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Atmospheric microplastic and nanoplastic: The toxicological paradigm on the cellular system

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ABSTRACT

The increasing demand for plastic in our daily lives has led to global plastic pollution. The improper disposal of plastic has resulted in a massive amount of atmospheric microplastics (MPs), which has further resulted in the production of atmospheric nanoplastics (NPs). Because of its intimate relationship with the environment and human health, microplastic and nanoplastic contamination is becoming a problem. Because microplastics and nanoplastics are microscopic and light, they may penetrate deep into the human lungs. Despite several studies demonstrating the abundance of microplastics and nanoplastics in the air, the potential risks of atmospheric microplastics and nanoplastics remain unknown. Because of its small size, atmospheric nanoplastic characterization has presented significant challenges. This paper describes sampling and characterization procedures for atmospheric microplastics and nanoplastics. This study also examines the numerous harmful effects of plastic particles on human health and other species. There is a significant void in research on the toxicity of airborne microplastics and nanoplastics upon inhalation, which has significant toxicological potential in the future. Further study is needed to determine the influence of microplastic and nanoplastic on pulmonary diseases.

Abbreviation: MP, Microplastic; NP, Nanoplastic; PTFE, Polytetrafluoroethylene; H_2O_2, Hydrogen Peroxide; HNO_3, Nitric Acid; KOH, Pottasium Hydroxide; NaOH, Sodium Hydroxide; FTIR, Fourier Transferred Infrared; IR, Infrared; ATR-FTIR, Attenuated Total reflectance- Fourier Transferred Infrared; Pyr-GC MS, Pyrolysis gas Chromatography Mass Spectrometry; LOD, Limit of detection; LOQ, Limit of quantification; PES, Polyethersulfone; CsFC, Continuous flow centrifugation; FFF, Field flow fractionation; EM, Electron microscopy; SEM, Scanning electron microscopy; TEM, Transmission electron microscopy; ESEM, Environmental scanning electron microscopy; SPM, Scanning probe microscopy; DLS, Dynamic Light Scattering; NTA, Nanoparticle Tracking Analysis; SLS, Static light scattering; MALS, Multi-angle laser light scattering; AF4, Asymmetric flow field-flow fractionation; TED-GC-MS, Thermal extraction desorption gas chromatography-mass spectrometry; PE, Polyethylene; PP, Polypropylene; PS, Polystyrene; PVS, Polyvinyl stearate; FVC, Forced vital capacity; FEF, Forced expiratory volume; PVC, Polyvinyl chloride; AED, Aerodynamic diameter; PET, Polyethylene terephthalate; ROS, Reactive Oxygen Species; A549, Adenocarcinomic human alveolar basal epithelial cells; BEAS-2B, Non-tumorigenic epithelial cell line from human bronchial epithelium; HO-1, Heme oxygenase-1; DCFH-DA, 2′,7′-Dichlorofluorescein diacetate; IL-6, Interleukin-6; IL-8, Interleukin-8; MCP-1, Monocyte chemoattractant protein-1; TNF-α, Tumor necrosis factor α; ICAM-1, Intercellular Adhesion Molecule 1; COPD, Chronic Obstructive Pulmonary Disease; IL-10, Interleukin-10; NADPH, Nicotinamide adenine dinucleotide phosphate; T_H, T helper cells; DCs, Dendritic Cells; LDH, Lactate dehydrogenase; CK-MB, Creatine kinase-MB; TGF-β, Transforming growth factor β; α-SMA, Smooth muscle alpha-actin; Caco-2, Epithelial cells isolated from colon tissue; POPs, Persistent organic pollutants; BPA, Bisphenol A; Bcl-2, B-cell lymphoma 2; Bax, BCL2-Associated X Protein; SP-C, Surfactant protein-C; KL-6, Krebs von den Lungen 6; TCF-4, ranscription factor 4.

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1. Introduction

The Global production of plastic emerged around the 1950s (Lebreton and Andrady, 2019) and gradually it reached to a high level production status due to its use in everyday life. The excessive use of plastics led to an increase in the production of plastics with approximately 275 million tonnes in 2010 from 19 coastal countries (García Rellán et al., 2023). While global plastic production in 1960 was 1.5 million tons, it increased to 335 million tons in 2016 (Alimba and Faggio, 2019; Plastic production worldwide, 2021 | *Statista*, n.d.). A report from China accounted for 30% of the plastic based material production which accounts for 107.7 million tons of plastic, and 18% of plastics were reposted from America (Facciolà et al., 2021). A report was made based on literature from different corners of the world, which marked that 79% of plastics are not being treated adequately leading to plastic pollution (Chamas et al., 2020; Moshood et al., 2021; Rhodes, 2019)). It is estimated that by 2025, there will be an accumulation of 250 million tonnes of plastic (Jambeck et al., 2015). The in turn plastic pollution has become a global concern because of its effects to the land, marine environment, and the atmosphere.

Plastics are synthetic polymers that are long-chain polymeric materials consisting of a main chain organic link, side-linked molecular groups, and some organic groups. Carbon, hydrogen, nitrogen, oxygen, chlorine, and bromine are the elements that could be used to produce plastic (Kusenberg et al., 2022). These are lightweight materials with high plasticity and flexibility, as well as great thermal and electrical insulation and corrosion resistance (Abdiev et al., 2022). These are inexpensive to create, making them the most sought and useful materials in our daily life. Plastic polymers are formed by the polymerization of monomers taken from diverse sources (Taib et al., 2023). The preparation procedure might make use of chemical additives.

Plastic's global consumption and ineffective disposal have resulted in its long-term persistence in the environment (R. Kumar et al., 2021). With the continuous degradation of plastic into fine particles, plastic debris resides in the environment (MacLeod et al., 2021). Depending on the variation in size of these plastics, they are categorized as, mega plastic with a size range greater than 50 cm, macroplastics ranging between 5 and 5 cm, mesoplastics ranging between 0.5 and 5 cm, microplastic (MPs) ranging from 1 μm to 5 mm, and lastly, nanoplastics (NPs) which are less than 1 μm (Frias and Nash, 2019). Irrespective of being inert substances, microplastics and nanoplastics can be traced anywhere starting from water resources, sediments, seafood, and even in take-out containers (F. Du et al., 2020). Microplastics and nanoplastics are formed with the continuous breakdown of the plastic because of various physiochemical changes, mechanical breakdown, and continuous UV exposure and are known as secondary MPs and NPs (Okoye et al., 2022; Tong et al., 2022). The degree of MP contamination corresponds to the amount of synthesis of thermoplastics such as polyethylene (PE) of high density (HDPE) and low density (LDPE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), and polyethylene terephthalate (PET) (Koelmans et al., 2019). Microplastics and nanoplastics created for desired objectives, such as clothes and personal care goods are categorized as primary MPs and NPs(García-Muñoz et al., 2023). Other major sources of microplastic are wipes and surgical masks. From a recent survey, it was discovered that with the outbreak of COVID-19, the demand for COVID-19 masks and surgical masks has increased, which is responsible for the release of microplastic into the atmosphere(Ma et al., 2021a; Panda et al., 2022). Irrespective of the small number of research, it is possible to infer that human exposure to MPs and NPs from ingestion of indoor dust, as well as the potential harm of such exposure, should not be overlooked, particularly for children (Ageel et al., 2022).

Several research has been conducted to investigate the cytotoxicity of MPs and NPs, which constitute a major health concern to people and other organisms(Eram et al., 2021; Husain et al., 2021; Makkar, Verma, Panda, Pramanik et al., 2018). There is little literature concentrating on the risks posed to people by inhaling MPs and NPs (Noventa et al., 2021). MPs and NPs particles infiltrate the human body primarily through three routes: inhalation, ingestion, and direct contact (Yuan et al., 2022). Because microplastic and nanoplastic are nearly everywhere, the possibility of inhaling these plastic fibers increases, rendering them harmful to human health. The literature on the toxicity of atmospheric MPs and NPs includes in-vivo and in-vitro research on human cell lines as well as numerous model species. The toxicity depends on the type of interaction between the MPs and NPs particles with the cells (González-Acedo et al., 2021). The toxicity of microplastics and nanoplastic increases with a decrease in their size. MPs and NPs due to their extremely small size and high surface-to-volume ratio can absorb organic and inorganic contaminants which are toxic to human health (Panda et al., 2022). Apart from pulmonary toxicity, MPs and NPs can have physiological effects on the human body, as demonstrated by research in which polyethylene terephthalate microplastics were introduced and affected reproduction and spontaneous activity in Drosophila (Shen et al., 2021). Studying the toxicity response will give us an idea of how the accumulation of microplastic and nanoplastic in humans causes pulmonary diseases.

2. Methods of literature survey

The review paper was written without any biases towards any author or journal. Studies and works of literature were mainly focussed from 2019. The study aimed to give a proper review focusing on the microplastic and nanoplastic in the atmosphere. Databases such as Google Scholar, PubMed, ResearchGate, and Scopus were used for obtaining the literature. The most common terms that were used for the search were: atmospheric, microplastic, nanoplastic, human exposure, pulmonary, and toxicity. For specific chapters, we examined different literature that had similarities with each other aiming toward a particular subject with different experimentation conditions to summarize the issues. Some references were taken from papers around the early 2000 s to state the prevalence of atmospheric microplastic and nanoplastic during that period. To end with, all the citations were added using Mendeley program.

3. The plastic cycle

The large-scale production and the enormous use of plastics have been dated till the 1950 s. The first synthetic plastic was seen in the 20th century. The largest market for plastics belongs to packaging. Fossil hydrocarbons are the major source from which the monomers are derived to make the plastics. The monomers responsible for the formation of plastic materials are non-biodegradable, the reason for their accumulation in the environment. According to the research conducted by Geyer et al., (Geyer et al., 2017) nanofibers plastic contains polyethylene (36%), polypropylene (21%), polyvinylchloride (12%), and other materials are usually less than 10%.

Plastic pollution has been a concern for over a decade. The plastic cycle idea was developed to better comprehend microplastic contamination throughout the environment and its compartments (D. Huang et al., 2022). The "Plastic cycle" model was created to explain the biogeochemical cycle of plastics amongst segments of the ecosystem and to represent the worldwide problem. This model focuses on big plastic waste, which includes meso and microplastic (Bianco and Passananti, 2020). The plastic cycle explains the ongoing transit of plastic between ecological components, including humans. Plastic contamination is a by-product of the Anthropocene epoch (Bank and Hansson, 2019). Humans are exposed to plastic through the air, water, and seafood. The combination of microplastics and nanoplastics with chemical compounds makes analysis more challenging.

4. Atmospheric microplastic and nanoplastic

Microplastics enter the atmosphere through several mechanical processes. Microplastic and nanoplastics can form aerosol particles through wind waves, sea spray, and even sea waves (S. Allen et al., 2020) There can also be upward movement through gas bubbles. Plastics are contained in vehicle tires, brakes, and road surfaces. Atmospheric microplastics can be obtained from these after they wear out. With heavy industrialization, the smoke emitted contains microplastics and nanoplastics. Plastics are also obtained from the dust generated from the agriculture fields during tilling or fallow (Brahney et al., 2021). With the widespread of microplastics and nanoplastics in the environment, the potential risk to the ecosystem increases. Numerous deaths of the organism have been observed in the environment due to over-exposure to microplastics (Horton and Dixon, 2018a). Fig. 1 depicts the plastic cycle and how plastic originates from different sources and circulates among the various aspects of our environment. It also gives us a summary of the plastics that originated over the years and the different sources where plastics are being consumed the most.

We can define microplastics as “synthetic solid particles or matrices with a wide range of shapes which are considerably insoluble in water with a size of less than 5 mm (Campanale et al., 2020; Y. Yao et al., 2022; X. Yao et al., 2022). Microplastics can be categorized as primary and secondary microplastics. The primary microplastics are manufactured particles for specific applications whereas the secondary microplastics are generated through fragmentation and degradation from particles such as fibers or synthetic textiles (Y. Zhang, Xu et al., 2020; Q. Zhang, Xu et al., 2020). Table 1 shows the different areas of studies conducted on microplastic for their characterization and toxicity study. Atmospheric microplastic, due to its large surface area and hydrophobicity can absorb toxic chemicals and heavy metals (Amelia et al., 2021). Microplastics have the potential to act as vectors due to their ability to transport harmful traits and exhibit carcinogenic, mutagenic, and endocrine-disrupting properties, which can pose significant health risks (Avazzadeh Samani and Meunier, 2023). In addition, microplastics can carry trace elements, including chromium, copper, manganese, and zinc (Enyoh et al., 2019).

