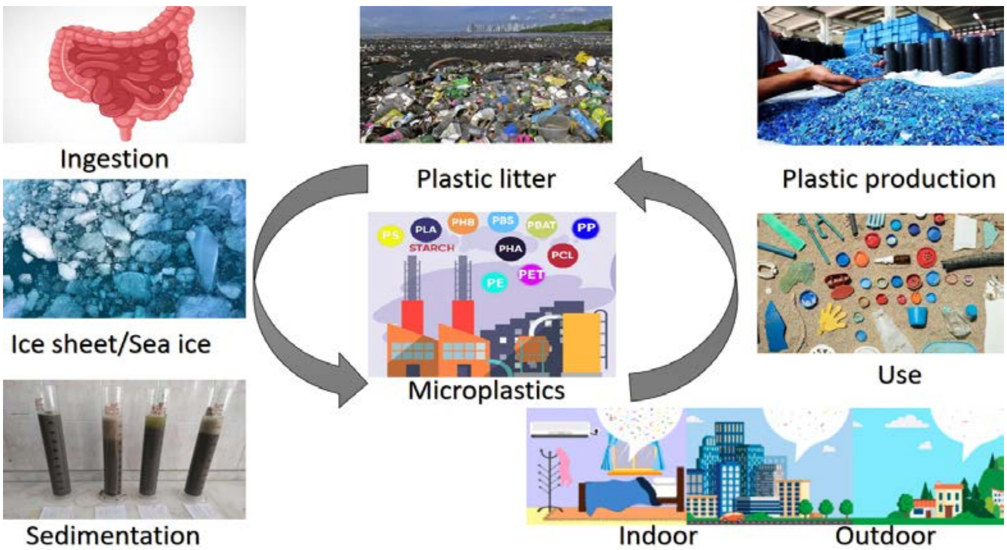

**Fig. 1.** Schematic representation of the distribution of MPs in the atmosphere

As a result, MPs become heavier and settle towards the Earth's surface under the influence of gravity. The combination process can occur through various mechanisms such as electrostatic interactions, chemical bonds, or physical interactions (López et al., 2023). Atmospheric deposition allows MP particles to accumulate in the environment and reach ecosystems such as soil, water sources, and seas (Wright et al., 2020), contributing to the accumulation of MP particles in the environment and their dissemination to different ecosystems (Yao et al., 2022; Haque and Fan, 2023).

Atmospheric precipitation plays an important role in the deposition of MPs from the atmosphere to the surface (Jia et al., 2022). MP particles in the atmosphere can fall to the Earth's surface with precipitation. The rain, snow, or hail play a significant role in the transportation of MPs. The dispersion of MP particles into the receiving environment through precipitation contributes to the global problem of MP pollution (Smith et al., 2018; Yang et al., 2021). MPs can attach to rain droplets or ice crystals and move downwards in this way. During this process, MPs become part of rain droplets or ice crystals and fall to the Earth's surface. With the impact of precipitation, MPs can be transported to soils, plants, water sources, and seas, enhancing environmental interaction and transporting MP particles to soils, plants, water sources, and seas (Yao et al., 2022). The rain is an effective mechanism for the deposition of MPs from the atmosphere to the surface. Raindrops trap MP particles and fibers in the atmosphere and bring them to the ground (Allen et al., 2019). Heavy rain causes MPs to precipitate faster and more. The amount, type, intensity and duration of rainfall affect the rate and distribution of MPs (Cordova et al., 2022). Rain can increase the settling of MP fibers, while snow can reduce the settling of MP particles (Huang et al., 2021). Snow is a less effective mechanism for precipitating MPs from the atmosphere to the surface (Abbasi et al., 2022), but snowflakes exhibit more efficient scavenging compared to raindrops. Snowflakes can trap MP particles and fibers in the atmosphere but can melt or be blown back up before landing on the ground (Österlund et al., 2023). The density and thickness of snow can affect the rate and amount of MP precipitation (Abbasi et al., 2022). The work by Abbasi et al. (2022) showed snow seems to encompass a broader range of MP sizes and shapes compared to rainfall, mostly nylon and cellulose-based materials (Abbasi et al., 2022). However, which factor is most decisive in the transportation of MPs may vary depending on geographical, climatic, and environmental conditions. For example, although some studies claim that wind is more effective than precipitation, it is unclear which factor is the most determining factor in transporting MPs. Therefore, understanding these mechanisms is a crucial step in combating MP pollution and protecting the environment.

## 3. Biological effects of MPs

### *3.1. Effects of atmospheric MPs on humans*

Plastic products and by-products from various industrial processes may contain toxic components (da Costa et al., 2022). MPs' chemical composition and surface properties can contribute to their toxic effects (Potthoff et al., 2017). According to Gasperi et al. (2018), when MPs settle in the lungs, these particles can pass through cell membranes and release the toxic substances contained, which induce various biological responses in lung cells. The observed health outcomes suggest that MPs have the potential to elicit localized biological responses due to their uptake and persistence in organisms. Sangkham et al. (2022) reported that exposure to MPs can lead to a range of severe health consequences, including oxidative stress, cytotoxicity, DNA damage, inflammation, immune response abnormalities, neurotoxicity, metabolic disruption, and impacts on various physiological systems such as the digestive system, immune system, respiratory system, reproductive system, and nervous system, causing significant implications for overall well-being and biological functioning. The work by Choudhury et al. (2023) explained MPs can enter the human body through three main routes: inhalation, ingestion, and cutaneous contact. Also, when inhaled, MPs typically settle in the upper respiratory tract but can also enter the bloodstream and distribute throughout the body. The study showed that inhalation of these particles can lead to respiratory tract irritation, inflammation, oxidative stress, and genotoxicity, which can have adverse effects on respiratory health. According to the work by Ornatowski et al. (2020), chronic inflammation can be associated with lung damage, fibrosis (formation of scar tissue), and the development of respiratory diseases. Additionally, the surface properties of MPs can contribute to increased oxidative stress and the formation of free radicals that can damage cellular DNA (Liu et al., 2023). The work by Qiao et al. (2019) has shown that MPs can accumulate in the gastrointestinal system, affecting gut flora, digestive system functions, and nutrient absorption, leading to impaired digestive health and the emergence of metabolic effects. According to Persiani et al. (2023), the presence of plastic particles in the mammalian body initiates interaction with circulating cells, subsequently triggering an inflammatory response, leading to genotoxicity and cytotoxicity in immune cells, enhanced hemolysis, and adhesion to the endothelium. In addition, the interaction between MPs and nanoparticles with plasma proteins facilitates transportation to remote organs, including the heart. As a result of the internalization of plastic fragments into cardiomyocytes, oxidative stress is increased, and metabolic parameters may be altered, which can have detrimental effects on cardiovascular health and overall metabolic function. Segovia-Mendoza et al. (2020) examined bisphenol and phthalates, which belong to two broad chemical classes associated with plastics, and have significant implications for human health. The researchers noted that these compounds are not covalently bonded to the plastic matrix, making them prone to leaching and resulting in high human exposure. The study also showed that these compounds exhibited diverse cellular effects by influencing various endocrine pathways, including estrogen, androgen, peroxisome proliferator-activated receptor gamma, and arylhydrocarbon receptor pathways. Based on the findings, the researchers concluded that exposure to both classes of plastic derivatives during critical periods can have detrimental effects on human health. As a result of these interactions, changes and disturbances in immune system functions can occur. Thus, the entry of MPs into living organisms through inhalation is recognized as an environmental concern because these particles can pose health risks when inhaled into the body. Fig. 2 shows the impact of MPs on humans.

### *3.2. Effects of atmospheric MPs on animals*

The effects of atmospheric MPs on animals usually occur due to exposure through the respiratory tract, digestive tract and skin. Respiratory exposure can lead to adverse consequences such as inflammation, oxidative stress, cell damage, fibrosis and cancer in lung tissue. Exposure through the digestive system can cause irritation and blockage of the stomach and intestines, reduced nutrient absorption and microbiota imbalance. Skin exposure can cause skin conditions such as allergic reactions, inflammation, infection and delayed wound healing. Atmospheric MPs can also negatively affect animals' hormones, immune, nervous and reproductive systems. The impacts vary depending on factors such as size, shape, chemical composition, surface properties, concentration, duration and frequency of exposure. For example, in mice, exposure to atmospheric MPs has been shown to impair lung function, cause inflammation and fibrosis in lung tissue, oxidative stress and DNA damage in lung cells (Lu et al., 2022; Woo et al., 2023). In fish, exposure to atmospheric MPs has been found to cause inflammation and bleeding in the gills, oxidative stress and lipid peroxidation in the liver, increased mucus secretion in the intestines and disruption of microbiota balance (Kaloyianni et al., 2021; Kim et al., 2021; Bhuyan, 2022; Subaramaniyam et al., 2023). A study by Chan et al. (2019) examined the presence of MPs in over 100 fish species and observed the presence of hard fragments and fibers in the stomach cells. The study further noted that fish samples collected from areas close to urban populations exhibited higher ingestion of MPs. Additionally, the researchers found that other additives, such as dyes, heavy metals, and chemical compounds, made the MPs more toxic in nature (Chan et al., 2019). Similarly, Oliveira et al. (2013) investigated the toxic effects of a combination of pyrene and MPs on *Pomatoschistus sp.* under controlled conditions. The research revealed oxidative damage in the organisms and a decrease in the activity of the isocitrate dehydrogenase enzyme. This is clear evidence of the presence of MPs and their potential toxic effects on various fish species inhabiting marine environments (Oliveira et al., 2013). In a study aiming to evaluate the effects of MPs on bees, Al Naggar et al. (2023) investigated the possible toxicity of irregularly shaped polystyrene (PS)-MP fragments on honey bee health. In the first such experiment with honey bees, which exposed bees with a well-established gut microbiome to small (27 ± 17 µm) or large (93 ± 25 µm) PS-MP fragments at varying concentrations (1, 10, 100 µg/mL) for 14 days. In the study, bee mortality, nutrition and body weight were analyzed. The study found that chronic exposure to PS-MP fragments did not affect honey bee survival but reduced feeding rate and body weight, especially at 10 µg PS-MP fragments per mL, which may have long-term consequences for honey bee health (Al Naggar et al., 2023). Overall, the effects of atmospheric MPs on animals show that inhaled particles cause a wide range of biological effects, from the digestive system to the circulatory system, leading to disruptions in a range of important biological processes, from the feeding habits of animals to the reproductive system, endangering interspecies interactions and biodiversity. Fig. 3 shows the effects of MPs in the atmosphere on animals.

### *3.3. Effects of atmospheric MPs on plants*

The effects of atmospheric MPs on plants generally occur due to exposure through leaves, seeds, roots and soil. Foliar exposure may affect physiological processes such as photosynthesis, respiration, transpiration, gas exchange, and light energy utilization (Li et al., 2022). Exposure through seeds may alter factors that determine plant performance, such as germination, growth, development and yield (Roy et al., 2023). Exposure through the root can disrupt important functions such as water and nutrient uptake, root growth, root microbiota, and plant-stress tolerance (Li et al., 2020). Exposure through soil can affect soil physicochemical properties, soil microorganisms, soil nutrient cycles and soil health (Li et al., 2022; Roy et al., 2023). The effects of atmospheric MPs on plants may also vary depending on variables such as the properties of the MPs and plants, exposure conditions, and environmental factors (Li et al., 2020). A study by Zhang et al. (2022) indicated that various forms (fibers, films, foams, and fragments) and types of MPs could result in a 25% decline in soil aggregation, contributing to elevated soil water evaporation and a decrease in both aboveground and root biomass of plants (Zhang et al., 2022). The work by Shorobi et al.

(2023) showed MPs changed the elemental uptake of plants, but this change depended on the elements and plant varieties. Cu increased a lot in the stem of the tomato but decreased in the root of the cherry tomato.