Research is being carried out in the respective area to elucidate a proper definition of nanoplastic. There are discussions about these concerns since sampling and experimenting can be difficult due to the restricting techniques identified. (Kokalj et al., 2021). Nanoplastics must not be confused with nanoparticles. Nanoparticles are considered chemically inert substances and are present significantly everywhere posing a threat to humanity. They can be toxic to the environment and serve as vectors for pollutants and pathogens (Hojjati-Najafabadi et al., 2022). Nanoplastic is the plastic matter with a size of less than 1 µm (size $<<$ 1 µm). Both microplastics and nanoplastic differ in physical, chemical, and biological characteristics. These particles have a large surface area allowing the organic contaminants to associate with their surface (Reichel et al., 2021). Nanoplastics are highly polydisperse and heterogeneous in nature (Gigault et al., 2018). Nanoplastics are interesting to research since they serve as important precursors of information on greater particles that can impact global climate change and atmospheric chemistry. Also, atmospheric nanoplastic is playing a leading role in deteriorating human health (Bhat et al., 2023). It is believed that nanoplastic can easily enter human cells and tissues as compared to microplastic. Nanoplastics are even reported in the deep ocean and soil. The toxicity of atmospheric nanoplastic increases with the decrease in the size of the plastic particles (Trevisan et al., 2019). It

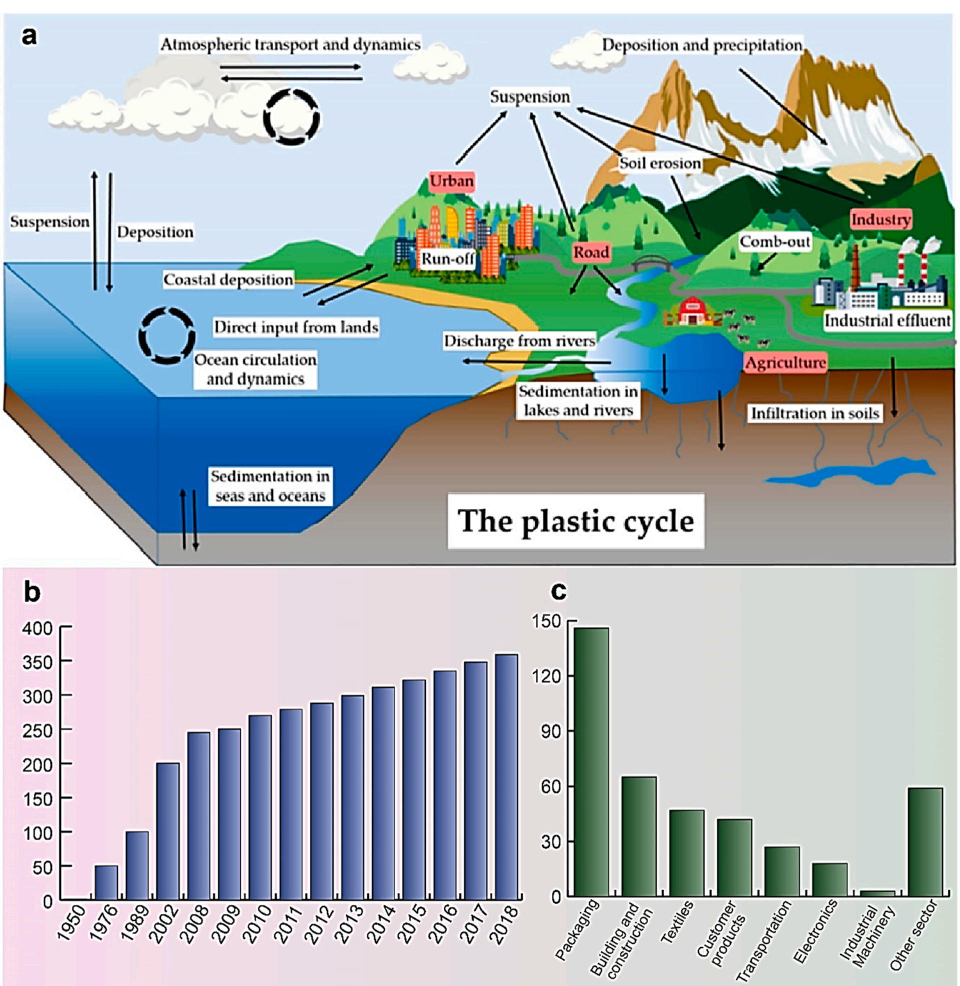

Fig. 1. **(a)** The plastic cycle model was hypothesized to explain the transport of plastic material across the various sections of environment. It represents the different sources from which the microplastic and nanoplastic are released into the atmosphere. These microplastic and nanoplastic released in the atmosphere can travel long distances and often accumulate in the environment due to improper clearance mechanism. The Plastic Cycle is a continuous process that occurs within the different parts of the environment. **(b)** The graphs represent the production of plastic over the years. The escalating use of plastic by humans have increased throughout. Plastic being a light wight particle and its durability, plastic is preferred material, and it has a wide range of applications. **(c)** Graph represent the plastic consumed in different sectors.
(Diagram taken from (Bianco and Passananti, 2020; Shanmugam et al., 2020)).

Table 1
A summary of characteristics, occurrence, and identification of microplastics (MPs) found in the form of wet and dry deposition worldwide. The MPs reported in previous studies that are mentioned here were discovered in remote and urban areas from diverse sources such as the atmosphere.

Study area	Properties of the study area	Sample types	MP abundance	MP size	Shapes	Identification & Characterization	Reference
Paris, France	Urban	Atmospheric wet and dry deposition	29–280 particles m^{-2} d^{-1} Ave: 118 particles m^{-2} d^{-1} (110 particles m^{-2} d^{-1} in urban, 53 particles m^{-2} d^{-1} in suburban)	100–500 µm 500–1000 µm 1–5 mm (50% fibres >1000 µm)	> 90% fibers ~10% fragments	Stereomicroscope + µFT-IR	(Dris et al., 2015)
Paris, France	Urban and sub-urban	Atmospheric wet and dry deposition	2.1–355.4 fibres m^{-2} d^{-1}	50–200 µm:3% 200–600 µm: 42% 600–1400 µm: ~40% (50–4850 µm)	Fibers	Stereomicroscope + µFT-IR	(Dris et al., 2015) (Dris et al., 2016)
Paris, France	Private apartments and office	Indoor and outdoor air	Outdoor: 0.3–1.5 fibers m^{-3} (1586–11,130 fiber m^{-2} d^{-1}) Indoor: 1–60 fibers m^{-3}	50–450 µm: > 80%	Fibers	Stereomicroscope + µFT-IR	(Dris et al., 2017.)☆ Author links open overlay panelRachidDris
Dongguan, China	City center	Atmospheric fallout (dry&wet deposition)	175–313 particles m^{-2} d^{-1} (Natural fibers 73%; PP 9%, PE 14%)	majority of fibers to be 200–700 µm in length (200–4200 µm)	Fibers (80%) foams Films	Stereomicroscope µ-FTIR	(L. Cai et al., 2017)
Shanghai, China	Urban	Outdoor air	1.42 ± 1.42 items m^{-3} (Maximum 4.18 items m^{-3})	23–500 µm: > 50% (23–5000 µm)	Fibers: 67% Fragment: 30% Granules: 3%	Stereomicroscope µ-FT-IR	(K.Liu et al., 2019b)
Shanghai, China	Municipal districts	Outdoor air	1.42 ± 1.42 items m^{-3} (Maximum 4.18 items m^{-3})	23.07–9554.88 µm	Fiber, fragment, granule	Stereomicroscope µ-FTIR	(Liu et al., 2019a)
Beijing, China	Urban	Urban outdoor air deposition		5–200 µm (>80%)	Fiber	SEM SEM-EDX	(Y.Li et al., 2020)
Hamburg, Germany	Urban and rural	Atmospheric deposition	275 particles m^{-2} day^{-1} (Range: 136–512 particles m^{-2} day^{-1})	< 63 µm: ~60% 63–300 µm:~30% > 300 µm: ~20% Fibers: 300–5000 µm: 68% 63–300 µm: 25% < 63 µm: 7%	Fragment: > 90% Fibres: < 10%	µ-Raman	(Klein et al., 2019)
Tehran metropolis, Iran	Urban	Street Dust	88–605 items per 30 g dry dust	Predominant: 250–500 µm (100–1000 µm)	Granule dominant:60% Fibres:35% Sphere:5%	Fluorescence microscopy SEM/ EDS	(Dehghani et al., 2017)
Asaluyeh County, Iran	Urban	Suspended dust, urban dust	0.3–1.1 item m^{-3}	100–1000 µm	Fibers Granules	Fluorescence microscopy SEM/ EDS	(Abbasi et al., 2018)
Pyrenees mountains, Europe	Atmospheric air	Atmospheric dry & wet deposition	249 fragments, 73 films and 44 fibers m^{-2} d^{-1}	predominant fiber lengths of 100–200 µm and 200–300 µm (10–5000 µm)	Fragments; 68% fibers films	Stereomicroscope µ-Raman	
Europe and Arctic	European snow Arctic snow	wet deposition	190–154 × 10^3 NL^{-1} European snow 0–14.4 × 10^3 NL^{-1} Arctic snow (N-items)	11–150 µm 11–250 µm more than 80% ≤ 25 µm (11–475 µm)	Fibers	µ-Raman FTIR imaging	(Bergmann et al., 2019)
Helsinki, Finland	Urban snow	wet deposition	700 Nm^{-1} of melted snow (marketplace) 1400 (roadside) 16,600 (residential area)	0.3–4 mm	N/A	FTIR	(Bergmann et al., 2019)
Italian Alps	Forni Glacier	Supraglacial debris	74.4 items kg of sediments (dry weight)	N/A	N/A	µ-FTIR	(Ambrosini et al., 2019)
Surabaya, Indonesia	Ambient Air	Suspended atmospheric microplastics	132.75–174.97 items m^{-3}	< 500 µm: 5% 500–1000 µm: ~13% 1000–1500 µm: ~30% 1500–2000 µm: ~14% 2000–2500 µm: ~20% 2500–3000 µm: ~7% 3000–3500 µm: ~2% 3500–4000 µm: ~2% 4000–4500 µm: ~3% 4500–5000 µm: ~4%	Fibers dominant, fragments, films, pellets	FTIR	(Syafei et al., 2019)

(continued on next page)

Table 1 (*continued*)

Study area	Properties of the study area	Sample types	MP abundance	MP size	Shapes	Identification & Characterization	Reference
Nottingham, UK	Urban	Atmospheric wet and dry deposition, urban dust	0–31 fibers m^{-2} d^{-1}	38 μm-5 mm	fibers	FTIR	(Stanton et al., 2019)
Edinburg, UK	Private home	Indoor air	N/A	N/A	Fibre	FTIR	(Catarino et al., 2018)
Trent catchment, UK	River catchment area	Wet and dry deposition	88–605 items per 30 g dry dust	Predominant: 250–500 μm (100–1000 μm)	Granule dominant:60% Fibres:35% Sphere:5%	Fluorescence microscopy SEM/ EDS	(Stanton et al., 2019)
London, UK	Urban	Atmospheric deposition	N/A	75–1080 μm	Fragment, film, granule, foam	Fluorescence microscope FTIR	(Wright et al., 2020)
West Pacific Ocean (Open Ocean)	Ocean air	Suspended atmospheric microplastics	0–1.37 (# m^{-3})	16.14–2086.69 μm 142 ± 99 μm 94 ± 33 μm 39 ± 22 μm	Fiber, fragment, granule, microbead	Stereomicroscope + μFT-IR	(K.Liu et al., 2019b)
Sakarya, Turkey	Intercity terminal/-crowded area	Outdoor air	N/A	0.05–0.5 mm	Fiber, fragment	Light microscope μ-FTIR	(Kaya et al., 2018)
Aarhus, Denmark	Apartment	Indoor air	N/A	4–398 μm	Fragment, fiber	Optical microscope μ-FTIR	(Vianello et al., 2019)
The South China Sea and East Indian Ocean	Ocean air	Suspended particles	0–3.1 (# 100 m^{-3}) 0–0.8 (# 100 m^{-3})	286–1862 μm 59–988 μm	Fibers (80%), fragments	Stereomicroscope μ-FTIR	(Wang et al., 2020)
Karimata Strait	Remote	Strait air	0–0.08 (# 100 m^{-3})	382 μm	Fibers	Stereomicroscope μ-FTIR	(Wang et al., 2020)
Pearl River Estuary	Remote	River estuary air	3–7.7 (# 100 m^{-3})	288–1118 μm	Fibers	Stereomicroscope μ-FTIR	(Wang et al., 2020)
Artic snow	Remote	wet deposition	1.76×10^3 (# L^{-1}) 1.38×10^3 (# L^{-1})	< 100 μm 65–14,000 μm	Fragments Fibers	μRaman + μFT-IR	(Wang et al., 2020)
European snow	Remote	wet deposition	24.6×10^3 (# L^{-1}) 1.43×10^3 (# L^{-1})	< 100 μm 65–14,000 μm	Fragments Fibers	μRaman + μFT-IR	(Wang et al., 2020)
Alcalá de Henares Guadalajara, Valladolid	Rural and sub-rural	PBL air	1.5 m^{-3}	0–9.8 μm	Fiber	μFT-IR	(González-Acedo et al., 2021)
Kattegat, borders the Baltic Sea, surrounded by Denmark and Sweden	Urban	Wet deposition	0.6–84.1 μg m^{-3}	< 100 μm 10–800 μm	Fragment dominated, fibers	FPA- μFT-IR	(Liu et al., 2023)

was acknowledged that smaller nanoplastics are taken up by the cells during the process of endocytosis and these nanoplastics could cause health hazards to humans, because of their high surface-to-volume ratio making them a vector for pulmonary diseases (H. Lai et al., 2022).

4.1. Sources of atmospheric microplastic and nanoplastic

Plastic use has skyrocketed because of intensive industrialisation. Daily, individuals are exposed to ambient microplastics through air conditioners, road dust particles, and even mobile sources. (Y. Zhang, Zhao et al., 2020; Q. Zhang, Zhao et al., 2020). When plastic is deposited in the environment, the fragmentation of plastic matter causes the creation of microplastics, which is followed by further degradation into nanoplastics (Materić et al., 2021). Microplastics have the capability of absorbing hydrophobic organic pollutants, organochlorinated pesticides, and polychlorinated biphenyls, and hence are considered pollutants (Can-Güven, 2021). Atmospheric microplastics are formed through the production, usage, and disposal of plastic articles and synthetic textiles. The presence of atmospheric microparticles contributes to atmospheric particulate matter (Wright et al., 2021). There are two main sources from which the nano-sized particles enter the atmosphere, these are mineral dust from wind and sea salt particles (van Pinxteren et al., 2022). There are two types of nanoplastics in the environment as in the case of microplastics. Primary nanoplastics are produced intentionally whereas secondary nanoplastics are the products of the degradation of larger plastics in the atmosphere (Pfohl et al., 2022). The different secondary sources from which we can obtain nanoplastics could be household furniture, buildings, industrial emission, wear-tear of vehicle components, and agricultural products (Facciolà et al., 2021). Microplastic pollution occurs both due to the direct release of engineered microplastic and because of the fragmentation of plastic debris which can occur because of mechanical fracture, UV radiation, and biological degradation (Andrady et al., 2022). There is also discharge from the wastewater that leads to the release of atmospheric microplastics. One of the main sources of atmospheric microplastics is fibers present in synthetic textiles. Clothing fibers are fragmented and released into the atmosphere as fine particles which are produced by photo-oxidation, namely atmospheric microparticles (Gong, Xie, 2020).

With the excessive use of face masks during the covid-19 pandemic, face masks have become a major source of nanoplastic to the environment. In a study, it was estimated more than one billion nanoplastics and microplastics were released from each of the N95 or surgical masks (Ma et al., 2021b) One of the main sources of these nanoplastics comes from the cosmetics products used daily as it consists of fine bead particles which are made from nanoplastics (Kiran et al., 2022). The increased amount of plastic accumulation in the sewage increases the degradation of plastics into fine particles which break down into nanoplastics and are comparatively difficult to remove from the sewage system (da Costa et al., 2016).

4.2. Formation of atmospheric microplastic and nanoplastic

The prevalence of microplastics in the environment has prompted study into the processes of microplastic formation. Plastic degradation contributes to one of the most common ways through which microplastics are formed. The aging of plastic is a continuous process that takes place over the years. In this process, the properties of the polymer such as its composition, physical integrity, and surface properties change over time (Chamas et al., 2020). In Photo oxidative degradation, with the presence of natural lights and UV lights, polymer degradation takes place. Here, the optical, physical, and mechanical properties of the plastic change. (Yousif et al., 2023). In Thermal degradation, the process of degradation starts with UV light and thermal light. As in the case of Ozone degradation, the exposure of the polymer to the ozone starts the degradation of plastics resulting in the formation of different carbonyl products (Manzoor et al., 2022). Plastic degradation also occurs under the presence of string ultrasonic radiations and mechanical stress. This process is called Mechano-chemical degradation. The waste polymers are often catalysed to form minute particles. These polymers are catalysed into oils and gases (Rosenboom et al., 2022) and to conclude, through biodegradation, plastic polymers are degraded by increasing the surface area or by decreasing the molecular weight. In all these degradations, the plastic polymers lose their extensibility, and shelf life, and increase their capability to attract microbes (Manzoor et al., 2022). According to research, nanoplastics are the product of long-term plastic deterioration and the disintegration of microplastics. When microplastics are subjected to UV light, weathering, and biodegradation, nanoplastics are formed (Patil et al., 2022; Tong et al., 2022). Microbes play a crucial role in the degradation of plastic particles to extremely small-sized nanoplastics (Elert et al., 2017; Paul et al.,) At the nanoscale level, sedimentation of particles is prevented and there is a random collision of particles in the water molecules, called Brownian motion (Jiao et al., 2022). Polystyrene samples taken from the different sample was observed to break down when exposed to UV radiation forming nanoplastics (Ekvall et al., 2019) Synthetic textiles are the major source of microplastic in the atmosphere. These textile polymers break down into atmosphere microplastic, which further degrades to form nanoplastic (Acharya et al., 2021; Can-Güven, 2021).

5. Characterization of microplastic and nanoplastic

5.1. Analytical methods to detect microplastics

The analysis of atmospheric microplastics is crucial for their characterization and provides details regarding their pathways and deposition. This is a three-step process: Sample collection, Sample preparation (includes pre-treatment), and Characterization (C. Wang et al., 2021; Y. Wang et al., 2021). It is of utmost importance to record the weather changes during the collection of samples to predict the correct analysis between the weather and microplastic deposition (S. Allen et al., 2019).

5.1.1. Sample collection

For the analysis of microplastic in the air, sample collection serves as the first step. In general, there are two procedures followed for the collection of samples.

5.1.2. Passive and active sampling

Passive sampling is the gathering of particles in a collection container using a glass funnel and stainless steel (X. Yao et al., 2022; Y. Yao et al., 2022). Atmospheric microplastic can fall to the ground because of gravity and meteorological conditions (G. Chen et al., 2020). We can obtain information on these atmospheric microplastics existing on the surface through passive sampling. Active sampling refers to the gathering of samples utilizing pumping equipment (Q. Zhang et al., 2020; Y. Zhang et al., 2020; Sajid, 2022). Microplastics are particulate matter subdivisions (Yu et al., 2021). Active sampling aids in the collection of particle concentration data and the assessment of microplastic exposure. Active sampling gives us information on the microplastics in the air. When compared to passive sampling, active sampling takes less time (Habibi et al., 2022b).

5.1.3. Sample preparation

The sample collected must be treated before it is further analyzed for different purposes. The three steps that are followed in the pre-treatment process of atmospheric microplastics are (i) Concentration, (ii) Purification, and (iii) Separation (C. Wang et al., 2021; Y. Wang et al., 2021). The sample containing the microparticles must be separated from the particulate matter present along with them. The following can be achieved by washing the solution with Sodium Iodide or Zinc Chloride as microparticles are lower in density (Bianco and Passananti, 2020). The fallouts that were collected using passive methods must be first filtered using different filters such as glass fibers filters, quartz fibers filters, nitrocellulose filters, and PTFE filters (Y. Huang et al., 2020). It is necessary to remove the organic matter present on the surface of the atmospheric microplastic. The samples are subjected to H_2O_2 (30% of the total volume), HNO_3, KOH, or NaOH for effective removal of the organic matter (Y. Huang et al., 2020; Lavoy and Crossman, 2021).

5.1.4. Analysis of the microplastic sample

After the sample has been collected and the pre-treatment has been done, it is further advanced for different spectrometric analyses. After the treatment, the sample must be characterized according to different colors and configurations. Different methods have been developed for the identification and characterization of microplastics. Similar methods have been used for both airborne microplastics and microplastics present in aquatic and terrestrial environments (G. Chen et al., 2020).

5.1.4.1. Visual observation. Visual sorting of samples for microplastic identification involves the removal of plastic debris and other residues that can hamper the visualization. This separation can be done by observing the sample with the naked eye or using a dissecting microscope (Hidalgo-Ruz et al., 2012) Using a stereomicroscope, we can characterize microplastic depending on size, shape, and color. Different software has been developed to analyse and quantify the microplastic sample (G. Chen et al., 2020). The visualization of the microplastics is done based on their size and configuration (He et al., 2023). Supposedly in the case of large microplastics, visual inspection is done whereas for smaller microplastics dissection microscope is preferably used. While visual identification of large microplastic is an easy and fast method, it is not reliable for smaller microplastics as visual sorting can be challenging. Hence, we rely on other methods for smaller microplastics (Shim et al., 2017; Vidal and Pasquini, 2021).

5.1.4.2. Fourier transform infrared (FTIR) spectroscopy. FTIR spectroscopy is a more precise way for the identification of microplastics and their characterization since it provides information about the chemical bonds present in the plastic sample (Shim et al., 2017). FTIR spectroscopy identifies the polymeric composition of the microplastic sample. The spectra of our target particles are compared to that present in the libraries thus discovering the polymeric composition (Zhao et al., 2022). Large microplastics can be analyzed using the FTIR surface technique known as "attenuated total reflectance" (Zvekic et al., 2022). With the successive experiment, it was found that micro-FTIR spectroscopy can be employed to identify airborne microplastic because it easily identifies microplastics even around 20 μm (Cunsolo et al., 2021; Duarte et al., 2022).

5.1.4.3. Raman spectroscopy. In general, Raman spectroscopy provides information on a compound's chemical composition. As a result, it is used as one of the microplastic identification techniques. It is an extremely dependable approach that employs monochromic laser sources (Samanta et al., 2022). The laser's wavelength can range from 500 to 800 nm. Excitation happens when a monochromatic wavelength is applied to a sample owing to the difference in frequencies. This change in frequencies is known as Raman-shift, and it is determined by the molecular structure and chemical composition of the polymers (Bai et al., 2022). When Raman spectroscopy allows for further investigation of the microplastic sample, a non-contact approach is preferred (Nava et al., 2021). It can detect plastic particles ranging in size from nanometres to micrometers, but it can also distinguish between different types of plastic particles (Lv et al., 2020). One disadvantage of Raman spectroscopy is that it is highly sensitive to additives and pigments present in the microplastic sample, which hinders the identification process (Shim et al., 2017).

5.1.4.4. Pyrolysis gas chromatography-mass spectrometry. This method measures the changes in the physical and chemical properties of the polymers. It is a thermo-analytical technique (Shim et al., 2017). Analysing the thermal degradation of the sample with Pyr-GC-MS can help us identify the composition of the microplastic sample. In the analysis technique, neither the shape, size, and color of the microplastic, nor the additives present in it have any impact on the result (G. Chen et al., 2020a). Although this identification method does not get affected by the composition, it has certain disadvantages such as (i) the particles each time must be manually added into the pyrolysis tube; (ii) because of the manual addition requirement, a lower size limitation for the analysis occurs; (iii) only one particle per run is allowed (Löder and Gerdts, 2015; Picó and Barceló, 2020).

5.2. Analysis of atmospheric nanoplastic

Nanoplastic is emerging with a lot of research being carried out for the detection of nanoplastic samples in the atmosphere. It is of utmost importance that we study the characteristics of nanoplastics to get a clear idea of the fate of nanoplastic and the different challenges related to them (Patel et al., 2021; Valsesia et al., 2021). The characterization of atmospheric nanoplastic involves the following steps: (i) pre-treatment, (ii) separation of the sample, (iii) identification, and (iv) quantification (Karimi Estahbanati et al., 2023). Although microplastic pollution has gained more importance, it is important to analyze the nanoplastic sample for being extremely small, they can create more destruction and havoc to the environment and pose a serious health risk.

5.2.1. Sample preparation

Plastics are found in diverse shapes and conformations, across the globe and are utilized to great extents which make it difficult for sampling as the risk of contamination is high (Soong et al., 2022). It is crucial to take some prevention before the sampling begins and follow it throughout the sampling process. Pre-treatment of samples is essential as nanoplastics, and natural plastics are found heterogeneously (Cerasa et al., 2021). The setup and the instruments used should be designed with non-polymers materials to reduce the risk of contamination of the sample. Both laminar airflow and air filtration systems should be equipped to avoid external contamination from airborne particles and synthetic fibers. Blank samples and recovery tests should be performed to ensure minimal contamination during the steps (H. Cai et al., 2021; Schwaferts et al., 2019).

5.2.1.1. Matrix digestion. The matrix should be removed in circumstances where the concentration of matrices is remarkably high in the samples such as in sediments, soils, wastewater, or organism. Nanoplastics should be removed from all the matrices for analysis and characterization. Many techniques are applied for the digestion of matrices. Agents used for the digestion of matrixes contain acids application such as nitric acid (65%), and hydrogen peroxide (30%), and alkaline treatment is performed using sodium peroxide (Pfeiffer and Fischer, 2020; Schrank et al., 2022) Apart from acidic and alkaline treatment, the enzymatic protocol is also followed where the enzyme is mild and non-destructive is used for the digestion process (Correia and Loeschner, 2018).

5.2.1.2. Nanoplastic preconcentration. Preconcentration of nanoplastic sample is essential as the concentration of sub-micro and nanoplastic particles are very less in the plastic debris sample. Ultracentrifugation, continuous flow centrifugation, cloud point extraction, and ultrafiltration are some of the techniques that help in improving the limit of detection (LOD) and limit of quantification (LOQ) (de Bruin et al., 2022).

Ultrafiltration in the case of seawater and drinking water uses polyethersulfone (PES) based cells to separate the nanoplastics. Apart from ultrafiltration, crossflow filtration could also be used the increase the concentration of the MPs and the NPs (Mintenig et al., 2018; Rout et al., 2022). Ultracentrifugation is especially important for sub-micron and nanoplastics at a higher centrifugal force as it helps in collecting the particles by bringing their densities closer to water (Schwaferts et al., 2019). It ensures the concentration of nanoplastic reaches the LOD by increasing the concentration of nanoplastics in the sample (Abdolahpur Monikh et al., 2019) Using density gradient ultrafiltration, we can separate the plastic particles from the high-density matrices which further helps in sample preparation (Bank Editor, 2021). Continuous flow centrifugation (CFC) can be equipped to enrich the sample with both microplastics and nanoplastics (Hildebrandt et al., 2019). Cloud Point extraction is a simple technique that is inexpensive, and non-polluting. It solubilizes the surfactant solution which is followed by phase separation to separate the analytes (Arya et al., 2019).

5.2.1.3. Separation of nanoplastics. Separation of nanoplastic according to their size is an important step for the analysis part as it would provide a uniform size distribution for the respective sample. Various approaches such as filtration, field flow fractionation (FFF), chromatography, and electrophoresis have been employed. For simple separation such as to exclude macro- and large micro-particles, membrane filters were used (Ter Halle et al., 2017).

In Field flow fractionation (FFF), particles are separated based on their size and molar mass molecules such as proteins, polymers, and nanoparticles. Here, because of the diffusivity, the particles separate from each other as in the flow the particles are retained in the flow channel at different times (Giddings, 1993; Quattrini et al., 2021). Chromatographic techniques are employed to separate the analytes using a stationary phase and have a wide range of use for the separation of nanoplastics (Jiménez-Skrzypek et al., 2021; Zhou et al., 2014). In electrophoresis, due to the electric field, the charge particles attain mobility which allows them to separate from each other. In practice, capillary electrophoresis is more efficient compared to gel electrophoresis because of its wide range of applications (Adam and Vaculovicova, 2017).

5.2.2. Identifying the nanoplastics

Identification of nanoplastic is crucial after the separation of nanoplastic because it confirms the presence of nanoplastic count in the sample. A variety of spectroscopic techniques and different microscopy techniques are employed for the identification of nanoplastics. These techniques provide information and a picture of the polymer, size, and morphology of the nanoplastics (H. Cai et al., 2021).

5.2.2.1. Spectroscopy. The chemical identification of nanoplastic is made possible due to the application of various spectroscopic techniques. Attenuated total reflectance Fourier transform infrared (ATR-FTIR) and Fourier transform infrared(FT-IR) spectroscopy have been widely used for the chemical identification of nanoplastic (H. Cai et al., 2021). FT-IR spectroscopy can be equipped for a sample where the concentration of submicron and nanoplastic are in a bulk (Ivleva et al., 2017; Pereao et al., 2020). Apart from FT-IR spectroscopy, Raman spectroscopy can also be employed as it can identify even smaller particles that come in the size range of 1 μm. Raman microspectroscopy yields a spectrum that is complementary to the FT-IR spectrum. This allows for the precise identification of nanoplastic particles (Primpke et al., 2022). Techniques such as X-Ray photoelectron spectroscopy and Mass spectroscopy can also be employed for the characterization of the nanoplastic present in the sample (Lai et al., 2021).

5.2.2.2. Microscopy. Microscopy is the most utilized technique to obtain the morphology of a sample where different types of interaction with the samples provide us with different resolutions through the different microscopic techniques (X. Chen et al., 2021). The most common type of microscopy, optical microscopy, is an essential tool for the visualization of sub-micron and nanoplastic samples. The limitation of optical microscopy is that factor where it can only visualize samples with a diffraction limit of 0.3–0.5 μm (Caputo et al., 2021; Araujo et al., n.d). In the case of electron microscopy, using an electron gun, the sample is scanned with electron beams, focusing on the electron optics. SEM and TEM are two powerful electron microscopy techniques that are widely used for the characterization of submicron and nanoplastic particles (Chou et al., 2022). A variant of SEM, known as Environmental scanning electron microscopy(ESEM), is employed to detect the environmental samples for analysis and characterization (Schwaferts et al., 2019). Cryo-EM is another microscopy technique equipped to analyze the environmental sample. This technique is widely used for the employed for the study of the agglomeration behavior of PS nanoplastic particles (L. Cai et al., 2018; Koning et al., 2022) . Another type of microscopy technique used is known as scanning probe microscopy (SPM). Here, using a sensor or sharp tips, the sample is scanned, and the detectors portray the interaction (Enyoh et al., 2021).

5.2.3. Nanoplastics quantification

Quantification of nanoplastic is generally the final step of the analysis and characterization of nanoplastics. Identifying the polymer present in the sample must be done before the quantification process. The quantification of nanoplastics is performed on three parameters: size distribution, particle concentration, and mass concentration (Molenaar et al., 2021).