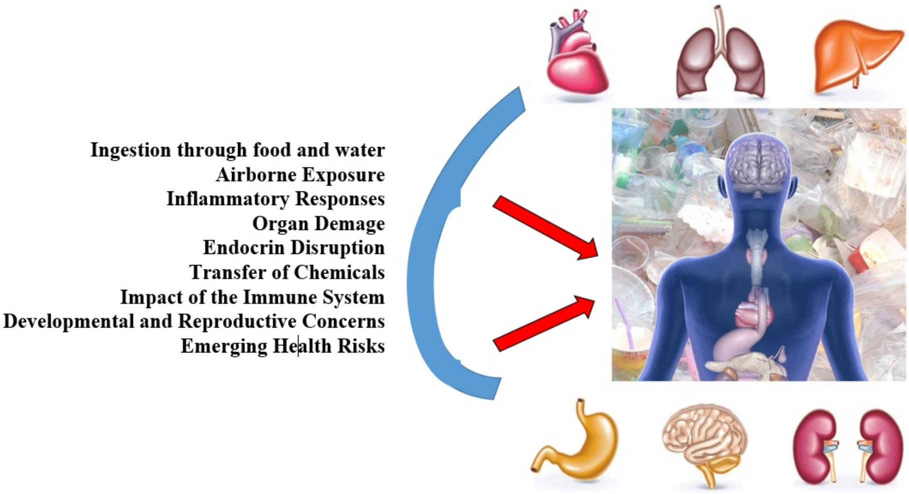


**Fig. 2.** The impact of MPs on humans

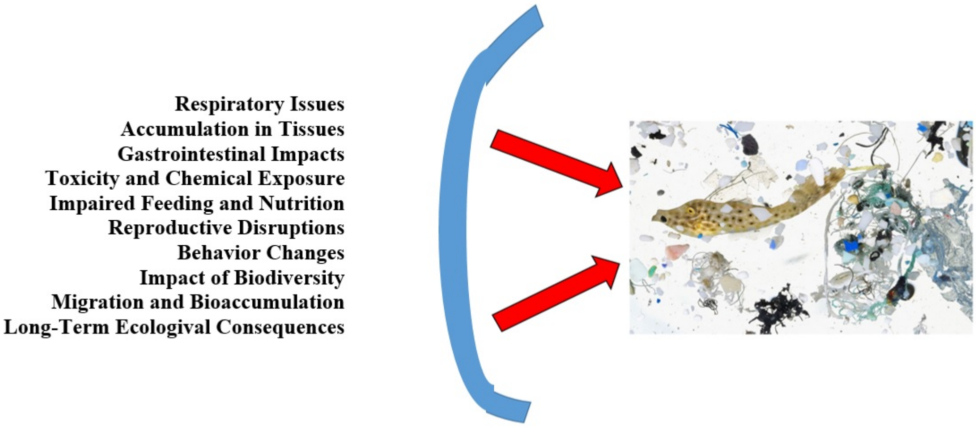


**Fig. 3.** Effects of atmospheric MPs on animals

Nitrogen uptake was lower in MP-treated plants compared to the control group, and phosphorus uptake was much lower in the stem of cherry tomatoes. However, the root-to-stem transit rate of many macronutrients decreased with exposure to PP-MP, indicating that prolonged exposure to MP may disrupt the nutrient balance in plants (Shorobi et al., 2023). It has been determined that exposure to atmospheric MPs in onions can reduce germination rate, root length, seed weight and seed health, causing morphological and anatomical changes in the seeds. In a study by Giorgetti et al. (2020), experiments were conducted using *Allium cepa* seeds to explore the impact of nanoplastics (NPs) on plants. In the study, the germination process lasted for 72 hours in the presence of polystyrene NPs with a size of 50 nm at concentrations of 0.01, 0.1, and 1 g/L. However, no significant effect on seed germination percentage was observed at any NP concentration, but root growth was hindered at 0.1 and 1 g/L NP concentrations. Cytological examination of root meristems revealed cytotoxicity (reduction in mitotic index) and genotoxicity (induction of cytogenetic anomalies and micronuclei) even at the lowest dose. Additionally, biochemical and histochemical analysis of oxidative stress markers indicated stress induction, particularly at higher doses. The reported damages attributed to mechanical surface contact in the outer root layers, as characterized by histological localization and the internalization of NP in various cellular compartments, were observed through a transmission electron microscope (Giorgetti et al., 2020). Therefore, the adverse effects of atmospheric MPs on plants are characterized by problems that occur through various mechanisms, ranging from changes in soil structure to reduced water-holding capacity. Plant growth, photosynthesis, nutrition and stress tolerance can be affected by atmospheric MPs, hindering the healthy development of plants and negatively affecting agricultural productivity and ecosystem balance. Figure 4 shows the effects of MPs in the atmosphere on plants.

## 4. Review of policies and regulations, and measures

**for controlling MPs in the atmosphere**

Policies, regulations and measures are important to control and reduce MPs in the atmosphere (Gong and Xie, 2020). Steps to be taken in this area can contribute to reducing MP pollution and protecting the environment. Some policies and measures that need to be reviewed to combat MPs in the atmosphere are shown in Table 1. In the projected scenario 2040, greenhouse gas emissions are anticipated to maintain the same levels as recorded in 2019. This marks a noteworthy 40% decline in greenhouse gas emissions within the global plastics system compared to the Business as Usual Scenario's forecasted levels for 2040. To achieve this reduction,

a comprehensive set of plastic emission restriction policies has been outlined, which encompass minimizing the use of virgin plastic, ensuring the affordability of plastics throughout their lifecycle, implementing specialized applications to decrease plastic usage, enforcing bans on preventable single-use plastics, establishing targets for avoidable single-use plastics, and taking measures to eliminate threatening chemicals and problematic plastics.

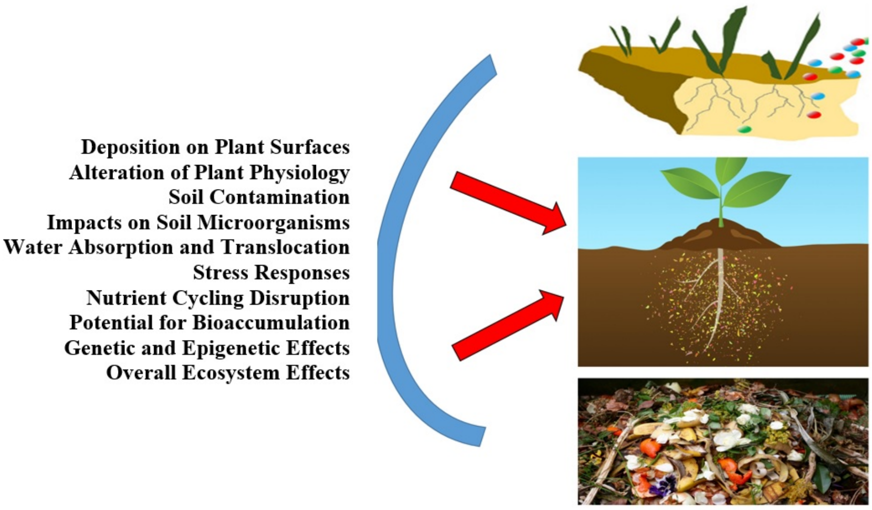


**Fig. 4.** Effects of MPs in the atmosphere on plants

**Table 1.** Critical steps in tackling MPs

| ***Policy and measures*** | ***Action plans*** | ***References*** |
|---|---|---|
| Reducing plastic use | Implementing regulations to curtail the production and use of single-use plastics is imperative. Encouraging the development and utilization of environmentally friendly alternatives to plastic products should be prioritized. Furthermore, plastic manufacturers ought to embrace sustainable production practices. | Viera et al. (2020); Tan et al. (2023) |
| Recycling and waste management | Establishing effective waste management systems is crucial to ensuring proper disposal and recycling of plastics. Promoting recycling and adopting a circular economy approach should be encouraged. Additionally, policies must be implemented to minimize plastic waste leakage into the environment. | Raveesh et al. (2015); Silva et al. (2020); Kurniawan et al. (2021) |
| Updating air quality standards | Establishing air quality standards and regulations to address MP pollution is essential. Regular monitoring and measurement of MP concentrations in the atmosphere should be conducted. Furthermore, implementing emission control measures is necessary to mitigate and reduce MP emissions into the atmosphere. | Mbachu et al. (2020); Shen et al. (2020; Lusher et al. (2021) |
| Industrial regulations | Establishing regulations controlling MP emissions in the industrial and manufacturing sectors is crucial. Encouraging industrial enterprises to adopt more sustainable production methods is essential to minimize the release of MPs into the environment. | Shen et al. (2020); Yu and Ma (2022) |
| Research and monitoring | Policymakers and regulators need to implement more effective measures. Funding and support for research on MPs' sources, behavior, and health effects are essential. Additionally, there is a need to develop innovative technologies and methods to detect, monitor, and remove plastics from the atmosphere. | Chen et al. (2020; Mitrano and Wohlleben, (2020); Prata et al. (2020) |
| International cooperation | To combat MPs, there is a need to develop coordinated strategies and initiatives in collaboration with international organizations and governments. Sharing best practices, research findings, and technological advancements can enhance collective efforts in addressing MP pollution. | Yang et al. (2021; Munhoz et al. (2022) |
| Public awareness | To raise awareness about the risks of MPs, creating campaigns that inform individuals is crucial. Promoting sustainable lifestyle choices and encouraging responsible consumer behavior are important aspects of this initiative. Collaborating with educational institutions | Jiang et al. (2021); Omoyajowo et |

| | | |
|---|---|---|
| and education | to incorporate MPs-related topics into curricula can also be beneficial in fostering understanding and responsible attitudes toward plastic pollution. | al. (2021); Raab and Bogner (2021) |

Additionally, there is a focus on promoting reliable reuse, durability, and cost-effective recycling strategies and setting targets for waste collection and recycling rates. The policies advocate for adopting management programs across sectors, ensuring fair management planning instead of informal sectors, and concerted efforts to curb unregulated plastic waste trade.

European Commissioner responsible for Environment, Oceans, and Fisheries, Virginijus Sinkevičius, served as the Minister of Economy and Innovation in the Lithuanian government and as a member of the Lithuanian parliament before joining the EU Commission in 2019. With a focus on evaluating the pollution of European seas, particularly emphasizing the need for a shift in our habits, including the pervasive use of single-use packaging, Sinkevičius has articulated the challenges posed by marine pollution. The European Environment Agency's consecutive reports highlighting these issues have played a pivotal role in assessing pollution in European seas. Sinkevičius asserts, "Pollution comes from the coast. It's industrial pollution - urban wastewater that is not properly treated. It's also partially agricultural pollution. All this pollution is worsening with additional pressures such as climate change. We see a rise in sea temperatures."

Regarding the actions taken in this context, Sinkevičius states, "Concerning chemical and fertilizer pollution, we have taken concrete steps within our Farm to Fork strategy. However, it is equally crucial for us to address our waste, such as plastic packaging." He claims an "inescapable plastic crisis" associated with recycling and warns against complacency, saying, "Plastic pollution, especially originating from packaging, has increased significantly. While recycling has increased, the rise in plastic pollution has been even more pronounced. Essentially, there is a growing gap between the two."

When asked about the lobbying activities of industries behind single-use packaging, Sinkevičius responds, "At times, we've encountered some absurd debates; for instance, claiming that a certain coating on plastic forks or spoons is not considered when declaring an item as single-use. It makes the product disposable. I believe civil society is very active in this regard. However, I am content with our progress, and currently, we have 10 products within the scope of the single-use directive."

He adds, "But we want to go further. We want to eliminate unnecessary packaging. Therefore, I find it absolutely unnecessary for you to have those small bottles for refillable shampoo and shower gel when staying at a hotel." Sinkevičius then shifts the discussion to Ocean Governance, a part of his portfolio in the European Commission, and the COP28 summit held in Dubai. "At COP28, we celebrated Ocean Day, indicating its centrality in climate discussions. If the oceans cannot reduce and regulate temperatures, we will perish. So, we undoubtedly need healthy oceans. It has been a significant year because, after 20 years of negotiations, we managed to conclude the Agreement on the High Seas, and now we are moving forward, putting great effort into getting 60 countries to ratify the agreement. This will provide us with a tool to have a rule-based system for ocean areas outside national jurisdiction, which actually constitute the majority of ocean ecosystems" (France24, 2023).

The emphasis lies in promoting dependable reuse, durability, and economically efficient recycling methodologies, accompanied by establishing targets for waste collection and recycling rates. The advocated policies underscore the implementation of comprehensive management programs spanning various sectors, endorsing equitable management planning instead of informal sectors and concerted endeavors to mitigate the unregulated trade of plastic waste. Standard procedures for the controlled destruction of non-recyclable plastics are being developed, along with systems to mitigate the environmental impact of outdated plastics. In this context, policies regarding measures to reduce the use and emissions of MPs and policies regarding measures for the collection and controlled destruction of MPs are also addressed. As part of the commitment to combat MPs, as outlined in the European Green Deal and the Circular Economy Action Plan, the policies aim to reduce MP pollution by 30% by 2030, as specified in the Zero Pollution Action Plan. The focus extends beyond traditional plastic sources, encompassing restrictions on plastic waste, litter, tire degradation, clothing release, and intentional product use, underscoring a multifaceted approach to curbing plastic pollution from diverse origins (Dennis, 2023; Johannes et al., 2023).

In his statement dated 25.09.2023, Commissioner for Environment, Oceans, and Fisheries Virginijus Sinkevičius expressed serious concerns regarding the deliberate use of MPs and its potential repercussions on the environment and human health. MPs, pervasive in seas, rivers, and on land, extend their presence to food and drinking water. While today's restrictions primarily target these minute particles, deeming a significant stride in curbing human-induced pollution (Johannes et al., 2023).

The plastic emissions restriction policy is poised to prevent the release of approximately half a million tonnes of MPs into the environment, accompanying a discontinuation of products responsible for MP emissions. Businesses can sustain operations by adhering to the prescribed procedures and aligning with the new regulations. The overarching objective is to minimize the MP population as much as possible. Notable products falling under the purview of these restrictions include granular filling materials on synthetic sports surfaces, posing a significant threat to the formation of environmental MP residues. Additionally, products such as cosmetic items, which release microbeads to enhance color, scent, and texture, along with detergents, glitters, fertilizers, plant protection products, toys, pharmaceuticals, medical devices, and softeners, are identified as contributors to MP pollution. Industrial products that do not release MPs into the environment post-use are currently exempt from the sales ban. However, future regulations will necessitate manufacturers to provide instructions on product usage and disposal methods to prevent MP emissions effectively. This holistic approach aligns with the overarching goal of mitigating the impact of MPs on the environment and human health.

These policies and regulations play a significant role in reducing MP pollution. The effective implementation and continuous review of these measures are essential for environmental protection and safeguarding human health. Innovative approaches and perspectives are crucial in combating MP pollution for environmental sustainability and human health preservation. Encouraging scientific research, data sharing, and international collaboration are crucial for developing more effective solutions to combat MP pollution. Furthermore, the collaboration between policymakers, regulators, and industry in creating appropriate regulations and policies is critical, establishing a framework for more effective MP pollution control, protecting the environment and human health. These innovative perspectives represent significant steps towards progress in combating MP pollution and working towards a sustainable future. Constant exploration and implementation of new ideas are crucial in addressing this issue that harms the environment and human health.

## 5. Effect of MP concentration in the atmosphere indoors and outdoors

Much research has been conducted on marine and terrestrial MPs. However, the dynamics of MPs are limited. Studies on MPs in the atmosphere have generally been conducted on samples collected from the atmosphere. Direct measurements of MPs in air are very few. Furthermore, the concentration of airborne MPs is an important factor in assessing the health risk of MP exposure through human inhalation.

Airborne MPs in indoor and outdoor environments in urban and rural areas in a coastal city in eastern China were investigated. The indoor airborne MP concentration was $1583 \pm 1180$ n/m$^3$, the urban airborne MP concentration was $224 \pm 70$ n/m$^3$ and the rural airborne MP concentration was $101 \pm 47$ n/m$^3$. MPs smaller than 100 µm dominated in air and were found in fragments of very different shapes than fibrous MPs. Larger MPs had a higher proportion of fibers, while smaller MPs were almost entirely composed of small fragments. The fact that there are no concentrations of MPs in the air does not necessarily mean that it is safe from a health risk perspective. This is because while the annual outdoor exposure to airborne MPs is 1 million, indoor MP exposure is higher because indoor MP concentration is higher than outdoors (Liao et al., 2021).

Sample collection tools to detect MPs vary depending on the location of the indoor and outdoor areas examined. A sampling pump is used as the sample collection tool for the interior. The independent sampling pump used by Dris et al. (2016) was introduced. However, while indoor dust particles can be removed with devices such as vacuum cleaners and vacuum pumps, the resulting dust is also collected from the environment with the help of cleaning bags. Outdoor analysis for airborne MPs includes a rain sampler, a particulate fallout collector, and a filter sampler. These equipment were placed in areas with certain heights on the ground, in the air and at the upper levels, and the density in the air was determined (Dris et al., 2016; Liu et al., 2019).

In a study aimed at the presence of airborne MPs, Dris et al. (2016) conducted research on atmospheric fallout in dense urban and less dense suburbs in Paris, France. The study used an outdoor rain sampling technique; MPs were collected and filtered. Subsequently, observation was carried out using microscopes. Along with observation, counting was also carried out, and it was observed that the fibers were dense. However, a lower MP density was observed in suburban areas than in urban areas. Another study by Dris et al. (2017) addressed the concentration of MPs in France's indoor and outdoor air quality. As the subject of the study, private flats and offices were considered interior spaces, whereas the sampled exterior was taken as the apartment's exterior.

When the results were examined, the possible rooms' partitioning, ventilation and airflow conditions showed more dense accumulation and fiber concentration indoors than outdoors. Therefore, MP density in indoor and outdoor factors indicates that attention is paid and precautions should be taken regarding environmental threats (Dris et al., 2016; Dris et al., 2017; Prata, 2018). The effect of the concentration of MPs in the indoor and outdoor atmosphere is shown in Fig. 5.

## 6. Analysis methods used for the identification of MPs and quality control challenges

MP pollution drivers have emerged as a recent concern for ecosystems, prompting the need to develop advanced analytical methods. The analysis of MPs holds significant importance in monitoring their presence and assessing the effectiveness of removal strategies in various environments (Zhang et al., 2018). MP analysis is a crucial prerequisite for devising effective interventions to mitigate this pollution. Despite the plethora of MP analysis techniques developed to date, it is important to note that irregularities and inconsistencies often characterize the information obtained. Many techniques are used to detect MP, including fourier transform infrared spectroscopy (FTIR), flow cytometry and matrix-assisted laser desorption/ionization, stereomicroscope, scanning electron microscopy (SEM), and Raman spectroscopy. Table 2 provides an overview of the methods used for detecting MPs. When scrutinizing MP analysis results, it becomes evident that they are highly susceptible to selecting sampling methods (Razeghi et al., 2022). Therefore, the foundational step in MP analysis lies in meticulous sampling, as it significantly influences the accuracy of the results. Various techniques, including visual inspection, density difference analysis, flotation, sieving and filtering based on size classification, digestion methods, biological removal, and ingestion, as well as chemical methods, stand out as the most commonly utilized approaches for MP detection in our environment (Mai et al., 2018; Padervand et al., 2020).

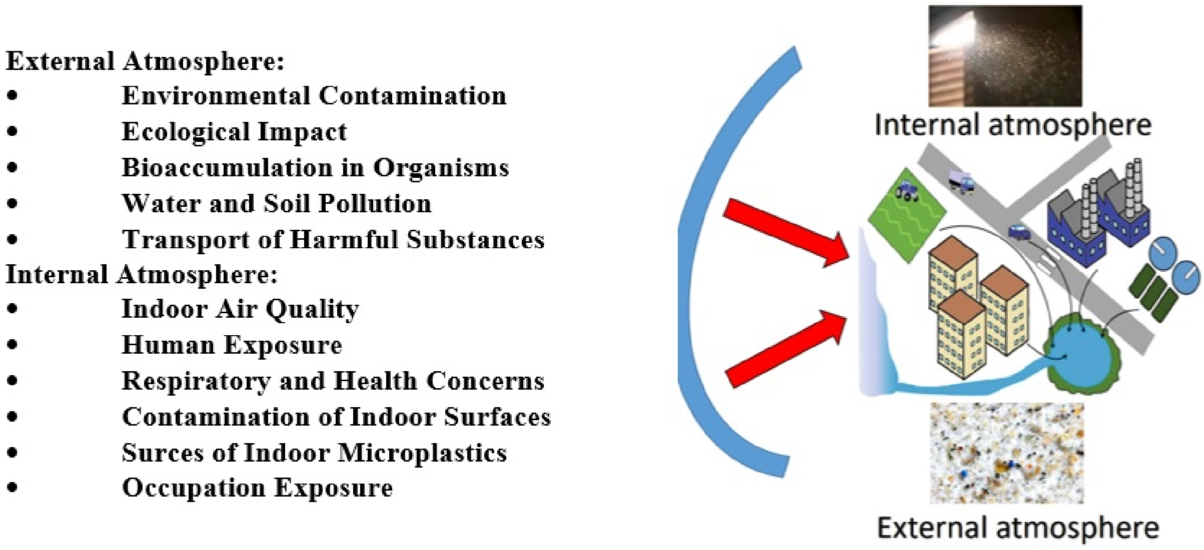


**Fig. 5.** Effect of the concentration of MPs in the internal and external atmosphere

**Table 2.** Methods used in MP detection

| ***Methods*** | ***Advantages*** | ***Limitations*** |
|---|---|---|
| Visual analysis | A traditional method in terms of MP definition and quantity (Hidalgo-Ruz et al., 2012). | Visual analysis proves to be time-consuming and challenging for detecting MP objects. Due to their diminutive size and diverse composition, incorporating both organic and inorganic substances from the environment, the stand-alone application of visual analysis is no longer suitable for the accurate identification of MPs (Hidalgo-Ruz et al., 2012; Shim et al., 2017). |
| Scanning electron microscope-energy dispersive X-ray (SEM-EDS) | This technique contributes to the simultaneous analysis of MPs regarding their surface properties and elemental contents (Eriksen et al., 2013; Fries et al., 2013). | The pretreatment process is complex (Fu et al., 2020). Business activity performance is low, and costs are high. It does not have a very high detection rate in MP prediction. Since SEM devices will give black and white images, MP colors cannot be easily distinguished (Wagner et al., 2017). |
| FTIR | It is a vibration spectroscopy technology that can provide information about chemical bonds and functional groups in samples (Löder and Gerdts, 2013; Araujo et al., 2018). It is widely used in the qualitative detection and component analysis of MPs. | It can only be used to identify MPs larger than 20 μm (Araujo et al., 2018; Prata et al., 2019), easily affected by various environmental factors such as sample preparation, purity of the sample, solvents used, temperature and humidity conditions. In addition, properties such as the chemical structure, density, and size of the analyzed MPs can also affect the results (Rocha-Santos and Duarte, 2015). |
| Raman spectroscopy | There is no need for pretreatment before the samples are detected (Araujo et al., 2018). With FTIR, the structural analysis process is completed (Wright et al., 2019) | The analysis time is long (Araujo et al., 2018). |
| Thermal analysis | It analyzes samples by examining them according to temperature and time (Majewsky et al., 2016). This method is used to perform chemical and mass density analyses. | The sample preparation process is difficult and arduous. This method causes severe damage to environmental samples. This shows that MPs cannot be applied in physical property determination studies (Majewsky et al., 2016; Huppertsberg and Knepper, 2018) |
| Mass spectrometry | It is an important technique for polymer analysis in MPs (Weidner and Trimpin, | The method's application area is limited (Kirstein et al., 2016; Huppertsberg and Knepper, 2018). Currently, this method is |

| | | |
|---|---|---|
| | 2010). This method provides support for chemical characterization. | insufficient to analyze the population in MP density measurement in the environment (Wang et al., 2017; Zhang et al., 2021). |

Since MP and NP structures are present in air, water, soil, food, plant, human and animal tissues, as well as in various environmental situations, the detection of plastics in this complex structure and the determination of their population cannot be achieved with a single method. On the contrary, in MP detection, the processes of first determining the area to be taken, sampling, creating a concentration difference, separation, detection and identification, and then quantifying it as the last part have critical importance. Because if a situation is overlooked at any step, the MP population will be determined incorrectly.