5.2.3.1. Characterization of the particle by light scattering. Several ways employ laser light scattering to retrieve information about physical qualities. DLS is the most often used method for estimating the size of particles ranging from 1 nm to 3 μm. DLS has long been used to characterize the size of nanosized particles. Here, the scattering of light is proportional to the sixth power of the particle's diameter (d6). As a result, the approach can be extremely sensitive, overestimating large-sized particles. These mistakes can be caused by a variety of pollutants such as larger-sized particles from the matrix or aggregates (Clayton et al., 2016; Filipe et al., 2010).

NTA is employed to generate images and videos of image nanoparticles that are in Brownian motion. Lasers are illuminated in NTA to obtain the images. Here, first, the laser is passed through the sample, and then the scattered light is measured and projected using a camera device (Malloy and Carr, 2006). Apart from DLS, Static light scattering(SLS) is also equipped to determine the size of nanoplastics. SLS is also known as multi-angle laser light scattering (MALS). SLS measures the scattered laser lights from different angles. A monodisperse solution must be used to ensure precise information. MALS is often coupled with AF4 or CF3 and can separate the nanoplastics present in different size ranges (Caputo et al., 2021).

5.2.3.2. Concentration of mass. There are two most common methods used for the mass concentration of nanoplastic in the polymer, which is Py-GC-MS and GS-MS (Hæggernes, 2022). To estimate the mass concentration in Pyrolysis - Gas Chromatography-Mass Spectrometry (Py-GS MS), a specific plastic particle is thermally destroyed in an inert environment. After thermal decomposition, the pyrolysis fragments are isolated using gas chromatography and subsequently analyzed using mass spectrometry (Yakovenko et al., 2020; Dümichen et al., n.d). Fig. 2 illustrates the systematic approach developed for the characterization of atmospheric microplastic and nanoplastic.

5.2.3.3. Small angle scattering. The small angle scattering method is a versatile and powerful technique and one of the most reliable methods for the detection of nanoparticles which can also provide morphology, and arrangement of submicron division (Londoño et al., 2018). SAXS has no particle size constraints and may be employed in a variety of integrated ways to reveal critical insights regarding folding-unfolding, flexible area movement, conformational changes, and complex creation that would otherwise be impossible to get (Lombardo et al., 2020). The scattering of X-rays or neutrons by the sample is the mechanism of small angle scattering (SAS) for detecting and characterising microplastic and nanoplastic. When the sample is subjected to X-rays or neutrons, the particles within the sample scatter the radiation, resulting in a measurable scattering pattern (Jakubauskas et al., 2021). SAS reports on the size, surface area of the particles in the sample, as well as their degree of aggregation.

6. Distribution of atmospheric microplastic and nanoplastic

6.1. Distribution and transportation

The improper disposal of plastic contaminants in the environment, from both domestic and industrial use, contributes to the main source of plastic in the environment (Zhang, Xu, 2022). Apart from the main sources of microplastics such as cities, agriculture, and industry, microplastics are discovered in remote areas and mountain regions (K. Liu et al., 2019b). This evidence makes it crucial for the study of the transport and distribution of microplastics. Microplastic and nanoplastic should be found in sites where the population is high. These plastics have an extremely high surface area and hydrophobicity, which allows them to sorb organic components (Cao et al., 2022). The distribution of atmospheric microplastics depends on air currents, winds, and particle density (Prata, 2018).

Samples were collected from three places namely, Kusatsu, Japan; Da Nang, Vietnam; and Kathmandu, Nepal to study the distribution and characteristics of MPs and NPs in the atmosphere. From the analysis, it was concluded that the hit quality of plastics depends on the size and the polymer types. There were different compositions of MPs based on area. The major compositions were polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl stearate (PVS), etc. These compositions were found in different concentrations of different plastic found in the atmosphere (Yukioka et al., 2020). There is a widespread of microplastic and nanoplastic which originates from vehicle tires, bands, hoses, shoe soles, rubber products, or electrical insulations. The presence of MPs and NPs was distinctly observed in road dust (Kiran et al., 2022). Littering on the roads and outdoors contribute to the presence of extensive plastic. The main composition of road dust was fibers, fragments, spherules, and films. The wind flow helped the particles transport across. (Munyaneza et al., 2022).

Seminal work on the transport of microplastic suggested that microplastics are present in dust particles and atmospheric deposition is a component mechanism of transport (D. Allen et al., 2022). Atmospheric microplastic's presence is diverse, and their transport depends on various natural as well as physicochemical properties of those microplastics (C. C. Wang et al., 2021; Y. Wang et al., 2021). Atmospheric microplastics are transported by air from both regional and faraway places (Hoellein and Rochman, 2021). Understanding the air transport of microplastics and nanoplastics is critical because it can help minimize plastic pollution and its exposure to humans.

Microplastics are extremely light and hence have the potential to be carried by air current leading to means of particulate transfer. The density and shape of microplastics play a crucial role in the transport of

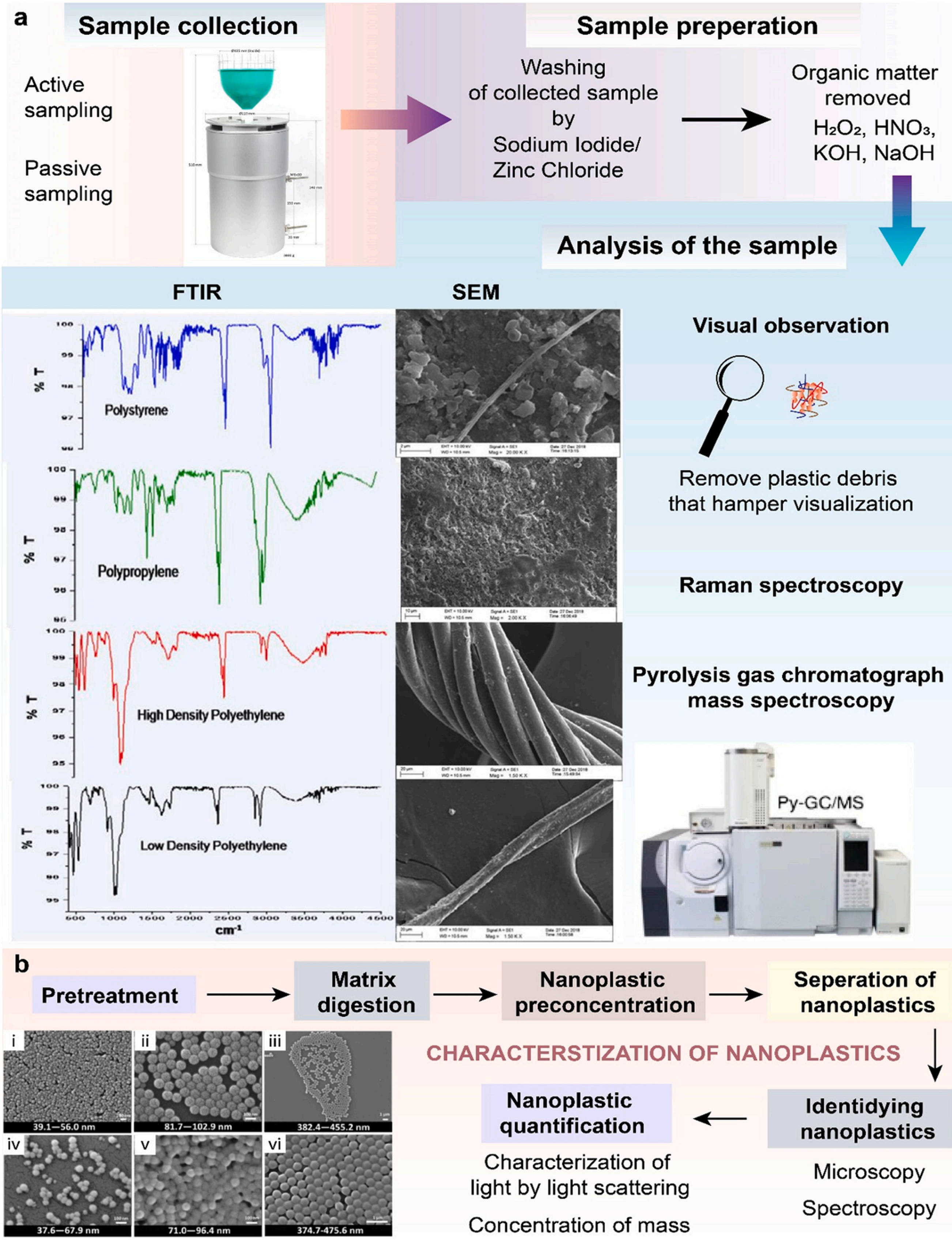

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Fig. 2. (a)The diagram represents the methodical manner for the collection and the analysis of sample to characterize the presence of microplastic in the atmosphere. After the collection of samples, it is important for the sample to be prepared as impurities must be removed and the sample must be concentrated. There are different ways for the analysis of sample including, visual observations, FTIR, SEM, Raman Spectroscopy and Pyrolysis gas chromatograph mass spectroscopy. These different methods for analysis have their unique importance in the characterization of the different microplastic present in the sample. (b) Characterization of nanoplastic is important because it poses a severe threat to then humans due to their small size and shape. The diagram illustrates the systematic order for the analysis of nanoplastic in the atmosphere. The preconcentration of nanoplastic is a crucial step in the process as it helps in the separation and identification of nanoplastic in the atmosphere. The various spectroscopic methods available helps in the identification of the various components present in the sample.
(Concept generated from (Cai et al., 2021; Schwaferts et al., 2019)).

microplastics (Horton and Dixon, 2018b). The transportation and deposition of microplastics and nanoplastics depend on factors such as vertical pollution concentration gradient, meteorological conditions, population density, human activities, urban topography, thermal cycling, local elevation, and even geographical environment (Y. Huang et al., 2021). Atmospheric transport of microplastics and nanoplastics is the widest means of transportation as there are fewer environmental constraints. The movement of MPs and NPs in the air is greatly influenced by the direction of air movement as compared to unidirectional flow (Horton and Dixon, 2017). The term “Trojan-Horse effect” was introduced to the study of the transportation of hazardous chemicals and contaminants through the micro and nanoplastic in the environment. Compared to the other means of transport, the transportation of microplastic and nanoplastics through the atmosphere is flexible as they can divert in many directions thus exposing major threats (Y. Zhang and Xu, 2020; Q. Zhang and Xu, 2020).

6.2. Sources of human exposure

Humans are exposed to microplastics and nanoplastic through a variety of sources, which can range from packaged drinking water, cosmetics, table salt, consumption of seafood, and indoor and outdoor dust, to inhalation from flocking, the textile industry, and polyvinyl chloride manufacturing industry. With the outburst of covid-19 cases, masks have been a constant source of MPs and NPs. Apart from these major sources, emissions due to traffic, burnt tires, and weathering of plastic polymers could also be sources of microplastic and nanoplastic.

6.2.1. Flocking and polyvinyl chloride

Flock workers are constantly inhaling airborne microplastics despite the source whether they are nylon, polyethylene, or polypropylene. A study conducted by the National Institute for Occupational Safety and Health (NIOSH), concluded that serious health hazards possess to the workers employed at the nylon flock processing plants (Burkhart et al., 1999). There were cases of interstitial lung diseases among the workers in the nylon processing industry (Carlier et al., 2022). In the experiment conducted by Porter, it was seen that due to the prolonged exposure to the nylon dust, there was damage in the cells resulting in changes in the cell shape and a significant increase in breathing rate (Porter et al., 1999).

Polyvinyl chloride (PVC) is mainly produced from the polymerization of vinyl chloride monomer. A clear difference has been observed between synthetic materials and PVC(Zarus et al., 2021). A study has shown severe lung and liver damage by the workers inhaling the PVC -MP produced (Vinyl Chloride - Cancer-Causing Substances - NCI 2022.). The high concentration of polyvinyl chloride dust and the particle size was attributed to the increased number of lung cancer cases (Bentrad, 2022; Mastrangelo et al., 2003). The size of the PVC dust plays a crucial role in exposure to humans. It was concluded that the smaller the size of the particles, the more exposure. (Q. Chen et al., 2022; X. Chen et al., 2022).

6.2.2. Synthetic textiles

Microplastic from the textile industry is one of the main sources of contaminants in the environment. It was estimated in 2016 that around 60 million tons of synthetic textiles were produced, and production per year increased by 6% (Balasaraswathi and Rathinamoorthy, 2022). The synthetic fibers produced from the synthetic textiles could cause acute respiratory effects along with colorectal cancer (Kristanti et al., 2022).

A study was conducted including 309 female and 92 male workers employed in a textile factory to study the respiratory findings in these workers. They recorded chronic respiratory symptoms and occupational asthma among the workers. Cough, dryness of the nose, dryness of the throat, and eye irritation were some of the major symptoms. There was also a serious reduction in the forced vital capacity (FVC) and forced expiratory volume (FEF) (Valic and Zuskin, 1977; Zuskin et al., 1998).

6.2.3. Diet intake

The presence of microplastic and nanoplastic in the freshwater ecosystem is the most prevalent contributor to marine ecosystem pollution (Uddin et al., 2022). Daily, drinking water serves as a constant source of microplastic to the human body. Plastic bottles contribute to the major source of microplastic and nanoplastic in the human body. There is a huge amount presence of microplastic in the table salt consumed by humans (Wu et al., 2022). Seafood is a major source of microplastics and is frequently used in studies to estimate human ingestion of microplastics. The quantity of microplastic exposed to individuals through different seafood varies depending on the constitution of microplastic in each organism. (Makhdoumi et al., 2022; Mortensen et al., 2021). Several kinds of literature report the presence of microplastic in various beverages such as sugar, honey, beer, and milk (Diaz-Basantes et al., 2020; Shruti et al., 2021). Since mussels are filter feeders, they unwittingly consume NMPs with their food. They are thus a potential vector of NMPs as a protein source for humans. Mussel tissues included a variety of polymer kinds with varying shapes and sizes. (Ramsperger et al., 2023).

6.2.4. COVID-19 masks

With the onset of the pandemic, the wear of surgical masks has increased rapidly. Not only face masks but also face wipes for sanitization purposes have been used tremendously. With the increasing use of these masks, they serve to be a source of microplastic and nanoplastic. The face wipes and the Covid-19 masks are made up of plastic fibers (Kutralam-Muniasamy et al., 2022). The plastic polymers present in these face masks can be polypropylene (PP), polystyrene, polycarbonate, polyethylene, and polyester. These fibers can degrade and eventually form microplastics and nanoplastics. These disrupted face masks and wipes can circulate billions of microplastic fibers. These fibers usually go unnoticed but are the new challenge regarding microplastic pollution (Hu et al., 2022).