In recent years, researchers to detect plastic pollution have focused on NPs instead of MPs, which greatly threaten humans, animals, plants, and the environment. Developments and improvements have been made in MP and nanoplastic (NP) detection and measurement methods. FTIR spectra could not help detect increases in monomer types of organic and inorganic substances in plastic production. The wide variety of monomers and additives used in plastic production brings uncertainty in reporting data on the plastic population that creates environmental pollution. Working with multiple analysers can obtain a meaningful value for these uncertainties. Although different analysis types are used in MP detection, analysis with more than one and combined analysis systems in NP detection have great importance in confirming plastic detection. Standardizing various analysis methods will make reporting criteria for plastic pollution analysis an elusive goal.

Besides analytical and methodological systems, many questions arise in modern plastic pollution reduction. Consistency and identification of MPs obtained by different analysis methods will be a serious step. In addition, it is critical in terms of reporting. If attention is not paid to the report, the measures to be taken will be insufficient, and environmental threats can cause major problems.

Despite notable advancements in MP analysis detection in recent years, the methods employed in MP analysis are not without their limitations. Relying on a singular method introduces a potential information gap regarding MPs. The sensitivity of a single method to false positive and/or negative signal reception and potential interference can adversely impact the analysis process, leading to measurement inconsistencies. A common practice in environmental MP analysis involves employing various methods to enhance the reliability of information regarding MPs. By amalgamating the results from different methods, a more comprehensive and logical conclusion can be drawn, mitigating the impact of individual method limitations and bolstering the overall accuracy of the analysis (Shim et al., 2017).

The significance of MP analysis has been heightened with the development of integrated and effective detection techniques (Nguyen et al., 2019). MPs exhibit distinctive characteristics, including diverse composition, small particle size, widespread distribution, and various shapes, aligning with findings from studies such as those conducted by Masud et al. (2023). The study focused on four beaches in the Bodrum peninsula, collecting twenty-four samples comprising sandy gravel, gravel, and/or gravel sand from coastlines and the middle of 1 $m^2$ areas. After the light intensity and ethanol density analyses, they performed the analyses using a separation system twice. The identified MPs included polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), polyethylene terephthalate (PET), and polyurethane (PU), present in both fiber and particle forms. The researchers correlated the results with FTIR and SEM analyses to enhance the overall analysis, attributing the presence of MPs in the study areas primarily to anthropogenic activities, as indicated by the study results (Masud et al., 2023).

MPs are highly susceptible to the influence of external factors, making it impractical to create MP samples completely isolated from the surrounding environment. The intricate structures formed by these external factors pose challenges in verifying MP detection and constrain the practical applications of MP analysis techniques. Hence, there is a pressing need for methods that facilitate rapid, accurate, and consistent information transfer and are cost-effective and practical for MP analysis and sample creation, which are essential for preserving ecosystem health. Among the various methods employed for MP samples, the flotation method is emerging as a promising approach with the potential to evolve into a distinctive technique for efficiently removing and recycling MPs from the external environment.

It is important to increase further studies to address risk factors regarding the electrostatic effects of MPs and their ability to absorb environmental pollutants. This study is of critical importance in the field of MP, as the number of MPs and NPs in our environment will increase day by day. Since MP and NP structures harm humans, animals, plants, and the environment, and considering that these damages are increasing day by day, optimizing the methods used in the detection of these MPs should focus on advanced single-type analysis devices instead of combined systems and simple techniques, as well as MP and NP. It is also necessary to focus on non-plastic particles. No matter how dangerous MPs and NPs are, when literature studies are examined, all non-plastic particles are not drawn to attention and are not given importance.

To date, one of the main reasons for environmental pollution, deterioration of human health and increase in diseases is the fact that plastic products have been identified, but it is not possible to detect non-plastic ones. In the future, repairing all structures alongside MP and NP will contribute to taking correct environmental precautions and successfully preventing and reducing potential threats.

## 7. Future perspectives and challenges

Assessing MPs' ecological impacts and atmospheric fate is still largely unexplored, with many knowledge gaps and potential research areas. The distribution of respirable MPs in the environment, their sources, exposure pathways, and their effects on human health and ecosystems are not yet fully understood. The analysis of MPs in biological samples is a significant challenge in laboratories (Jacob et al., 2020). The small size, diverse physical forms, chemical composition and colours of MPs make them challenging to identify and distinguish from natural matrices (Fu et al., 2020). The lack of standardized methods, protocols and quality control for analyzing MPs limits the comparability and reliability of results (Scopetani et al., 2020). The atmospheric sources, emissions, transport, deposition, accumulation, sedimentation and removal of MPs are complex and dynamic processes (Darabi et al., 2021). Although several studies have examined the effects of atmospheric precipitation, wind (Yang et al., 2023), rain (Jia et al., 2022), snow (Bergmann et al., 2019) and hail (Kozjek et al., 2023) on MP transport, the specific roles of these factors in determining the fate of MPs in the atmosphere are still poorly understood. This uncertainty may hinder a more complete understanding of the environmental impacts of MPs. In future research, further efforts should be made to understand in more detail the interactions between these factors and the mechanisms involved in determining the behavior of MPs in the atmosphere. This would be an important step towards developing more effective strategies to manage environmental impacts and combat MP pollution.

MP pollution is recognized as a global environmental problem, and a multidisciplinary approach is required to address it (Kumar et al., 2021). Further research on the fate and transport of MPs in the hydrosphere, pedosphere and atmosphere is important to understand the dynamics and distribution of MPs between environmental compartments. Furthermore, more comprehensive and standardized test methods need to be developed to assess the ecotoxicological effects of MPs in the atmosphere. Further measurement, inventory, modelling, monitoring and experimental studies are needed to understand their emissions, transport, sources, behavior and impacts on the atmosphere.

Developing and implementing plastic waste management strategies is vital to control MP pollution (Sarkar et al., 2022). Measures such as reducing plastic waste at source, recycling, reusing, and recovering energy should be taken. To identify sources of MPs, the chemical composition, shape, size, colour and reflectivity of MPs can be analyzed, and the plastic products, industries, regions or activities where MPs originate can be identified. To reduce the sources of MPs, stricter regulations, standards and inspections can be introduced on the design, production, consumption and disposal of plastic products. The principle of sustainability in the production and consumption of plastics should be adopted, and more research and innovation should be done on the design, lifecycle and recycling of plastic products. Furthermore, raising public awareness on plastic pollution's environmental and health impacts is an important step towards properly disposing of plastic waste and reducing plastic consumption (Kumar et al., 2021). Education and awareness-raising campaigns can be organized to provide information on the causes, consequences and solutions to plastic pollution, provide incentives for recycling, reusing and reducing plastic waste, and encourage using alternative materials to replace plastic products (Sandu et al., 2020).

The impacts of MPs on ecosystems include both biotic and abiotic factors (Darabi et al., 2021). Biotic impacts of MPs can affect vital functions of organisms (Al-Thawadi, 2020), such as physiology (Costantini, 2014), behavior (Costa et al., 2020), nutrition (Franzellitti et al., 2019), growth (Yu et al., 2021), reproduction (Sharifinia et al., 2020), stress tolerance (Baihetiyaer et al., 2023) and survival (Jaikumar et al., 2021). Abiotic impacts of MPs can affect soil, water and air quality, nutrient cycles, carbon storage and climate change (Kumar et al., 2023). More ecotoxicological, biogeographic, and biochemical studies are needed to understand the effects of MPs on ecosystems. Furthermore, the entry pathways, distribution, accumulation, biological interactions and excretion of MPs into the environment are not yet fully understood and reliable and sensitive biomarkers need to be developed to monitor them. Further research in this area is vital to develop strategies to prevent and reduce MP pollution and take measures to protect ecosystems. Therefore, how MPs behave in nature and their impacts on ecosystems need to be investigated in more detail (Özgenç et al., 2024).

Nanotechnology and filtration systems can be developed to remove MPs from the atmosphere (Liu et al., 2020), aquatic (Ouda et al., 2023) and soil environments (Chellasamy et al., 2022). Nanotechnology can be used to identify, separate and destroy MPs (Chellasamy et al., 2022). Recycling plastic waste can be an important strategy to reduce plastic production and consumption (Chen et al., 2021). Innovative recycling methods can enable more efficient, economical and environmentally friendly utilization of plastic waste (Kumar et al., 2021). For example, methods such as converting plastic waste into energy sources such as biogas (Awogbemi and Von Kallon, 2023), biodiesel (Papari et al., 2021), electricity or heat (Nanda and Berruti, 2021), chemically or biologically decomposing plastic waste (Nanda and Berruti, 2021), and using plastic waste to produce new plastic products or composite materials can be developed (Awoyera and Adesina, 2020).

Promoting natural, biodegradable, renewable and recyclable materials that can replace plastic products effectively can prevent plastic pollution (Moshood et al., 2022). For example, plastic bags can be replaced with bags made from materials such as paper, cloth or cornstarch; plastic bottles can be replaced with bottles made from materials such as glass, metal or bamboo; and plastic packaging can be replaced with packaging made from materials such as algae, mushrooms or plant fibers.

Remediation methods can also be used to reduce MP pollution (Rai et al., 2021). For example, more research is needed on certain microorganisms that eat or break down MPs, plant-based materials that can trap or break down MPs, and marine organisms that filter or digest MPs. In addition, synthetic biology can be used to prevent or reduce MP pollution. Synthetic biology can be used to produce new microorganisms or enzymes that identify, sort, degrade or destroy MPs (Jenkins et al., 2019). Furthermore, synthetic biology can also be used to produce bioplastics derived from biological sources instead of petroleum used to produce plastics, which could enable biological waste management (Pooja et al., 2023).

Machine learning and artificial intelligence can be used as decision-making and optimization tools to develop and implement plastic waste management strategies (Huang and Koroteev, 2021). Machine learning and artificial intelligence can be used to analyze, improve and optimize the performance of the plastic waste management system, including plastic waste generation, collection, transport, recycling, disposal and energy recovery (Huang and Koroteev, 2021; Noman et al., 2022). Air quality monitoring and modelling networks can also be used to determine the concentration, distribution and sources of MPs in the atmosphere (Wright et al., 2021). Air quality sensors can identify MPs based on their characteristics, such as size, shape, chemical composition, colour and reflectance, and track the movement of MPs in the atmosphere (Munyaneza et al., 2022), which can be deployed on different platforms such as satellites, drones, balloons, airplanes or ground stations (Lambey and Prasad, 2021).

MP pollution poses a serious threat to humanity as it is a global problem (Al Mamun et al., 2023), and urgent and effective steps need to be taken to prevent it. The sources, sizes, shapes, chemical compositions and concentrations of respirable MPs vary widely, and no standardized identification or measurement method exists (Dioses-Salinas et al., 2020). MPs' entry routes into the human body, distribution, accumulation, biological interactions and excretion are not yet fully understood (Wu et al., 2022), and reliable and sensitive biomarkers must be developed to monitor them (Prokić et al., 2019). Understanding the biomarkers of MPs is important to assess their potential effects on human health and aquatic ecosystems (Patra et al., 2022). Reliable toxicity data is needed, necessitating a more comprehensive understanding of MP toxicity and a better characterization of its potential dangers. To better comprehend the potential health effects of MPs on humans and aquatic ecosystems, particularly in determining critical thresholds for health risks in drinking water and environmental waters, it is essential to address literature findings and rectify significant data gaps (Thornton Hampton et al., 2022). Efforts to enhance understanding of the potential risks of MPs on human health and aquatic ecosystems rely on addressing current data gaps (Rahman et al., 2021). This initiative can contribute to a clearer and more precise understanding of the primary drivers of MP toxicity and the specific concentrations at which adverse effects may occur.

Long-term and large-scale epidemiologic studies, experimental animal models, in vitro cell systems, and toxicologic and immunologic studies are needed to assess human health effects, but these face ethical, financial and methodological problems. Other environmental and vital factors need to be controlled and statistically adjusted to distinguish their impact on human health, but this is very difficult and complex. Therefore, studying the effects of respirable MPs on human health requires a multidisciplinary approach, international collaboration, standardized protocols, data sharing and communication between the scientific community, policymakers, industry and the public. Further research in this area is vital to develop strategies to prevent and reduce MP pollution and take measures to protect human health.

Collaborations and partnerships should be established at national, regional and international levels to combat MP pollution. Further scientific studies and policy action are needed to reduce MP pollution's environmental and health impacts and ensure a sustainable plastic-use future.

Collaborations and partnerships should be developed in areas such as scientific research, policy making, education, awareness raising, capacity building, financing, technology transfer and implementation on MP pollution. It shows the focus areas for a more comprehensive understanding of MPs' ecological impacts and atmospheric fate and for exploring new research areas. Further research in these areas will improve the effectiveness of strategies to combat MP pollution and develop strategies to ensure environmental sustainability, which helps better understand the environmental impacts of MPs and achieve our goal of ensuring that future generations live in a healthy environment. Innovative solutions and scientific advances will be an important step forward in the fight against MP pollution, but more work, resources and global cooperation are needed to achieve these goals.

## 8. Conclusions

The occurrence of MPs, their impacts on ecosystems, their fate in the atmosphere, measurement and detection methods, concentration determination and monitoring techniques, distribution estimation, potential impacts on ecosystems and human health, and existing policies and regulations are among the important issues that need to be reviewed. Research in these areas will help us understand the impacts of MP pollution and develop future protection strategies. Scientific research and data will be a valuable resource for health authorities, scientists and policymakers. These scientific studies will help us better understand the effects of MPs on human health and take more effective measures to combat plastic pollution. This process is vital for maintaining a healthy environment and ensuring a sustainable future.

Therefore, more research and scientific work is needed to tackle this complex problem and develop effective solutions. Learning more about the sources, dispersion mechanisms, impact on ecosystems, and potential effects on the human health of MPs is crucial. This information will help improve environmental protection policies and sustainability efforts and formulate effective strategies to combat plastic pollution. Within the realm of green management's emphasis on sustainability strategies, substantial progress can be realized in addressing the environmental threat posed by MPs (MPs) through enhancements in the subheadings of green management, namely risk/benefit perception, control power and belief, intention and action, and attitude and behavior.

By fortifying these dimensions, significant measures can be implemented to counteract the impact of MPs, fostering improvements that align with sustainability objectives. At the same time, measures such as raising public awareness and reducing plastic use will play an important role in addressing MPs' ecological impacts and atmospheric fate.

## References


Abbasi S., Alirezazadeh M., Razeghi N., Rezaei M., Pourmahmood H., Dehbandi R., Mehr M.R., Ashayeri S.Y., Oleszczuk P., Turner A., (2022), Microplastics captured by snowfall: A study in Northern Iran, *Science of the total environment*, **822**, 153451, https://doi.org/10.1016/j.scitotenv.2022.153451.

Ageel H.K., Harrad S., Abdallah M.A.-E., (2022), Occurrence, human exposure, and risk of microplastics in the indoor environment, *Environmental Science: Processes & Impacts*, **24**, 17-31.

Ahmad M., Chen J., Khan M.T., Yu Q., Phairuang W., Furuuchi M., Ali S.W., Nawab A., Panyametheekul S., (2023), Sources, analysis, and health implications of atmospheric microplastics, *Emerging Contaminants*, **9**, 100233. https://doi.org/10.1016/j.emcon.2023.100233

Al-Thawadi S., (2020), Microplastics and nanoplastics in aquatic environments: challenges and threats to aquatic organisms, *Arabian Journal for Science and Engineering*, **45**, 4419-4440.

Al Mamun A., Prasetya T.A.E., Dewi I.R., Ahmad M., (2023), Microplastics in human food chains: Food becoming a threat to health safety, *Science of the Total Environment*, **858**, 159834.

Al Naggar Y., Sayes C.M., Collom C., Ayorinde T., Qi S., El-Seedi H.R., Paxton R.J., Wang K., (2023), Chronic exposure to polystyrene microplastic fragments has no effect on honey bee survival, but reduces feeding rate and body weight, *Toxics*, **11**, 100, http://doi.org/10.3390/toxics11020100.

Allen S., Allen D., Phoenix V.R., Le Roux G., Durántez Jiménez P., Simonneau A., Binet S., Galop D., (2019), Atmospheric transport and deposition of microplastics in a remote mountain catchment, *Nature Geoscience*, **12**, 339-344.

Amato-Lourenço L.F., Carvalho-Oliveira R., Júnior G.R., dos Santos Galvão L., Ando R.A., Mauad T., (2021), Presence of airborne microplastics in human lung tissue, *Journal of Hazardous Materials*, **416**, 126124, http://doi.org/10.1016/j.jhazmat.2021.126124.

Ambrosini R., Azzoni R.S., Pittino F., Diolaiuti G., Franzetti A., Parolini M., (2019), First evidence of microplastic contamination in the supraglacial debris of an alpine glacier, *Environmental Pollution*, **253**, 297-301.

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

Auta H.S., Emenike C.U., Fauziah S.H., (2017), Distribution and importance of microplastics in the marine environment: a review of the sources, fate, effects, and potential solutions, *Environment International*, **102**, 165-176.

Awogbemi O., Kallon D.V., (2023), Achieving affordable and clean energy through conversion of waste plastic to liquid fuel, *Journal of the Energy Institute*, **106**, 101154, https://doi.org/10.1016/j.joei.2022.101154.

Awoyera P., Adesina A., (2020), Plastic wastes to construction products: Status, limitations and future perspective, *Case Studies in Construction Materials*, **12**, e00330, https://doi.org/10.1016/j.cscm.2020.e00330.

Baihetiyaer B., Jiang N., Li X., He B., Wang J., Fan X., Sun H., Yin X., (2023), Oxidative stress and gene expression induced by biodegradable microplastics and imidacloprid in earthworms (Eisenia fetida) at environmentally relevant concentrations, *Environmental Pollution*, **323**, 121285, https://doi.org/10.1016/j.envpol.2023.121285.

Bergmann M., Mützel S., Primpke S., Tekman M.B., Trachsel J., Gerdts G., (2019), White and wonderful? Microplastics prevail in snow from the Alps to the Arctic, *Science Advances*, **5**, eaax1157, https://doi.org/10.1126/sciadv.aax1157.

Bhuyan M.S., (2022), Effects of microplastics on fish and in human health, *Frontiers in Environmental Science*, **10**, 250, https://doi.org/10.3389/fenvs.2022.827289.

Camarero L., Bacardit M., de Diego A., Arana G., (2017), Decadal trends in atmospheric deposition in a high elevation station: effects of climate and pollution on the long-range flux of metals and trace elements over SW Europe, *Atmospheric Environment*, **167**, 542-552.

Caputo F., Vogel R., Savage J., Vella G., Law A., Della Camera G., Hannon G., Peacock B., Mehn D., Ponti J., (2021), Measuring particle size distribution and mass concentration of nanoplastics and microplastics: addressing some analytical challenges in the sub-micron size range, *Journal of Colloid and Interface Science*, **588**, 401-417.

Chan H.S.H., Dingle C., Not C., (2019), Evidence for non-selective ingestion of microplastic in demersal fish, *Marine Pollution Bulletin*, **149**, 110523, https://doi.org/10.1016/j.marpolbul.2019.110523.

Chellasamy G., Kiriyanthan R.M., Maharajan T., Radha A., Yun K., (2022), Remediation of microplastics using bionanomaterials: A review, *Environmental Research*, **208**, 112724, https://doi.org/10.1016/j.envres.2022.112724.

Chen G., Fu Z., Yang H., Wang J., (2020), An overview of analytical methods for detecting microplastics in the atmosphere, *TrAC Trends in Analytical Chemistry*, **130**, 115981, https://doi.org/10.1016/j.trac.2020.115981.

Chen H.L., Nath T.K., Chong S., Foo V., Gibbins C., Lechner A.M., (2021), The plastic waste problem in Malaysia: management, recycling and disposal of local and global plastic waste, *SN Applied Sciences*, **3,** 437, https://doi.org/10.1007/s42452-021-04234-y.

Cheng H., Luo H., Hu Y., Tao S., (2020), Release kinetics as a key linkage between the occurrence of flame retardants in microplastics and their risk to the environment and ecosystem: A critical review, *Water Research*, **185**, 116253, https://doi.org/10.1016/j.watres.2020.116253.

Choudhury A., Simnani F.Z., Singh D., Patel P., Sinha A., Nandi A., Ghosh A., Saha U., Kumari K., Jaganathan S.K., Kaushik N.K., Panda P.K., Suar M., Verma S.K., (2023), Atmospheric microplastic and nanoplastic: The toxicological paradigm on the cellular system, *Ecotoxicology and Environmental Safety*, **259**, 115018, https://doi.org/10.1016/j.ecoenv.2023.115018.

Cordova M.R., Ulumuddin Y.I., Purbonegoro T., Puspitasari R., Afianti N.F., Rositasari R., Yogaswara D., Hafizt M., Iswari M.Y., Fitriya N., et al., (2022), Seasonal heterogeneity and a link to precipitation in the release of microplastic during COVID-19 outbreak from the Greater Jakarta area to Jakarta Bay, Indonesia, *Marine pollution bulletin*, **181**, 113926, https://doi.org/10.1016/j.marpolbul.2022.113926, .

Costa E., Gambardella C., Piazza V., Vassalli M., Sbrana F., Lavorano S., Garaventa F., Faimali M., (2020), Microplastics ingestion in the ephyra stage of *Aurelia* sp. triggers acute and behavioral responses, *Ecotoxicology and Environmental Safety*, **189**, 109983, https://doi.org/10.1016/j.ecoenv.2019.109983.

Costantini D., (2014), *Oxidative Stress and Hormesis in Evolutionary Ecology and Physiology, A Marriage Between Mechanistic and Evolutionary Approaches*, Ist Edition, Springer Berlin, Heidelberg, Berlin, .

da Costa J.P., Avellan A., Mouneyrac C., Duarte A., Rocha-Santos T., (2022), Plastic additives and microplastics as emerging contaminants: Mechanisms and analytical assessment, *TrAC Trends in Analytical Chemistry*, **158**, 116898, https://doi.org/10.1016/j.trac.2022.116898.

Darabi M., Majeed H., Diehl A., Norton J., Zhang Y., (2021), A review of microplastics in aquatic sediments: occurrence, fate, transport, and ecological impact, *Current Pollution Reports*, **7**, 40-53.

de Souza Machado A.A., Kloas W., Zarfl C., Hempel S., Rillig M.C., (2018), Microplastics as an emerging threat to terrestrial ecosystems, *Global Change Biology*, **24**, 1405-1416.

Deng Y., Yan Z., Shen R., Huang Y., Ren H., Zhang Y., (2021), Enhanced reproductive toxicities induced by phthalates contaminated microplastics in male mice (*Mus musculus*), *Journal of Hazardous Materials*, **406**, 124644, https://doi.org/10.1016/j.jhazmat.2020.124644.