An experiment was performed to quantify the number of atmospheric microplastic and nanoplastic releases into the atmosphere because of these face masks. Plastic particles ranging from 5 nm to 600 nm were found in the analysis. There were reports from the Scanning Electron microscope that each mask releases $1.6 - 3.8\times10^9$ nanoplastics and $1.3 - 4.4\times10^3$ microplastics. It must be noted that N95 masks released a greater number of plastic debris and especially nanoplastics than surgical masks (Ma et al., 2021a).

7. Pulmonary impact

7.1. Routes of human exposure

7.1.1. Inhalation

Inhalation of microplastic and nanoplastic is proved to be one of the major pathways of these plastic particles into the human body. Aerodynamic equivalent diameter(AED) is the determining factor for the inhalation of microplastic as compared to geometrical size. This is because the aerodynamic equivalent diameter is based on the shape, surface structure, and density of the plastic particle (Reponen et al., 2001; Wieland et al., 2022). Microplastic with AED less than 10 μm can penetrate deeper parts of the respiratory tract. Both indoor and outdoor air has reported a large concentration of microplastic. A study was performed through meta-analysis in the American population, and it was concluded that 170 MPs were inhaled by the adult male population and 132 MPs were inhaled by the female population per day (Ageel et al., 2022).

Synthetic clothes, shedding from building materials, corrosions from plastic products, waste incineration, and landfilling were discovered to be some sources of microplastics in indoor and outdoor air (Bhat et al., 2023). From the various experimental data, it was documented that the concentration of microplastics in indoor air was more as compared to outdoor air (Kacprzak and Tijing, 2022; Perera et al., 2022). Apart from the different sources mentioned above, the wearing of masks worn during the covid times can increase the risk of microplastic inhalation during this pandemic. An interesting study reported that exposure to microplastics in toddlers was more compared to that in adults.

7.1.2. Ingestion

A good amount of microplastics get ingested into the human body without our knowledge. Microplastic-contaminated food and water sources are the main source of microplastic exposure in humans. From an analysis done by Cox et al., which was made to study the American diet and lifestyle, it was concluded that the average annual consumption of microplastics was around 39000–52000 particles per person. His study noted microplastic ingestion through diet by American male and female adults, as well as male and female youngsters. The estimated values were 142,113,126 and 106 particles per day, respectively. (Cox et al., 2019; Rahman et al., 2021). The microplastic concentration present in groundwater was much less compared to tap and bottled water. After proper examination, it was concluded that 80% of the microplastic present in bottled water was PET and PP of size about 5–20 μm (Gambino et al., 2022). The concentration of microplastics varies in different food components like fish, table salt, sugar, honey, milk, and beer. A recent study established that microplastics from polystyrene packing surfaces of meat products account for 4–18.7 MPs per kg of packed meat and which cannot be washed away from rinsing (Kedzierski et al., 2020). It is important to have proper research on the source of the release of microplastics from plastic packaging to food and beverages (Ageel et al., 2022).

7.1.3. Dermal contact

There is a wide range of applications of microplastic in the cosmetic industry and with the increasing use of cosmetics in our everyday lives, our exposure to microplastics profusely increases (Ageel et al., 2022). The Federal Institute of Risk Assessment evaluated the risk associated with a microplastic concentration in hand cleansers, face washes, masks, and toothpaste. It was concluded that the microplastics used in such products could result in skin damage due to local inflammation and cytotoxicity (Rahman et al., 2021). The microplastics contained in cosmetics that are below 100 nm can easily penetrate the epithelial barrier of our skin. Direct contact with microplastics can occur between the skin exfoliator and the cleanser (Ramsperger et al., 2023). Although dermal contact with fine plastic particles would not cause any serious health risks, one should be careful enough with what the skin gets exposed to. Studies showed the presence of microplastics and nanoplastics on the face and skin of the human body. When the exposure of these particles increases, because of their small size, they can cross the skin layer leading to different reactions in the body (Abbasi, 2021; Biswas et al., 2022).

7.2. Protein corona formation

Nanoplastics can absorb different macromolecules onto their surfaces, resulting in the formation of protein coronas, which can alter the physiochemical characteristics and environmental destiny of the plastic particles. These changes in characteristics have the potential to enhance the toxicity of nanoplastics (Panda, Kumari et al., 2022; Yu et al., 2022). The nature of the protein corona depends on the intrinsic properties of nanoparticles, shape, chemical composition, and surface chemistry (Akhter et al., 2021; Tenzer et al., 2013). Protein corona holds a significant influence on a variety of biological activities which include drug release, drug targeting, cell recognition, biodistribution, cellular uptake, and therapeutic efficacy (Pearson et al., 2014). Numerous attempts have been made to subsequently modify the nanoplastic structure to counteract protein adsorption. Fluorescent labelling can be employed to verify the presence of protein corona (Panda et al., 2021). Protein corona complexes can be soft, hard, or interfacial depending on their binding, affinity, and dissociation rate. The formation of three complexes also depends on the tightness of bonding, bounding time sequence and their distance to the nanoplastic surface (N. Liu et al., 2020). The soft protein corona-Nanoplastic complex is more unstable than the hard protein corona-Nanoplastic complex.

Ji et al.,(Ji et al., 2021) conducted an experiment in which polystyrene Benzopyrene (PS@Bap) nanoplastics were synthesized to evaluate their interaction with mucin and subsequent toxicity. The mucin corona was shown to be stably adsorbed on PS@Bap during the early stages of endocytosis before being eliminated throughout the lysosomal transport and maturation process. It will further delay PS@Bap intracellular trafficking and the progression of Bap detached from PS, while increasing PS@Bap uptake and decreasing PS@Bap cytotoxicity as measured by cell viability, reactive oxygen species generation, mitochondrial function impairment, and further cell apoptosis. In another study by (Du et al., 2023) investigated the cellular absorption and stability of protein corona produced on photo-aged polystyrene nanoplastics in human bronchoalveolar lavage fluid (BALF). The study not only revealed that environmental conditions influenced the stability of the protein corona produced on nanoplastic surfaces, but it also claimed that ageing of the material enhanced polystyrene nanoplastic absorption by lung macrophages, which causes toxicity.

7.3. Toxicity

The increase in microplastics and nanoplastics in the atmosphere is an emerging concern because of the increased risk to the human body causing toxicity in humans and other organisms. Upon inhalation, microplastics and nanoplastics can either, get cleared through the mucociliary clearance mechanism or they can translocate across the pleura and get absorbed by the epithelial cells (Banerjee and Shelver, 2021). Microplastics and nanoplastics are seen to cause inflammation, obstruction, and accumulation in the organs (Rahman et al., 2021). In addition to the chemical composition of these microplastics and nanoplastics, the size of these plastic particles plays a crucial role in the toxicity induced (H. Lai et al., 2022; Rubio et al., 2020). It was anticipated that during the polymerization process, the reactive oxygen species (ROS) contained in these microplastics and nanoplastics get released (Duan et al., 2022). Fig. 3 represents the different sources through which humans are exposed to microplastics and nanoplastics daily and how these particles generate toxicity in the cells.

MPs/NPs have the potential to affect the toxicity and bioavailability of pollutants by acting as carriers of bacteria, viruses, or pollutants (such

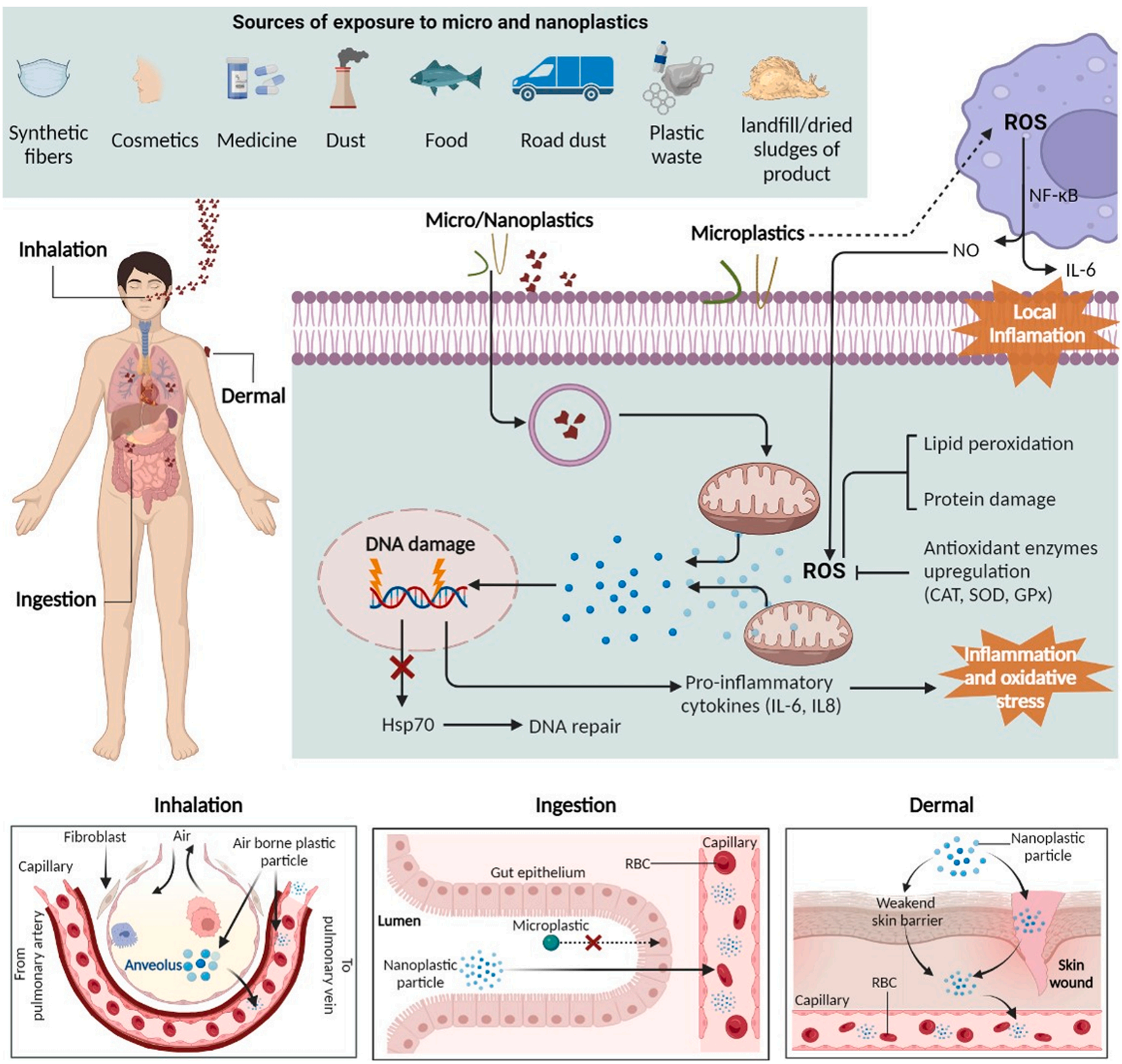

Fig. 3. A schematic illustration showing the different sources of microplastics and nanoplastic to which humans are exposed daily. The ubiquitous presence of microplastic and nanoplastic in the atmosphere results in the constant exposure of microplastic and nanoplastic to the environment. There exist three main routes though which humans are exposed to microplastics and nanoplastic, namely, inhalation, ingestion and through dermal contact. The diagram also represents the cellular toxicity due to the presence of microplastic and nanoplastics. The endocytosis of microplastic and nanoplastic leads to the translocation of MPs/NPs across the epithelial membrane and it can reach various organs in the body. Long term accumulation of these plastic particles leads to cell apoptosis and can affect the cell viability. A major production of ROS can be observed which in turns affects the cellular pathways resulting in inflammation and release of various cytokines. A significant amount of DNA damage can also be seen due to the overexposure of MPs/NPs.
(Concept generated from (Amato-Lourenço et al., 2020; Prata et al., 2020; Shi et al., 2021; Stapleton, 2021)).

as heavy metals and hazardous organic compounds) (Q. Zhang et al., 2022). Human consumption of microplastics can be through different ways such as different food sources, plastic bags, drinking water, and inhalation. MPs and NPs have been reportedly seen in human stool (Yong et al., 2020). Due to the accumulation of microplastics in the tissues, there have been reported severe health risks such as physical injury, immune responses, oxidative stress, neurotoxic responses, metabolic disorders, and genotoxicity (Deng et al., 2017). Different experiments were performed to understand the toxicity of microplastics and nanoplastic (Table 2).

7.3.1. *Translocation*

It is important to understand the translocation of microplastic and nanoplastic in the human body after inhalation. Overexposure to these atmospheric plastic particles and failed clearance mechanism leads to the accumulation and deposition of microplastic and nanoplastic (Yee et al., 2021). It was estimated that atmospheric microplastic could persist in the lung fluid for a total of 180 days without any change in its surface area (Cao et al., 2022) The transport of these atmospheric microplastics and nanoplastics depends on their hydrophobicity, size, and surface charge (Kumar et al., 2023). Microplastics and nanoplastics were traced in the intracellular space of pulmonary epithelial and

Table 2
A summary of properties, tissue accumulation, cellular uptake, and notable toxicological findings associated with microplastics (MPs) and nanoplastics (NPs) in living systems like Human cells, mice, and Fishes.