Dennis P., (2023), New report proposes 15 global policies to end plastic pollution, On line at: https://www.circularonline.co.uk/news/new-report-proposes-15-global-policies-to-end-plastic-pollution/

Dioses-Salinas D.C., Pizarro-Ortega C.I., De-la-Torre G.E., (2020), A methodological approach of the current literature on microplastic contamination in terrestrial environments: Current knowledge and baseline considerations, *Science of the Total Environment*, **730**, 139164, https://doi.org/10.1016/j.scitotenv.2020.139164.

Dris R., Gasperi J., Mirande C., Mandin C., Guerrouache M., Langlois V., Tassin B., (2017), A first overview of textile fibers, including microplastics, in indoor and outdoor environments, *Environmental Pollution*, **221**, 453-458.

Dris R., Gasperi J., Rocher V., Saad M., Renault N., Tassin B., (2015), Microplastic contamination in an urban area: a case study in Greater Paris, *Environmental Chemistry*, **12**, 592-599.

Dris R., Gasperi J., Saad M., Mirande C., Tassin B., (2016), Synthetic fibers in atmospheric fallout: a source of microplastics in the environment?, *Marine Pollution Bulletin*, **104**, 290-293.

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*, **2**, 1-25.

Enfrin M., Dumée L.F., Lee J., (2019), Nano/microplastics in water and wastewater treatment processes–origin, impact and potential solutions, *Water Research*, **161**, 621-638.

Eriksen M., Mason S., Wilson S., Box C., Zellers A., Edwards W., Farley H., Amato S., (2013), Microplastic pollution in the surface waters of the Laurentian Great Lakes, *Marine Pollution Bulletin*, **77**, 177-182.

Forte M., Iachetta G., Tussellino M., Carotenuto R., Prisco M., De Falco M., Laforgia V., Valiante S., (2016), Polystyrene nanoparticles internalization in human gastric adenocarcinoma cells, *Toxicology in Vitro*, **31**, 126-136.

France24., (2023), We cannot recycle our way out of the plastics crisis: EU Commissioner Sinkevičius, Talking Europe, On line at: https://www.france24.com/en/tv-shows/talking-europe/20231215-we-cannot-recycle-our-way-out-of-the-plastics-crisis-eu-commissioner-sinkevi%C4%8Dius

Franzellitti S., Canesi L., Auguste M., Wathsala R.H., Fabbri E., (2019), Microplastic exposure and effects in aquatic organisms: a physiological perspective, *Environmental Toxicology and Pharmacology*, **68**, 37-51.

Fries E., Dekiff J.H., Willmeyer J., Nuelle M.-T., Ebert M., Remy D., (2013), Identification of polymer types and additives in marine microplastic particles using pyrolysis-GC/MS and scanning electron microscopy, *Environmental Science: Processes & Impacts*, **15**, 1949-1956.

Fu W., Min J., Jiang W., Li Y., Zhang W., (2020), Separation, characterization and identification of microplastics and nanoplastics in the environment, *Science of the Total Environment*, **721**, 137561, https://doi.org/10.1016/j.scitotenv.2020.137561.

Gao X., Liang J., Zhu Z., Li W., Lu L., Li X., Li S., Tang N., Li X., (2023), Drought-induced changes in hydrological and phenological interactions modulate waterbird habitats dynamics, *Journal of Hydrology*, **626**, 130228, https://doi.org/10.1016/j.jhydrol.2023.130228.

Gasperi J., Wright S.L., Dris R., Collard F., Mandin C., Guerrouache M., Langlois V., Kelly F.J., Tassin B., (2018), Microplastics in air: are we breathing it in?, *Current Opinion in Environmental Science & Health*, **1**, 1-5.

Gavrilescu M., (2021), Water, soil, and plants interactions in a threatened environment, *Water*, **13**, 2746, https://doi.org/10.3390/w13192746.

Giorgetti L., Spanò C., Muccifora S., Bottega S., Barbieri F., Bellani L., Castiglione M.R., (2020), Exploring the interaction between polystyrene nanoplastics and Allium cepa during germination: Internalization in root cells, induction of toxicity and oxidative stress, *Plant Physiology and Biochemistry*, **149**, 170-177.

Gong J., Xie P., (2020), Research progress in sources, analytical methods, eco-environmental effects, and control measures of microplastics, *Chemosphere*, **254**, 126790.

Habibi N., Uddin S., Fowler S.W., Behbehani M., (2022), Microplastics in the atmosphere: A review, *Journal of Environmental Exposure Assessment*, **1**, https://doi.org/10.20517/jeea.2021.07.

Han Y., Shi W., Tang Y., Zhou W., Sun H., Zhang J., Yan M., Hu L., Liu G., (2022), Microplastics and bisphenol A hamper gonadal development of whiteleg shrimp (*Litopenaeus vannamei*) by interfering with metabolism and disrupting hormone regulation, *Science of the Total Environment*, **810**, 152354, https://doi.org/10.1016/j.scitotenv.2021.152354.

Haque F., Fan C., (2023), Fate and impacts of microplastics in the environment: hydrosphere, pedosphere, and atmosphere, *Environments*, **10**, 70, https://doi.org/10.3390/environments10050070.

Harmon S.M., (2018), *The Effects of Microplastic Pollution on Aquatic Organisms*, In: *Microplastic Contamination in Aquatic Environments*, Zeng E.Y. (Ed.), Elsevier, SC, United States.

He D., Luo Y., Lu S., Liu M., Song Y., Lei L., (2018), Microplastics in soils: Analytical methods, pollution characteristics and ecological risks, *TrAC Trends in Analytical Chemistry*, **109**, 163-172.

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**, 3060-3075.

Hollman P.C.H, Bouwmeester H., Peters R.J.B., (2013), Microplastics in aquatic food chain: Sources, measurement, occurrence and potential health risks, On line at: https://edepot.wur.nl/260490.

Horton A.A., Dixon S.J., (2018), Microplastics: An introduction to environmental transport processes, *Wiley Interdisciplinary Reviews: Water*, **5**, e1268, https://doi.org/10.1002/wat2.1268.

Huang J., Koroteev D.D., (2021), Artificial intelligence for planning of energy and waste management, *Sustainable Energy Technologies and Assessments*, **47**, 101426, https://doi.org/10.1016/j.seta.2021.101426.

Huang Y., He T., Yan M., Yang L., Gong H., Wang W., Qing X., Wang J., (2021), Atmospheric transport and deposition of microplastics in a subtropical urban environment, *Journal of Hazardous Materials*, **416**, 126168.

Huppertsberg S., Knepper T.P., (2018), Instrumental analysis of microplastics - benefits and challenges, *Analytical and Bioanalytical Chemistry*, **410**, 6343-6352.

Iroegbu A.O.C., Ray S.S., Mbarane V., Bordado J.C., Sardinha J.P., (2021), Plastic pollution: a perspective on matters arising: challenges and opportunities, *ACS Omega*, **6**, 19343-19355.

Issac M.N., Kandasubramanian B., (2021), Effect of microplastics in water and aquatic systems, *Environmental Science and Pollution Research*, **28**, 19544-19562.

Jacob H., Besson M., Swarzenski P.W., Lecchini D., Metian M., (2020), Effects of virgin micro-and nanoplastics on fish: trends, meta-analysis, and perspectives, *Environmental Science & Technology*, **54**, 4733-4745.

Jaikumar I.M., Periyakali S.B., Rajendran U., Joen-Rong S., Thanasekaran J., Tsorng-Harn F., (2021), Effects of microplastics, polystyrene, and polyethylene on antioxidants, metabolic enzymes, HSP-70, and myostatin expressions in the giant river prawn Macrobrachium rosenbergii: impact on survival and growth, *Archives of Environmental Contamination and Toxicology*, **80**, 645-658.

*Jenkins S., Quer A.M.i., Fonseca C., Varrone C., (2019), Microbial Degradation of Plastics: New Plastic Degraders, Mixed Cultures and Engineering Strategies*, In: *Soil Microenvironment for Bioremediation and Polymer Production*, Jamil N., Kumar P., Batool R., (Eds.), Wiley, 213-238, https://doi.org/10.1002/9781119592129.ch12.

Jeong C.-B., Won E.-J., Kang H.-M., Lee M.-C., Hwang D.-S., Hwang U.-K., Zhou B., Souissi S., Lee S.-J., Lee J.-S., (2016), Microplastic size-dependent toxicity, oxidative stress induction, and p-JNK and p-p38 activation in the monogonont rotifer (Brachionus koreanus), *Environmental Science & Technology*, **50**, 8849-8857.

Jia Q., Duan Y., Han X., Sun X., Munyaneza J., Ma J., Xiu G., (2022), Atmospheric deposition of microplastics in the megalopolis (Shanghai) during rainy season: Characteristics, influence factors, and source, *Science of the Total Environment*, **847**, 157609, https://doi.org/10.1016/j.scitotenv.2022.157609.

Jiang Y., Xia W., Zhao R., Wang M., Tang J., Wei Y., (2021), Insight into the interaction between microplastics and microorganisms based on a bibliometric and visualized analysis, *Bulletin of Environmental Contamination and Toxicology*, 1-12.

Johannes B., Ana M.S., Adalbert J., Daniela S., (2023), Protecting environment and health: Commission adopts measures to restrict intentionally added microplastics, European Commission, On line at: https://ec.europa.eu/commission/presscorner/api/files/document/print/en/ip_23_4581/IP_23_4581_EN.pdf.

Kaloyianni M., Bobori D.C., Xanthopoulou D., Malioufa G., Sampsonidis I., Kalogiannis S., Feidantsis K., Kastrinaki G., Dimitriadi A., Koumoundouros G., (2021), Toxicity and functional tissue responses of two freshwater fish after exposure to polystyrene microplastics, *Toxics*, **9**, 289, https://doi.org/10.3390/toxics9110289.

Kim J.-H., Yu Y.-B., Choi J.-H., (2021), Toxic effects on bioaccumulation, hematological parameters, oxidative stress, immune responses and neurotoxicity in fish exposed to microplastics: A review, *Journal of Hazardous Materials*, **413**, 125423, https://doi.org/10.1016/j.jhazmat.2021.125423.

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.

Kozjek M., Vengust D., Radošević T., Žitko G., Koren S., Toplak N., Jerman I., Butala M., Podlogar M., Viršek M.K., (2023), Dissecting giant hailstones: A glimpse into the troposphere with its diverse bacterial communities and fibrous microplastics, *Science of the Total Environment*, **856**, 158786, https://doi.org/10.1016/j.scitotenv.2022.158786.

Kumar A., Mishra S., Pandey R., Yu Z.G., Kumar M., Khoo K.S., Thakur T.K., Show P.L., (2023), Microplastics in terrestrial ecosystems: Un-ignorable impacts on soil characterises, nutrient storage and its cycling, *TrAC Trends in Analytical Chemistry*, **158**, 116869, https://doi.org/10.1016/j.trac.2022.116869.

Kumar R., Verma A., Shome A., Sinha R., Sinha S., Jha P.K., Kumar R., Kumar P., Shubham, Das S., (2021), Impacts of plastic pollution on ecosystem services, sustainable development goals, and need to focus on circular economy and policy interventions, *Sustainability*, **13**, 9963, https://doi.org/10.3390/su13179963

Kumar S., Singh E., Mishra R., Kumar A., Caucci S., (2021), Utilization of plastic wastes for sustainable environmental management: a review, *ChemSusChem*, **14**, 3985-4006.

Kurniawan T.A., Avtar R., Singh D., Xue W., Othman M.H.D., Hwang G.H., Iswanto I., Albadarin A.B., Kern A.O., (2021), Reforming MSWM in Sukunan (Yogjakarta, Indonesia): A case-study of applying a zero-waste approach based on circular economy paradigm, *Journal of Cleaner Production*, **284**, 124775, https://doi.org/10.1016/j.jclepro.2020.124775.