Living systems affected by Microplastics and Nanoplastics	Name of the system	Properties Microplastics and Nanoplastics Used	Tissue Accumulation/ Invasion or Cellular Uptake	Findings on Toxicological, Pathological, or Behavioural Observations	Reference
Human cells	Human Peripheral blood monocytic cells (PBMCs) U937 (human monocytic cell line) THP-1 (human monocytic cell line) DMBM-2 (mouse macrophage cell line)	Carboxylated polystyrene (PS) NPs (20–1000 nm)	Passive uptake- 20 nm NPs Active and passive uptake- larger NPs	20 nm NPs- Induced cytotoxicity to U937 and THP-1 cells, IL-8 secretion, and oxidative burst in monocytes. 500 and 1000 nm NPs- Induced IL-6 and IL-8 secretion in monocytes, macrophages, chemotaxis, and oxidative burst of granulocytes. 20 nm NPs decreased phagocytosis of bacteria by DMBM-2 at lower concentrations with minimal cytotoxicity, whereas 500 and 1000 nm NPs promoted phagocytosis of bacteria by DMBM-2.	(Prietl et al., 2014)
	A549 (Human alveolar type II epithelial cell line)	PS nanoparticles (25 and 70 nm)	Cellular uptake of NPs	Viability was reduced, and cell cycle arrest was induced. Transcripts for NF-B and several pro-inflammatory cytokines are upregulated. Changes in the expression of proteins involved in the cell cycle and apoptosis regulation.	(Xu et al., 2019)
	Human dermal fibroblasts Peripheral blood mononuclear cells (PBMCs) HMC-1 (human mast cell line 1) RBL-2H3 (human basophilic leukemia cell line) RAW 264.7 (mouse macrophage cell line)	Polypropylene (PP) particles (~20 μm and 25–200 μm)	N/A	At high doses of the smaller size 20 μm particles, there is some cytotoxicity. PBMCs have a low level of induction of proinflammatory cytokines IL-6 and TNF-α. HMC-1 and RBL-2H3 cells produced more histamine. Some ROS induction was observed at high doses of the smaller size 20 μm particles.	(Hwang et al., 2019)
	BEAS-2B (Human bronchial epithelial cells)	PS nanoparticles	Cellular uptake of NPs	Only at very high doses are PS NPs cytotoxic. Autophagic and endoplasmic reticulum (ER) stress-related metabolic alterations were discovered using metabolomics analysis.	(Lim et al., 2019)
	Hs27 (Human fibroblasts)	PS nanoparticles (100 nm at 5–75 μg/ml)	N/A	ROS production is stimulated. The cytokinesis-block micronucleus (CBMN) assay measures genotoxic stress and DNA damage.	(Poma et al., 2019)
	Caco-2 THP-1 monocytic line	PS microparticles (1, 4, and 10 μm)	Cellular uptake of MPs	There was no obvious reduction of cell viability, except at extremely high doses of 1 μm MPs. The ingestion of MPs did not affect macrophage differentiation or polarization.	(Stock et al., 2019)
	Caco-2 Polyethylene terephthalate (PET)	NPs (laser-ablated, ca. 100 nm)	Cellular uptake of NPs	There is no evidence of toxicity. Internalization of nano-PET into endo-lysosomal compartments. Nano-PET exhibits a significant proclivity for crossing the intestinal barrier in the Caco-2 model.	(Magrì et al., 2018)
Fish	Crucian Carp (*Carassius carassius*)	24 and 27 nm polystyrene (PS) NPs	Trophic transfer through an aquatic food chain to fish from algae through *Daphnia*	Feeding problems and shoaling behavior. Metabolic defects. Changes in the appearance and weight of the brain.	(Mattsson et al., 2015)
	Medaka (*Oryzias melastigma*)	PS microspheres (10–11 μm, $0.758 \pm 0.217 \times 10^5$ particles/L)	MPs were observed in the digestive tracts of larvae and dissected adult intestines.	Increased mortality, as well as a drop in average lengths and weights of larvae and adults. Female egg output has decreased significantly.	(Cong et al., 2019)
	Crucian Carp (*Carassius carassius*)	Amino-modified positively charged PS NPs(52 nm)	NPs found in the fish brain (trophic transfer to fish from algae through *Daphnia*.)	Changes in the feeding schedule. Morphological changes in the brain (gyri sizes).	(Mattsson et al., 2017)
	Fathead minnow (*Pimephales promelas*)	PS (41.0 nm) and polycarbonate (PC) (158.7 nm) NPs	Neutrophil phagocytosis of PS NPs.	Increases in the innate immune response are significant (in terms of degranulation of primary granules and neutrophil extracellular trap release).	(Greven et al., 2016)
	Zebrafish (*Danio rerio*)	PS NPs (50 nm, 1 mg/L)	Accumulation in larvae.	The larvae's movement is hampered. Acetylcholinesterase activity was	(Chen et al., 2017)

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Table 2 (*continued*)

Living systems affected by Microplastics and Nanoplastics	Name of the system	Properties Microplastics and Nanoplastics Used	Tissue Accumulation/ Invasion or Cellular Uptake	Findings on Toxicological, Pathological, or Behavioural Observations	Reference
				inhibited. Cytoskeletal markers are upregulated.	
	Zebrafish (*Danio rerio*)	Virgin PS MP beads (5 μm) + cadmium (Cd)	N/A	Cd levels in the liver, intestines, and gills have increased. Cd toxicity has increased. The combined exposure resulted in tissue oxidative damage and inflammation.	(S. Lu et al., 2018; L. Lu et al., 2018)
	Zebrafish (*Danio rerio*)	PS NPs (mean 51 nm)	Embryos and larvae absorb the nanoparticles. Throughout development, it migrated to the gastrointestinal tract, gallbladder, liver, pancreas, heart, and brain.	Reduced heart rate Changes in larval behavior (swimming hypoactivity in exposed larvae). PS nanoparticle transfer from mother to child. Swim bladder inflation is delayed or defective in exposed F1 larvae.	(Pitt, Kozal et al., 2018; Pitt, Trevisan et al., 2018)
	Zebrafish (*Danio rerio*)	PS microspheres (70 nm, 5 μm, and 20 μm, 20 mg/L)	Accumulation in gills, gut, and liver (Only the 5 μm particles)	Hepatic histopathology (signs of inflammation and lipid accumulation). Antioxidant stress enzymes are increased. Changes in metabolomics profile of the liver.	(Lu et al., 2016)
	Zebrafish (*Danio rerio*)	PS MPs (10–45 μm, 20 mg/L)	Ingested MPs observed in larvae gut.	After two days of exposure, zebrafish larvae showed significant changes in their transcriptome. Genes important in brain development and function are downregulated. Genes linked to metabolism are changing.	(LeMoine et al., 2018)
	Zebrafish (*Danio rerio*)	PS MPs beads (5-μm beads; 50 μg/L and 500 μg/L)	Accumulation of MPs in zebrafish gut.	Inflammation and oxidative stress in the gut of adult zebrafish. The metabolome and microbiota of adult zebrafish guts have changed significantly. Oxidative stress, inflammation, and lipid metabolism were all linked to changes.	(Qiao et al., 2019)
	Zebrafish (*Danio rerio*)	Polyethylene (PE) MPs (10–600 μm at 2 mg/L)	MPs accumulation in gill and Intestine.	MP feeding of adult fish causes abnormal behaviors such as erratic movement, convulsions, and morphological abnormalities. Intestinal Cytochrome P450 gene (cyp1a) and hepatic vitellogenin1 upregulation.	(Mak et al., 2023)
	Zebrafish (*Danio rerio*)	PS NPs-25 nm	NP accumulation in the intestine, pancreas, and gallbladder of exposed larvae.	Glucose homeostasis is disrupted. Cortisol levels rise, causing hyperactivity.	(Brun et al., 2019)
	Oryzias latipes	PS MPs, 10 μm	MP accumulation in gill and gut.	Egg number reduces in adult females in a dose-dependent manner. Swollen enterocytes and changes in the buccal cavity, head kidney, and spleen histologically.	(Zhu et al., 2020)
Mouse	N/A	PS microspheres 5 μm and 20, 0.01–0.5 mg/day	Accumulation in the gut, liver, and kidney.	Inflammation and fat build-up in the liver are visible. Changed lipid profile and energy metabolic impairment (lower ATP levels). Oxidative stress markers in the liver increased, but acetylcholinesterase reduced.	(Deng et al., 2017)
		PS and PE beads (0.5–1.0 μm) + organophosphorus flame retardants (OPFRs)	PS and PE beads detectable in the gut and liver.	Compared to OFPR alone, MPs increased OPFR-induced oxidative stress, neurotoxicity, and metabolic disturbance.	(Deng et al., 2018)
		PS particles (5 μm, 100 and 1000 μg/L)	Accumulation in the mouse gut.	Intestinal barrier dysfunction was the cause. Dysbiosis of the intestinal microbiota. Bile acid metabolism problem induced.	(Jin et al., 2019)
		PS particles (5 and 20 μm)	Accumulation in the mouse gut, liver, and kidney.	Organ-bioaccumulation and biomarker responses toxicokinetic/toxicodynamic (TBTK/TD) modeling. Changes in oxidative stress indicators and energy and lipid metabolism markers.	(Yang et al., 2019)
		PS MPs (0.5 and 5 μm)	N/A	Changes in serum and liver metabolic indicators were seen after MP exposure. The fatty acid metabolic disorder was caused by maternal MPs exposure in the F1 offspring.	(Luo et al., 2019)
Mice	N/A	PS-MPs(0.5 mg/L)	N/A	Testicular developmental toxicity injury through the Hippo signaling pathway	(Zhao et al., 2023)
Juvenile cod	Atlantic cod (*Gadus morhua*)	Polyethylene (PE) microplastics (150–300 μm)	Accumulates in liver and muscle tissues	PCB-126 adsorption to PE microplastics increases detoxifying enzyme activity in the liver. In extremely high	(Bogevik et al., 2023)

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Table 2 (*continued*)

Living systems affected by Microplastics and Nanoplastics	Name of the system	Properties Microplastics and Nanoplastics Used	Tissue Accumulation/ Invasion or Cellular Uptake	Findings on Toxicological, Pathological, or Behavioural Observations	Reference
				concentrations, MP causes decreased nutritional absorption, decreased appetite, and gastrointestinal obstruction.	

mesothelial cells. Increased cellular permeability was detected in cases where heterogenous polystyrene microplastic and nanoplastic were exposed orally. In this experiment, the mice were exposed to both microplastic and nanoplastic. Several assays that have been conducted, provided a clear demonstration that this micro-and nanoplastic could cross the alveolar epithelial barrier (Donkers et al., 2022).

In a study conducted by Fournier and co-workers, they observed the translocation of nanoplastics from the maternal lungs into the fetal tissues. Nano polystyrene particles were observed across the fetal placenta, liver, and lungs. The observation was confirmed by the presence of fluorescence in the placental tissue which implied that these plastic particles could cross the placental barrier. Another study also proves the transfer of MPs and NPs from mother to fetal cells confirmed by the fish model. Here, the fish were fed with MPs and NPs which caused abnormalities in the movement of adults and larvae which showed a difference in the reproduction pattern (Yong et al., 2020). It was observed that nanoplastics entered the cell lines through active energy pathways (Shi et al., 2022).

The inhaled nanoplastics can translocate to the brain and cause neurogenerative diseases such as Alzheimer's disease, and even primary brain tumors (Calderón-Garcidueñas and Ayala, 2022). The transfer of nanoparticles to the brain is possible through the direct disruption of the neuronal cell membranes (Win-Shwe and Fujimaki, 2011). Nanoplastics were observed in the spleen which was translocated by the lymphatic system to the bloodstream. Pulmonary hypertension and chemokine response increased in parts where the microplastics and nanoplastics got translocated (Prata, 2018).

7.3.2. *Cytotoxicity*

A549 cells act as a perfect model for human alveolar tissues. In an experiment reviewed by Huang et al, it was found that microplastics get accumulated in the cytoplasm. The accumulation resulted in the internalization of the polystyrene- nanoplastics which can cause some visible damage to the lungs (L. Liu et al., 2021).

In addition to microplastics, polystyrene nanoplastic of different sizes was found to accumulate in the cytoplasm of A549 cells. MTS assay was performed to measure the effect of nanoplastic on cell viability. Nanoplastics with a diameter of 25 nm reported significant toxicity on A549 cells with increased cell viability. There was an observation made on cell apoptosis as with the increase in the concentration of polystyrene nanoplastics in the cell, the apoptotic cell percentage increased. Using flow cytometry, it was concluded that there was an alteration in the cell cycles. The S phase of the cell cycle got arrested as the nanoplastic amounts increased in the cell (Xu et al., 2019).

In a similar experiment conducted by Q. Shi, the presence of polystyrene nanoplastics in the cytoplasm was detected (Shi et al., 2022). Hence, we conclude from the above that the major pathways for the uptake of microplastics and nanoplastic are endocytosis. The cytotoxicity due to the uptake of microplastics and nanoplastics was possible above a particular concentration. The cytotoxicity could cause cell damage, cell viability, and even alternation in the membrane function. Due to the endocytosis of microplastics and nanoplastics, the particles can easily reach the cytosol where it gets to react with the organelles disrupting the cellular processes (Hua, Wang, 2022). Due to the exposure to polymer dust like PVC, there is damage in the cell. This was demonstrated in rat alveolar and peritoneal macrophages culture (Ng et al., 1991). There was a disruption in the integrity of the mitochondrial membrane when there was over-exposure of nanoplastics as swollen mitochondria were observed. Nanoplastics are often responsible for autophagy, and they can interfere the energy metabolism (Lim et al., 2019).

7.3.3. *Oxidative stress*

Microplastics release oxidizing chemicals which are absorbed on their surface and the reactive oxygen radicals are released from the host. These free radicals could increase enormously when they interact with UV lights or any reactive metals (Rahman et al., 2021). In a study on *C. elegans*, along with ROS production, lipofuscin accumulation was examined where accumulation is a marker of cellular damage. It was also concluded that a low concentration of microplastics did not affect toxicity in *C. elegans* but only for a short duration (Y. Yu et al., 2020). Ingestion of nanoplastic into the cells has been shown to generate reactive oxidative species (ROS) in both mammalian cell lines and invertebrates. Toxicity from carbon nanotubes has also been established. The free radicals will lead to damage to lipids, nucleic acids, and proteins at the site of the nanoplastics deposition (Win-Shwe and Fujimaki, 2011).

Western blot assay was employed to study the ROS generation and HO-1 expression in BEAS-2B cells. An increase in ROS accumulation was observed with an increase in the graph of the protein levels of HO-1 in the BEAS-2B cells. Due to the immense ROS production by the cell, the antioxidant enzyme capacity of the cell was overcome. This resulted in oxidative stress among the cells (M. C.di C. di C.di Dong et al., 2020; M. Dong et al., 2020).

In an experiment conducted by (Shi et al., 2021; Wang et al., 2021), A549 cells were employed to study the toxicity due to polystyrene nanoplastics on human lung alveolar cells. Using a ROS assay kit that contains a sensitive fluorescent probe 2,7 – dichlorofluorescein diacetate (DCFH-DA), intracellular ROS production was measured. Results concluded that there would be enhanced ROS production in human lung cells after a period of exposure to polystyrene nanoplastics in the cells. Apart from A549 cells, there was a significant rise in ROS production in the human bronchus epithelial cells, BEAS-2B, when they were treated with 60 nm polystyrene nanoplastics.

In an experiment conducted by Jeong, they concluded the induction of ROS from microplastic in Rotifers. To prove their hypothesis, they exposed ROS scavengers with NAC. The NAC tends to block the intracellular ROS generation which proved the ROS generation is activated by p-JNK and p-P38 (Jeong et al., 2016). In the study conducted by Deng, it was observed there was microplastic accumulation in mice tissues which causes oxidative stress and neurotoxic responses (Deng et al., 2017). In an experiment conducted on zebrafish, it was observed that polystyrene microplastics were responsible for the increased activities of superoxide dismutase and catalase which are the markers of oxidative stress (Tagorti and Kaya, 2022; Verma et al., 2017).

7.3.4. *Genotoxicity*

There are several mechanisms through which genotoxicity is induced resulting in DNA damage. Through direct particle contact, the DNA around the nuclear membrane gets damaged as small particles can cross the nuclear membrane. When ROS generated from cytoplasm reaches the nucleus, it causes genotoxicity. When the concentration of microplastics and nanoplastics increases and it gets accumulated in the cell, they induce DNA damage as the replication and repair mechanism gets disrupted (Gao et al., 2021). Microplastic exposure for a stipulated period has resulted in the breakage of DNA. An experiment on shrimp *Neocaridina davidi* revealed that as the concentration of microplastics grew, so did the breaking of DNA. It has been proposed that the mechanism of genotoxicity is linked to the generation of reactive oxygen species (ROS), oxidative stress, inflammatory response, and DNA repair interference. Increased ROS production causes DNA lesions such as DNA-protein cross-links, intra- and inter-strand cross-links, and DNA modification. ROS may cause DNA damage by forming mutagenic lesions. Mutagenic lesions such as 8-nitroguanidine can also be formed because of peroxynitrite generation in macrophages and neutrophils because of inflammation (Tagorti and Kaya, 2022).

7.3.5. Cardiotoxicity

In an experiment conducted by Zekang Li et al., rats were employed to investigate the cardiotoxic impact of polystyrene microplastic. The spherical polystyrene microplastic has a hydrodynamic size of around 500 nm. Substantial interstitial hyperplasia was detected in cardiac tissues when PS-MP concentrations were greater, suggesting that the myocardium might tear and possibly grow thinner as the concentration increased. Polystyrene microplastic was found to cause collagen deposition in the mouse heart using Masson's trichrome staining and Sirius red staining. At a larger concentration of polystyrene microplastic, the integrated optical density of Bax increased significantly, perhaps leading to cell apoptosis (Z. Li et al., 2020a).

An experiment conducted by Mengqi Sun et al., (M. Sun et al., 2021) on-zebrafish model concluded that injection of polystyrene nanoplastic could induce pericardial edema in the zebrafish embryos when present in greater concentration. Although at a lower concentration, there wasn't much effect on the pericardial edema, a higher concentration reported significant pericardial edema in the zebrafish embryos (Makkar, Verma, Panda, Jha et al., 2018). Further research also concluded that there was a significant amount of thrombosis in the zebrafish embryos with a higher concentration of nanoplastic as compared to the embryos with a lower concentration of nanoplastic.

7.4. Immune responses

The accumulation of microplastics and nanoplastics in human lungs, limbs, and joints causes the release of toxic materials and free radicals due to the inflammatory response (Rahman et al., 2021). The immune response triggered due to exposure to microplastics and nanoplastics depends on their dissemination(Q.Zhang et al., 2022). Microplastic and nanoplastic are taken up by our cells by the process of endocytosis where these plastic materials are encapsulated in vessels and expelled from their cytoplasmic membrane. This is an energy-dependent process (Lehel and Murphy, 2021). With the help of flow cytometry and confocal microscopy, we can image the internalization of MPs and NPs. An increased amount of cytokines response was observed when the central nervous system was exposed to silver nanoparticles which in turn activates the chemokines (Barboza et al., 2018).

After an in-vitro evaluation of nanoplastics, using microarray analysis, the immune responses were recorded. The release of proinflammatory mediators including IL-6, IL-8, MCP-1, and TNF-α was observed. Apart from these mediators, a significant increase in the MCP-1 was observed. Cell adhesion molecule ICAM-1 was also detected after exposure of the cells to PS- NPs (polystyrene nanoplastics) (Donkers et al., 2022; C. Sun et al., 2016). The larger-sized nanoplastics could not only lead to the secretion of cytokines from monocytes and macrophages but also result in a measurable number of monocytes bursting (Yong et al., 2020).

The increased production of ROS because of long-term exposure to microplastics and nanoplastics resulted in the enhanced production of pro-inflammatory cytokines. Increase production of IL-6 and IL-8 was reported in the BEAS-2B human lung epithelial cells because of increased ROS production. These cytokines lead to the overexpression of NADPH oxidase 4, thus more DNA damage. The expression of the cytokines in the cells is associated with the aggravation of chronic obstructive pulmonary disease (COPD). Loss of barrier integrity between airway epithelial cells was observed in BEAS-2B cells (Aghapour et al., 2022).

Exposure to atmospheric microplastics and nanoplastic could result in chronic inflammation in human respiratory cells. Studies conducted by Dong et al.(M. Dong et al., 2020; C.di Dong et al., 2020), revealed the inflammatory responses caused by the polystyrene microplastics in the BEAS-2B cells by increasing the formation of reactive oxygen species. Inflammatory responses could occur because of the presence of microplastic and nanoplastic on the tissues or when they enter the cell.

An experiment conducted on mice showed lower activation of dendritic cells, production of IL-10, and suppression of T_H type 2 responses with impartment of T effector cell production. Activation of Lung DCs which determines the adaptive immune response was comparatively less. Apart from the production of IL-10, there was also IL-10^+ CD4 lymphocytes were also observed (Saravia et al., 2014). Donkers et al., conducted an experiment where they described the pro-inflammatory cell activation and harmful effects on barrier integrity due to microplastic and nanoplastic. The amount of lactate dehydrogenase (LDH) released by the cells, or the tissues was accessed to assess the cell viability as the damage to the cell and release of LDH is proportional. It was observed that a consistent amount of LDH levels were identified between the control and MNP-exposed conditions. It suggested that the microplastics and nanoplastics did not cause any decrease in cell viability until the number of MPs and NPs were extremely high. However, the lung cell barrier integrity was damaged because of immense exposure to microplastic and nanoplastic (Donkers et al., 2022). An elevated level of CK-MB and Troponin I was observed in rats with a higher concentration of polystyrene microplastic which suggested acute inflammation and can cause a heart attack. It was seen that in controls and lower concentration there weren't any significant secretion of Wnt, TGF-β, p- β-catenin, α-SMA, Collagen I, and fibronectin while in a higher concentration of PS-MPs, there was an observable expression of these proteins (Z. Li et al., 2020).

7.5. Diseases

The ability of microplastic and nanoplastics to interact with organic pollutants is a growing concern because it becomes a crucial source of exposure to humans (Chang et al., 2022). Considering the size of microplastics and nanoplastics, they can get deep within our lungs' respiratory tracts, posing possible health problems in the pulmonary area. The ability of nanoplastics to infiltrate cells and the gastrointestinal epithelium is a prevalent issue (Sana et al., 2020).

Upon inhalation of atmospheric microplastic and nanoplastic, they initially reach the upper respiratory tract. There exist generally four ways through which the MPs/NPs reach the upper respiratory tract, these are impaction, interception, sedimentation, and diffusion (Enyoh et al., 2019). The human body has a clearance mechanism that ensures the expulsions of microplastic and nanoplastic. Failing the clearance mechanism, microplastic and nanoplastic can reach deep inside the lung causing pulmonary diseases (H. Lai et al., 2022). The common cells that get affected because of the intake of atmospheric microplastics and nanoplastics are the A549, BEAS-2B, and Caco-2 cells (Donkers et al., 2022). Fig. 4 shows the effect of overexposure to microplastic and nanoplastic in A549 cells and BEAS-2B cells.

Microplastic can engender several critical conditions in the body as it carries several pollutants. MPs can carry chemical additives, dyes, persistent organic pollutants (POPs), endocrine disruptors like bisphenol A(BPA), phthalates, brominated flame retardants, triclosan, and organotin (Vieira et al., 2021). These pollutants are often used as additives while the manufacturing process of plastics. The POPs can carry heavy

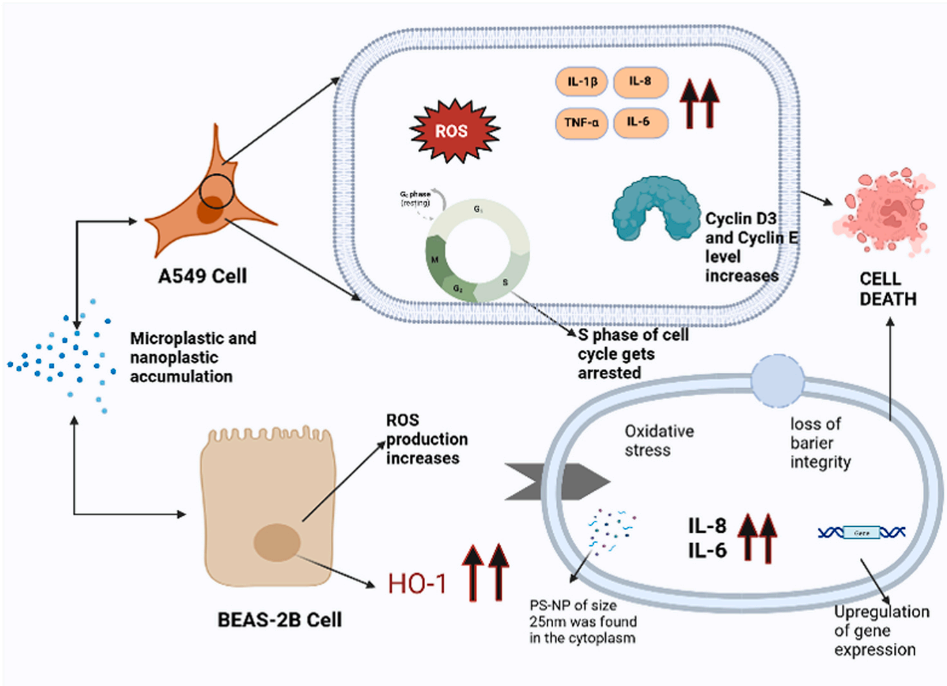

Fig. 4. The figure represents the toxicity induced on human A549 epithelial cell and human lung BEAS-2B cell due to the accumulation of microplastic and nanoplastic in greater concentration. It indicates how the cell death occurs ultimately when the toxicity increases.
Idea conceptualized from (C. di Dong et al., 2020; M. Dong et al., 2020; Tagorti and Kaya, 2022; Xu et al., 2019).

metals such as lead, nickel, cadmium, and zinc. These pollutants are released once the MPs encounter our body tissues (Rahman et al., 2021). In an experiment conducted on human lungs cell, it was confirmed using transmission electron microscopy the presence of nanoplastics in the deeper parts of the lungs can also cross the lung epithelial layer (Donkers et al., 2022). It was found that, with the decrease in the level of α1-antitrypsin levels in the BEAS-2B cells, the health risk caused by the polystyrene microplastics increases. The imbalance caused due to oxidative stress between the oxidants and antioxidants results in the pathogenesis of lung diseases. Pulmonary diseases such as asthma, chronic obstructive diseases, cancer, and dyspnea could occur (C. di M. Dong et al., 2020; C. di C.di Dong et al., 2020). Another pulmonary disease associated with exposure to microplastics and nanoplastics is idiopathic pulmonary fibrosis which is increasing every year (X. Li et al., 2022).

In research conducted by X. Chen et al. (2022); Q. Chen et al. (2022) they studied the role of MPs in the pathogenesis of lung ground-glass nodules (GGNs). Microplastic presence in the human lung tissue was confirmed by μ-FTIR which suggested the presence of microplastics in the GGNs was more as compared to in the normal lung tissues. Among the workers, those who were continuously exposed to fibers had a high mortality rate because of lung cancer. A similar experiment on a mouse model demonstrated that macrophages phagocytose microplastic particles. These microplastic particles have the potential to penetrate the pulmonary endothelium and go to other parts of the body. TNF- release, IgG1 synthesis, inflammatory cell infiltration, and macrophage aggregation were found in the lungs of normal mice after a period of exposure to microplastics. In asthmatic mice, mucus production increased along with inflammatory cell infiltration. B-cell receptor transmembrane proteins formed a complex with B-cell receptors in asthmatic mouse models, activating B-cell signaling and causing lung inflammation. (L. Lu et al., 2018; S. Lu et al., 2018). In the case of lung cancer, there has been an accumulation of both cellulosic and plastic microparticles. The entry of these particles is highly dependent on their size and shape. As microplastic can serve as vectors for carrying heavy metals and organic pollutants, they can often be carcinogenic. Studies on rat models have shown that microplastic can withstand chemical degradation and elimination when they are inhaled or ingested. Acute lung inflammation can be observed due to the persistent presence of polystyrene nanoplastic in the lungs causing an increase in neutrophil concentration (González-Acedo et al., 2021).

The alveolation surface of the human lung is wide with a very thin tissue barrier and hence it can allow the flow of nanoplastics into the bloodstream (Campanale et al., 2020). The effects on human due to atmospheric microplastic and nanoplastic depends on the metabolism and susceptibility. The immune response led in the human lung cells can lead to genotoxicity and induce cytotoxicity in the pulmonary cells and macrophages. Immune responses can lead to bronchial reactions such as asthma, it can diffuse interstitial fibrosis and granulomas with fiber inclusion leading to allergic alveolitis or chronic pneumonia. Inflammatory responses leading to fibrotic changes in the bronchial cells and parabronchial tissues can cause chromonic bronchitis and pneumothorax (Prata, 2018).

Research carried out by Xuran Li et al., found indications of pulmonary fibrosis in mice lungs after being exposed to polystyrene microplastic over a length of time. In the intratracheal groups, there was a significant increase in the production of α-SMA and collagen. Pulmonary fibrosis was shown to develop significantly as the amount of polystyrene microplastic increased. Surfactant protein-C (SP-C) production was reduced, which was related to the alveolar epithelial segment. Aside from SP-C, there was an increase in KL-6 production, which reflects the epithelial cell damage. These epithelial damages cause the release of IL- and TNF-α. These wounded epithelial cells trigger the creation of -SMA, vimen, and collagen in lung fibroblasts, resulting in lung fibrosis. These wounded epithelial cells trigger the creation of α-SMA, vimen, and collagen in lung fibroblasts, resulting in lung fibrosis. The Wnt/-catenin signaling pathway is activated, resulting in the overexpression of -catenin and TCF-4, confirming pulmonary fibrosis (X. Li et al., 2022; Zarreen Simnani et al., 2023).

Polystyrene microplastics when present in significant amounts can translocate to the cardiomyocytes which suggested that these plastic particles can enter the circulatory system. The increase in the secretion of CK-MB and Troponin I enzymes suggests myocardial damage. Upregulation of Bax and downregulation of Bcl-2 can induce cardiomyocyte apoptosis which is a result of oxidative stress and mitochondria damage (Z. Li et al., 2020; X. Zhu et al., 2023). Fig. 5 represents the scanning electron microscopy images of different microplastic and nanoplastic, along with the fluorescent images of toxicity induced due to these plastic particles in zebrafish, fetal tissues, and A549 cells.