Lambey V., Prasad A., (2021), A review on air quality measurement using an unmanned aerial vehicle, *Water, Air, & Soil Pollution*, **232**, 109. https://doi.org/10.1007/s11270-020-04973-5

Li H., Luo Q.-P., Zhao S., Zhou Y.-Y., Huang F.-Y., Yang X.-R., Su J.-Q., (2023), Effect of phenol formaldehyde-associated microplastics on soil microbial community, assembly, and functioning, *Journal of Hazardous Materials*, **443**, 130288, https://doi.org/10.1016/j.jhazmat.2022.130288.

Li W., Li X., Tong J., Xiong W., Zhu Z., Gao X., Li S., Jia M., Yang Z., Liang J., (2023), Effects of environmental and anthropogenic factors on the distribution and abundance of microplastics in freshwater ecosystems, *Science of the Total Environment*, **856**, 159030, https://doi.org/10.1016/j.scitotenv.2022.159030.

Li J., Yu S., Yu Y., Xu M., (2022), Effects of microplastics on higher plants: A review, *Bulletin of Environmental Contamination and Toxicology*, **109**, 241-265.

Li L., Yang J., Zhou Q., Peijnenburg W.J., Luo Y., (2020), *Uptake of Microplastics and their Effects on Plants*, In: *Microplastics in Terrestrial Environments: Emerging Contaminants and Major Challenges*, He, D., Luo, Y. (Eds), vol. 95, Springer, Cham, Netherlands, 279-298.

Liao Z., Ji X., Ma Y., Lv B., Huang W., Zhu X., Fang M., Wang Q., Wang X., Dahlgren R., (2021), Airborne microplastics in indoor and outdoor environments of a coastal city in Eastern China, *Journal of Hazardous Materials*, **417**, 126007.

Liu S., Huang W., Yang J., Xiong Y., Huang Z., Wang J., Cai T., Dang Z., Yang C., (2023), Formation of environmentally persistent free radicals on microplastics under UV irradiations, *Journal of Hazardous Materials*, **453**, 131277., https://doi.org/10.1016/j.jhazmat.2023.131277

Liu P., Li H., Wu J., Wu X., Shi Y., Yang Z., Huang K., Guo X., Gao S., (2022), Polystyrene microplastics accelerated photodegradation of co-existed polypropylene via photosensitization of polymer itself and released organic compounds, *Water Research*, **214**, 118209, https://doi.org/10.1016/j.watres.2022.118209.

Liu H., Cao C., Huang J., Chen Z., Chen G., Lai Y., (2020), Progress on particulate matter filtration technology: basic concepts, advanced materials, and performances, *Nanoscale*, **12**, 437-453.

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.

López A.P.A., Trilleras J., Arana V.A., Garcia-Alzate L.S., Grande-Tovar C.D., (2023), Atmospheric microplastics: exposure, toxicity, and detrimental health effects, *RSC Advances*, **13**, 7468-7489.

Löder M., Gerdts G., (2013), FT-IR analysis for monitoring marine microplastics, YOUMARES 4, Oldenburg, On line at: https://epic.awi.de/id/eprint/34387/.

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**, 958414, https://doi.org/10.3389/ftox.2022.958414.

Lusher A.L., Hurley R., Arp H.P.H., Booth A.M., Bråte I.L.N., Gabrielsen G.W., Gomiero A., Gomes T., Grøsvik B.E., Green N., (2021), Moving forward in microplastic research: A Norwegian perspective, *Environment International*, **157**, 106794, https://doi.org/10.1016/j.envint.2021.106794.

Mai L., Bao L.-J., Shi L., Wong C.S., Zeng E.Y., (2018), A review of methods for measuring microplastics in aquatic environments, *Environmental Science and Pollution Research*, **25**, 11319-11332.

Majewsky M., Bitter H., Eiche E., Horn H., (2016), Determination of microplastic polyethylene (PE) and polypropylene (PP) in environmental samples using thermal analysis (TGA-DSC), *Science of the Total Environment*, **568**, 507-511.

Masud A., Gül M., Küçükuysal C., Buluş E., Şahin Y.M., (2023), Effect of lithological properties of beach sediments on plastic pollution in Bodrum Peninsula (SW Türkiye), *Marine Pollution Bulletin*, **190**, 114895, https://doi.org/10.1016/j.marpolbul.2023.114895.

Mattsson K., Hansson L.A., Cedervall T., (2015), Nano-plastics in the aquatic environment, *Environmental Science: Processes & Impacts*, **17**, 1712-1721.

Mbachu O., Jenkins G., Pratt C., Kaparaju P., (2020), A new contaminant superhighway? A review of sources, measurement techniques and fate of atmospheric microplastics, *Water, Air, & Soil Pollution*, **231**, 1-27.

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.

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**, 1-26.

Munyaneza J., Jia Q., Qaraah F.A., Hossain M.F., Wu C., Zhen H., Xiu G., (2022), A review of atmospheric microplastics pollution: In-depth sighting of sources, analytical methods, physiognomies, transport and risks, *Science of the Total Environment*, **822**, 153339. https://doi.org/10.1016/j.scitotenv.2022.153339

Nakayama T., Osako M., (2023), Development of a process-based eco-hydrology model for evaluating the spatio-temporal dynamics of macro-and micro-plastics for the whole of Japan, *Ecological Modelling*, **476**, 110243, https://doi.org/10.1016/j.ecolmodel.2022.110243.

Nanda S., Berruti F., (2021), Thermochemical conversion of plastic waste to fuels: a review, *Environmental Chemistry Letters*, **19**, 123-148.

Nguyen B., Claveau-Mallet D., Hernandez L.M., Xu E.G., Farner J.M., Tufenkji N., (2019), Separation and analysis of microplastics and nanoplastics in complex environmental samples, *Accounts of Chemical Research*, **52** 858-866.

Noman A.A., Akter U.H., Pranto T.H., Haque A., (2022), Machine learning and artificial intelligence in circular economy: a bibliometric analysis and systematic literature review, *Annals of Emerging Technologies in Computing (AETiC)*, **6**, 13-40.

Oliveira M., Ribeiro A., Hylland K., Guilhermino L., (2013), Single and combined effects of microplastics and pyrene on juveniles (0+ group) of the common goby Pomatoschistus microps (Teleostei, Gobiidae), *Ecological Indicators*, **34**, 641-647.

Omoyajowo K.O., Raimi M.O., Waleola T.O., Odipe O.E., Ogunyebi A.L., (2021), Public Health Knowledge and Perception of Microplastics Pollution: Lessons from the Lagos Lagoon, Ecological Safety and Balanced Use of Resources 2, https://doi.org/10.31471/2415-3184-2021-2(24)-35-46

Onoja S., Nel H.A., Abdallah M.A.-E., Harrad S., (2022), Microplastics in freshwater sediments: Analytical methods, temporal trends, and risk of associated organophosphate esters as exemplar plastics additives, *Environmental Research*, **203**, 111830, https://doi.org/10.1016/j.envres.2021.111830.

Ornatowski W., Lu Q., Yegambaram M., Garcia A.E., Zemskov E.A., Maltepe E., Fineman J.R., Wang T., Black S.M., (2020), Complex interplay between autophagy and oxidative stress in the development of pulmonary disease, *Redox Biology*, **36**, 101679, https://doi.org/10.1016/j.redox.2020.101679.

Ouda M., Banat F., Hasan S.W., Karanikolos G.N., (2023), Recent advances on nanotechnology-driven strategies for remediation of microplastics and nanoplastics from aqueous environments, *Journal of Water Process Engineering*, **52**, 103543, https://doi.org/10.1016/j.jwpe.2023.103543.

Österlund H., Blecken G., Lange K., Marsalek J., Gopinath K., Viklander M., (2023), Microplastics in urban catchments: Review of sources, pathways, and entry into stormwater, *Science of the Total Environment*, **858**, 159781, https://doi.org/10.1016/j.scitotenv.2022.159781.

Özgenç E., Keleş E., Yıldız Töre G., (2024), Assessment of biomarker-based ecotoxic effects in combating microplastic pollution - A review, *Global NEST Journal*, **26**, 1-24.

Padervand M., Lichtfouse E., Robert D., Wang C., (2020), Removal of microplastics from the environment. A review, *Environmental Chemistry Letters*, **18**, 807-828.

Papari S., Bamdad H., Berruti F., (2021), Pyrolytic conversion of plastic waste to value-added products and fuels: A review, *Materials*, **14**, 2586, https://doi.org/10.3390/ma14102586.

Patil S., Bafana A., Naoghare P.K., Krishnamurthi K., Sivanesan S., (2021), Environmental prevalence, fate, impacts, and mitigation of microplastics-A critical review on present understanding and future research scope, *Environmental Science and Pollution Research*, **28**, 4951-4974.

Patra I., Huy D.T.N., Alsaikhan F., Opulencia M.J.C., Van Tuan P., Nurmatova K.C., Majdi A., Shoukat S., Yasin G., Margiana R., (2022), Toxic effects on enzymatic activity, gene expression and histopathological biomarkers in organisms exposed to microplastics and nanoplastics: a review, *Environmental Sciences Europe*, **34**, 80, https://doi.org/10.1186/s12302-022-00652-w.

Persiani E., Cecchettini A., Ceccherini E., Gisone I., Morales M.A., Vozzi F., (2023), Microplastics: A Matter of the Heart (and Vascular System), *Biomedicines*, **11**, 264, https://doi.org/10.3390/biomedicines11020264.

Pooja N., Chakraborty I., Rahman M.H., Mazumder N., (2023), An insight on sources and biodegradation of bioplastics: a review, *3 Biotech*, **13** 1-22.

Potthoff A., Oelschlägel K., Schmitt-Jansen M., Rummel C.D., Kühnel D., (2017), From the sea to the laboratory: Characterization of microplastic as prerequisite for the assessment of ecotoxicological impact, *Integrated Environmental Assessment and Management*, **13**, 500-504.

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

Prata J.C., da Costa J.P., Duarte A.C., Rocha-Santos T., (2019), Methods for sampling and detection of microplastics in water and sediment: a critical review, *TrAC Trends in Analytical Chemistry*, **110**, 150-159.

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, https://doi.org/10.1016/j.scitotenv.2019.134455.

Prokić M.D., Radovanović T.B., Gavrić J.P., Faggio C., (2019), Ecotoxicological effects of microplastics: Examination of biomarkers, current state and future perspectives, *TrAC Trends in Analytical Chemistry*, **111**, 37-46.

Qiao R., Deng Y., Zhang S., Wolosker M.B., Zhu Q., Ren H., Zhang Y., (2019), Accumulation of different shapes of microplastics initiates intestinal injury and gut microbiota dysbiosis in the gut of zebrafish, *Chemosphere*, **236**, 124334, https://doi.org/10.1016/j.chemosphere.2019.07.065.

Raab P., Bogner F.X., (2021), Conceptions of university students on microplastics in Germany, *PloS one*, **16**, e0257734, https://doi.org/10.1371/journal.pone.0257734.

Rahman A., Sarkar A., Yadav O.P., Achari G., Slobodnik J., (2021), Potential human health risks due to environmental exposure to nano-and microplastics and knowledge gaps: a scoping review, *Science of the Total Environment*, **757**, 143872, https://doi.org/10.1016/j.scitotenv.2020.143872.

Rai P.K., Lee J., Brown R.J., Kim K.-H., (2021), Micro-and nano-plastic pollution: Behavior, microbial ecology, and remediation technologies, *Journal of Cleaner Production*, **291**, 125240, https://doi.org/10.1016/j.jenvman.2024.120618.

Raveesh A., Mona C., Jayveer S., (2015), Waste management initiatives in India for human well being, *European Scientific Journal*, **7881**, 1857-7881.

Razeghi N., Hamidian A.H., Mirzajani A., Abbasi S., Wu C., Zhang Y., Yang M., (2022), Sample preparation methods for the analysis of microplastics in freshwater ecosystems: a review, *Environmental Chemistry Letters*, **20**, 417-443.

Rocha-Santos T., Duarte A.C., (2015), A critical overview of the analytical approaches to the occurrence, the fate and the behavior of microplastics in the environment, *TrAC Trends in Analytical Chemistry*, **65**, 47-53.

Roy T., Dey T.K., Jamal M., (2023), Microplastic/nanoplastic toxicity in plants: An imminent concern, *Environmental Monitoring and Assessment*, **195**, https://doi.org/10.1007/s10661-022-10654-z.

Sandu C., Takacs E., Suaria G., Borgogno F., Laforsch C., Löder M.M., Tweehuysen G., Florea L., (2020), *Society Role in the Reduction of Plastic Pollution*, In *Plastics in the Aquatic Environment-Part II: Stakeholders' Role Against Pollution*, *The Handbook of Environmental Chemistry*, Stock, F., Reifferscheid, G., Brennholt, N., Kostianaia, E. (eds), vol. 112, Springer, Cham, https://doi.org/10.1007/698_2020_483.,

Sangkham S., Faikhaw O., Munkong N., Sakunkoo P., Arunlertaree C., Chavali M., Mousazadeh M., Tiwari A., (2022), A review on microplastics and nanoplastics in the environment: Their occurrence, exposure routes, toxic studies, and potential effects on human health, *Marine Pollution Bulletin*, **181**, 113832, https://doi.org/10.1016/j.marpolbul.2022.113832.

Sarkar B., Dissanayake P.D., Bolan N.S., Dar J.Y., Kumar M., Haque M.N., Mukhopadhyay R., Ramanayaka S., Biswas J.K., Tsang D.C., (2022), Challenges and opportunities in sustainable management of microplastics and nanoplastics in the environment, *Environmental Research*, **207**, 112179, https://doi.org/10.1016/j.envres.2021.112179.

Scopetani C., Chelazzi D., Mikola J., Leiniö V., Heikkinen R., Cincinelli A., Pellinen J., (2020), Olive oil-based method for the extraction, quantification and identification of microplastics in soil and compost samples, *Science of the Total Environment*, **733**, 139338, https://doi.org/10.1016/j.scitotenv.2020.139338.

Segovia-Mendoza M., Nava-Castro K.E., Palacios-Arreola M.I., Garay-Canales C., Morales-Montor J., (2020), How microplastic components influence the immune system and impact on children health: Focus on cancer, *Birth Defects Research*, **112**, 1341-1361.

Sharifinia M., Bahmanbeigloo Z.A., Keshavarzifard M., Khanjani M.H., Lyons B.P., (2020), Microplastic pollution as a grand challenge in marine research: a closer look at their adverse impacts on the immune and reproductive systems, *Ecotoxicology and Environmental Safety*, **204**, 111109, https://doi.org/10.1016/j.ecoenv.2020.111109.

Sharma S., Chatterjee S., (2017), Microplastic pollution, a threat to marine ecosystem and human health: a short review, *Environmental Science and Pollution Research*, **24**, 21530-21547.

Shen M., Huang W., Chen M., Song B., Zeng G., Zhang Y., (2020), (Micro) plastic crisis: un-ignorable contribution to global greenhouse gas emissions and climate change, *Journal of Cleaner Production*, **254**, 120138, https://doi.org/10.1016/j.jclepro.2020.120138.

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

Shorobi F.M., Vyavahare G.D., Seok Y.J., Park J.H., (2023), Effect of polypropylene microplastics on seed germination and nutrient uptake of tomato and cherry tomato plants, *Chemosphere*, **329**, 138679, https://doi.org/10.1016/j.chemosphere.2023.138679.

Silva A.L.P., Prata J.C., Walker T.R., Campos D., Duarte A.C., Soares A.M., Barcelò D., Rocha-Santos T., (2020), Rethinking and optimising plastic waste management under COVID-19 pandemic: policy solutions based on redesign and reduction of single-use plastics and personal protective equipment, *Science of the Total Environment*, **742**, 140565, https://doi.org/10.1016/j.scitotenv.2020.140565.

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**, 375-386.

Song Y.K., Hong S.H., Jang M., Han G.M., Jung S.W., Shim W.J., (2017), Combined effects of UV exposure duration and mechanical abrasion on microplastic fragmentation by polymer type, *Environmental Science & Technology*, **51**, 4368-4376.

Subaramaniyam U., Allimuthu R.S., Vappu S., Ramalingam D., Balan R., Paital B., Panda N., Rath P.K., Ramalingam N., Sahoo D.K., (2023), Effects of microplastics, pesticides and nano-materials on fish health, oxidative stress and antioxidant defense mechanism, *Frontiers in Physiology*, **14**, https://doi.org/10.3389/fphys.2023.1217666.

Tan Q., Yang L., Wei F., Chen Y., Li J., (2023), Is reusable packaging an environmentally friendly alternative to the single-use plastic bag? A case study of express delivery packaging in China, *Resources, Conservation and Recycling*, **190**, 106863, https://doi.org/10.1016/j.resconrec.2022.106863.

Thornton Hampton L.M., Bouwmeester H., Brander S.M., Coffin S., Cole M., Hermabessiere L., Mehinto A.C., Miller E., Rochman C.M., Weisberg S.B., (2022), Research recommendations to better understand the potential health impacts of microplastics to humans and aquatic ecosystems, *Microplastics and Nanoplastics*, **2**, https://doi.org/10.1186/s43591-022-00038-y

Tran-Nguyen Q.A., Vu T.B.H., Nguyen Q.T., Nguyen H.N.Y., Le T.M., Trinh-Dang M., (2022), Urban drainage channels as microplastics pollution hotspots in developing areas: A case study in Da Nang, Vietnam, *Marine Pollution Bulletin*, **175**, 113323, https://doi.org/10.1016/j.marpolbul.2022.113323.

Verdú I., González-Pleiter M., Leganés F., Rosal R., Fernandez-Pinas F., (2021), Microplastics can act as vector of the biocide triclosan exerting damage to freshwater microalgae, *Chemosphere*, **266**, 129193, https://doi.org/10.1016/j.chemosphere.2020.129193,

Verla A.W., Enyoh C.E., Verla E.N., Nwarnorh K.O., (2019), Microplastic–toxic chemical interaction: a review study on quantified levels, mechanism and implication, *SN Applied Sciences*, **1**, 1-30.

Viera J.S., Marques M.R., Nazareth M.C., Jimenez P.C., Castro Í.B., (2020), On replacing single-use plastic with so-called biodegradable ones: The case with straws, *Environmental Science & Policy*, **106**, 177-181.

Wagner J., Wang Z.-M., Ghosal S., Rochman C., Gassel M., Wall S., (2017), Novel method for the extraction and identification of microplastics in ocean trawl and fish gut matrices, *Analytical Methods*, **9**, 1479-1490.

Wang C., Zhao J., Xing B., (2021), Environmental source, fate, and toxicity of microplastics, *Journal of Hazardous Materials*, **407**, 124357, https://doi.org/10.1016/j.jhazmat.2020.124357.

Wang L., Zhang J., Hou S., Sun H., (2017), A simple method for quantifying polycarbonate and polyethylene terephthalate microplastics in environmental samples by liquid chromatography–tandem mass spectrometry, *Environmental Science & Technology Letters*, **4**, 530-534.

Weidner S.M., rimpin S., (2010), Mass spectrometry of synthetic polymers, *Analytical Chemistry*, **82**, 4811-4829.

Woo J.-H., Seo H.J., Lee J.-Y., Lee I., Jeon K., Kim B., Lee K., (2023), Polypropylene nanoplastic exposure leads to lung inflammation through p38-mediated NF-κB pathway due to mitochondrial damage, *Particle and Fibre Toxicology*, **20**, 2, https://doi.org/10.1186/s12989-022-00512-8

Wright S., Ulke J., Font A., Chan K., Kelly F., (2020), Atmospheric microplastic deposition in an urban environment and an evaluation of transport, *Environment International*, **136**, 105411, https://doi.org/10.1016/j.envint.2019.105411.

Wright S.L., Gouin T., Koelmans A.A., Scheuermann L., (2021), Development of screening criteria for microplastic particles in air and atmospheric deposition: critical review and applicability towards assessing human exposure, *Microplastics and Nanoplastics*, **1**, 6, https://doi.org/10.1186/s43591-021-00006-y

Wright S.L., Levermore J.M., Kelly F.J., (2019), Raman spectral imaging for the detection of inhalable microplastics in ambient particulate matter samples, *Environmental Science & Technology*, **53**, 8947-8956.

Wu P., Lin S., Cao G., Wu J., Jin H., Wang C., Wong M.H., Yang Z., Cai Z., (2022), Absorption, distribution, metabolism, excretion and toxicity of microplastics in the human body and health implications, *Journal of Hazardous Materials*, **437**, 129361, https://doi.org/10.1016/j.jhazmat.2022.129361.

Yang M., Tian X., Guo Z., Chang C., Li J., Guo Z., Li H., Liu R., Wang R., Li Q., (2023), Wind erosion induced low-density microplastics migration at landscape scale in a semi-arid region of northern China, *Science of the Total Environment*, **871**, 162068, https://doi.org/10.1016/j.scitotenv.2023.162068.

Yang H., Chen G., Wang J., (2021), Microplastics in the marine environment: Sources, fates, impacts and microbial degradation, *Toxics*, **9**, 41, https://doi.org/10.3390/toxics9020041.

Yang Y., Chen L., Xue L., (2021), Looking for a Chinese solution to global problems: The situation and countermeasures of marine plastic waste and microplastics pollution governance system in China, *Chinese Journal of Population, Resources and Environment*, **19**, 352-357.

Yao X., Luo X.-S., Fan J., Zhang T., Li H., Wei Y., (2022), Ecological and human health risks of atmospheric microplastics (MPs): a review, *Environmental Science: Atmospheres*, **2**, 921-942.

Yu H., Peng J., Cao X., Wang Y., Zhang Z., Xu Y., Qi W., (2021), Effects of microplastics and glyphosate on growth rate, morphological plasticity, photosynthesis, and oxidative stress in the aquatic species Salvinia cucullata, *Environmental Pollution*, **279**, 116900, https://doi.org/10.1016/j.envpol.2021.116900.

Yu J., Ma X., (2022), Exploring the management policy of marine microplastic litter in China: Overview, challenges and prospects, *Sustainable Production and Consumption*, **32**, 607-618.

Zhang Z., Cui Q., Chen L., Zhu X., Zhao S., Duan C., Zhang X., Song D., Fang L., (2022), A critical review of microplastics in the soil-plant system: Distribution, uptake, phytotoxicity and prevention, *Journal of Hazardous Materials*, **424**, 127750, https://doi.org/10.1016/j.jhazmat.2021.127750.

Zhang Y., Peng Y., Peng C., Wang P., Lu Y., He X., Wang L., (2021), Comparison of detection methods of microplastics in landfill mineralized refuse and selection of degradation degree indexes, *Environmental Science & Technology*, **55**, 13802-13811.

Zhang K., Hamidian A.H., Tubić A., Zhang Y., Fang J.K., Wu C., Lam P.K., (2021), Understanding plastic degradation and microplastic formation in the environment: A review, *Environmental Pollution*, **274**, 116554, https://doi.org/10.1016/j.envpol.2021.116554.

Zhang Y., Gao T., Kang S., Sillanpää M., (2019), Importance of atmospheric transport for microplastics deposited in remote areas, *Environmental Pollution*, **254**, 112953, https://doi.org/10.1016/j.envpol.2019.07.121.

Zhang S., Yang X., Gertsen H., Peters P., Salánki T., Geissen V., (2018), A simple method for the extraction and identification of light density microplastics from soil, *Science of the Total Environment*, **616**, 1056-1065.

Zhou A., Zhang Y., Xie S., Chen Y., Li X., Wang J., Zou J., (2021), Microplastics and their potential effects on the aquaculture systems: a critical review, *Reviews in Aquaculture*, **13**, 719-733.

Zylstra E., (2013), Accumulation of wind-dispersed trash in desert environments, *Journal of Arid Environments*, **89**, 13-15.