8. Future perspective

Microplastic and nanoplastic pollution is becoming a concern for the world. There is very less literature about the sources, pathways, and degradation of microplastics and nanoplastic in the atmosphere (Enyoh et al., 2019). A significant research gap exists in the plastic cycle pathways in the atmosphere (Hoellein and Rochman, 2021). There are not

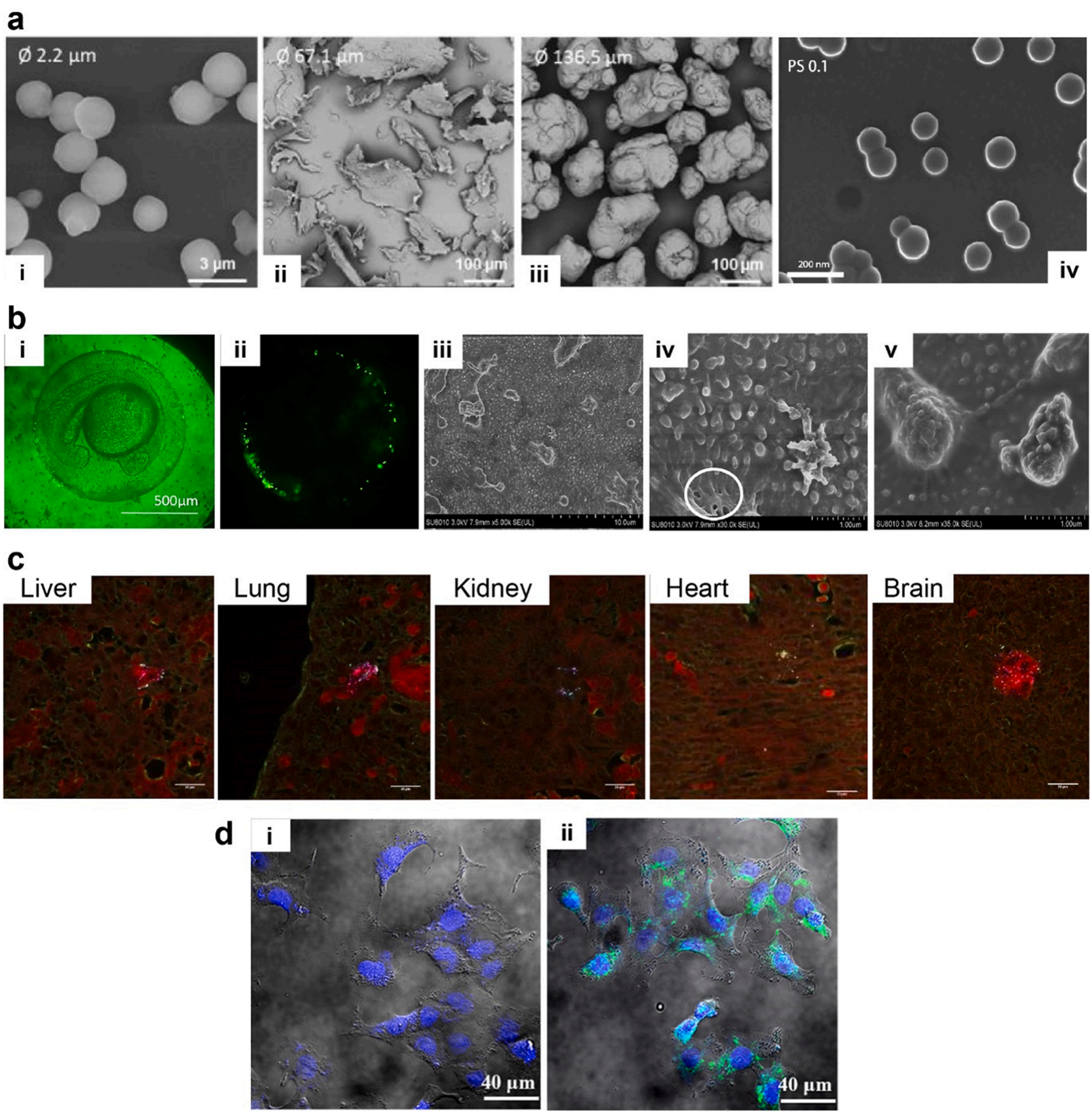

Fig. 5. This figure represents the Scanning electron microscope(SEM) images of (a) (i) Polyethylene microplastic, (ii) Polypropylene microplastic, (iii)polyvinyl chloride(PVC) microplastic, (iv)polystyrene nanoplastic. (b) (i) fluorescent observations of zebrafish embryos under natural light,(ii)Fluorescent images of microplastic accumulation on the chorion membrane of the zebrafish when exposed to microplastic for 24 h, (iii, iv, v) SEM images of the outer membrane of zebrafish embryos when exposed to microplastics for 48 h. (c) Visualizations of the presence pf polystyrene nanoplastics in the fetal tissue, which includes liver, lung, kidney, heart, and brain. These images are produced using hyperspectral microscopy. (d) It represents a comparative view of the A549 cells with and without the treatment of nanoplastics using confocal microscopy, (i) Without NPs treatment; (ii) A549 cells treated with green, fluorescent polystyrene NPs. These cells show distinct viability and accumulations of nanoplastics.
Concept generated from (Donkers et al., 2022; Fournier et al., 2020; Stock et al., 2019; Wang et al., 2021).

enough journals stating the methods which focus on the sources of human exposure to atmospheric microplastic and nanoplastic with a huge knowledge gap on the pulmonary diseases caused due to these plastic particles. (Revel et al., 2018). Pertaining to the increased percentage of pulmonary cases in recent times,(Q. X. Chen et al., 2022; Q. Chen et al., 2022; Jenner et al., 2022) it is of utmost importance that enough research should be focused on the pulmonary diseases caused due to these microplastic and nanoplastic as their presence is now becoming a global concern (Kutralam-Muniasamy et al., 2023; Yee et al., 2021).

The abundance of microplastic and nanoplastic in the atmosphere makes it difficult to study the MPs and NPs. A sampling of nanoplastic can be difficult since it is extremely small and present everywhere. There is a huge knowledge gap in the fragmentation process of plastic (Jakubowicz et al., 2021). Although the size of MP has been assumed to be around 5 mm, research is still being carried out for the proper definition of microplastic (Waldschläger et al., 2022). The smaller-size microplastic particles, which have a high potential for transmission into human lungs via aerosolization, are poorly characterized (Habibi et al., 2022a). Methods and protocols are still under preparation and review for detection and sampling (Mintenig, Bäuerlein, Koelmans, Dekker, and van Wezel, 2018). There exists a methodological gap between particles from size 1 nm to 1 μm. There must be the development of techniques, and which enable the sampling of these particles for further characterization and particle toxicity (Schwaferts et al., 2019).

Future investigation should focus on the type and shape to predict the origin of microplastic and nanoplastic. A standardized protocol must be developed in the future which does not affect the shape of the plastic particle and does not cause aggregation (Mariano et al., 2021). Understanding the intricate composition of atmospheric MPs and their complex with other pollutants will allow for improved management and decreased levels of pollution produced (X. X. Yao et al., 2022; Y. Yao et al., 2022). Many studies are focused on the presence of MPs and NPs in the marine environment. This creates a knowledge gap in the presence of atmospheric microplastic and nanoplastic. It is of utmost importance that people should be aware of the presence of microplastics and nanoplastic in the atmosphere as the global presence of these plastics results in continuous exposure to humans and other organisms (Dash et al., 2022). Research conducted by Carlos Baeza-Martínez et al, showed the presence of atmospheric microplastic in the lower respiratory tract. Emphasis on the research could lead to the discovery of toxicity and pulmonary disease caused due to the accumulation of microplastics (Baeza-Martínez et al., 2022). Apart from the effect of microplastic and nanoplastic on the pulmonary system, research conducted by Mengqi Sun et al, concluded that the accumulation of nanoplastic in the lungs could implement cardiotoxicity in the zebrafish (M. Sun et al., 2021; Verma et al., 2021) Thus the upcoming years expect to come up with more atmospheric microplastic and nano plastic-based studies that hold integrity in competing with the difference that exists today between aqueous and terrestrial MPs and NPs.

9. Conclusion

The magnitude of the mismanagement of plastics in the environment has led to global concern regarding plastic pollution which paves the way for the omnipresence of microplastic and nanoplastic. Microplastics and nanoplastics though found in large amounts in the marine ecosystem, there are comparatively few studies focusing on the presence of MPs and NPs in the atmosphere. There are developing techniques for sampling and characterization of these MPs and NPs, establishing relatively few parallels across the studies that are being undertaken in this field. This could be because of the different properties considered during the study such as size, shape, concentration, and atmospheric condition while the experimentation process. Research should be focused in the future on techniques for successful characterization of MPs and NPs present in the atmosphere which could give an insight into the distribution of these plastic particles.

These plastic particles can enter the human body through three major routes: inhalation, ingestion, and cutaneous contact. The MPs usually reside in the upper part of the respiratory tract but can travel across the bloodstream. According to research, inhaling these particles can cause respiratory tract irritation, inflammation, oxidative stress, and genotoxicity. These particles' toxicological paradigm is complicated, and further study is needed to properly understand their methods of action and possible long-term impacts. Future studies should focus on the potential toxicity of airborne MPs and NPs on the human pulmonary system as there is a very knowledge gap in that perspective. Moreover, particle size, shape, surface area, and chemical makeup can all affect their capacity to penetrate deep into the lungs and interact with lung tissue. Although there are studies that state the exposure of microplastics and nanoplastics to humans, more studies need to be done to elucidate the risks associated with the inhalation of atmospheric MPs and NPs. These atmospheric MPs and NPs can cause diseases including lung cancer, bronchitis, and dyspnea, but the mechanism of action of these particles remains unknown. Furthermore, effective solutions for reducing atmospheric plastic pollution, such as enhanced waste management practices and the usage of alternative materials, are critical.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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References

Abbasi, S., 2021. Routes of human exposure to micro(nano)plastics. Curr. Opin. Toxicol. 27, 41–46. https://doi.org/10.1016/J.COTOX.2021.08.004.

Abbasi, S., Keshavarzi, B., Moore, F., Turner, A., Kelly, F.J., Oliete Dominguez, A., Jaafarzadeh, N., 2018. Distribution and potential health impacts of microplastics and microrubbers in air and street dusts from Asaluyeh County, Iran. Elsevier. https://doi.org/10.1016/j.envpol.2018.10.039.

Abdiev, J., Safarov, O., Julanov, H., 2022. Study of the properties of polymer composites – reinforcement based on glass and basalt fibers. Eurasia Sci. Her. 7, 77–88. 〈https://geniusjournals.org/index.php/esh/article/view/1001〉.

Abdolahpur Monikh, F., Grundschober, N., Romeijn, S., Arenas-Lago, D., Vijver, M.G., Jiskoot, W., Peijnenburg, W.J.G.M., 2019. Development of methods for extraction and analytical characterization of carbon-based nanomaterials (nanoplastics and carbon nanotubes) in biological and environmental matrices by asymmetrical flow field-flow fractionation. Environ. Pollut. 255 (2019), 113304 https://doi.org/10.1016/j.envpol.2019.113304.

Acharya, S., Rumi, S.S., Hu, Y., Abidi, N., 2021. Microfibers from synthetic textiles as a major source of microplastics in the environment: a review, 91 (17–18), 2136–2156. https://doi.org/10.1177/0040517521991244. 〈Https://Doi.Org/10.1177/0040517521991244〉.

Adam, V., Vaculovicova, M., 2017. Capillary electrophoresis and nanomaterials – part I: capillary electrophoresis of nanomaterials. Electrophoresis 38 (19), 2389–2404. https://doi.org/10.1002/elps.201700097.

Ageel, H.K., Harrad, S., Abdallah, M.A.E., 2022. Occurrence, human exposure, and risk of microplastics in the indoor environment. Environ. Sci.: Process. Impacts 24 (1), 17–31. https://doi.org/10.1039/d1em00301a.

Aghapour, M., Ubags, N.D., Bruder, D., Hiemstra, P.S., Sidhaye, V., Rezaee, F., Heijink, I.H., 2022. Role of air pollutants in airway epithelial barrier dysfunction in asthma and COPD. Eur. Respir. Rev. 31 (163) https://doi.org/10.1183/16000617.0112-2021.

Akhter, M.H., Khalilullah, H., Gupta, M., Alfaleh, M.A., Alhakamy, N.A., Riadi, Y., Md, S., 2021. Impact of protein corona on the biological identity of nanomedicine:

understanding the fate of nanomaterials in the biological milieu. Biomedicines 9 (10), 1496. https://doi.org/10.3390/biomedicines9101496.

Alimba, C.G., Faggio, C., 2019. Microplastics in the marine environment: current trends in environmental pollution and mechanisms of toxicological profile. Environ. Toxicol. Pharmacol. 68, 61–74. https://doi.org/10.1016/j.etap.2019.03.001.

Allen, D., Allen, S., Abbasi, S., Baker, A., Bergmann, M., Brahney, J., Butler, T., Duce, R. A., Eckhardt, S., Evangeliou, N., Jickells, T., Kanakidou, M., Kershaw, P., Laj, P., Levermore, J., Li, D., Liss, P., Liu, K., Mahowald, N., Wright, S., 2022. Microplastics and nanoplastics in the marine-atmosphere environment. *2022 3:6* Nat. Rev. Earth Environ. 3 (6), 393–405. https://doi.org/10.1038/s43017-022-00292-x.

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. Nat. Geosci. 12 (5), 339–344. https://doi.org/10.1038/s41561-019-0335-5.

Allen, S., Allen, D., Moss, K., le Roux, G., Phoenix, V.R., Sonke, J.E., 2020. Examination of the ocean as a source for atmospheric microplastics. PLoS One 15 (5), e0232746. https://doi.org/10.1371/JOURNAL.PONE.0232746.

Ambrosini, R., Azzoni, R., Pittino, F., … G. D.-E, & 2019, undefined. (n.d.). First evidence of microplastic contamination in the supraglacial debris of an alpine glacier. *Elsevier*. Retrieved March 9, 2023, from ⟨https://www.sciencedirect.com/science/article/pii/S0269749119316422⟩.

Amato-Lourenço, L.F., Galvão, L.D.S., De Weger, Hiemstra, P.S., Vijver, M.G., Mauad, T., 2020. An emerging class of air pollutants: Potential effects of microplastics to respiratory human health? Science of the Total Environment 749, 141676. https://doi.org/10.1016/j.scitotenv.2020.141676.

Amelia, T.S.M., Khalik, W.M.A.W.M., Ong, M.C., Shao, Y.T., Pan, H.J., Bhubalan, K., 2021. Marine microplastics as vectors of major ocean pollutants and its hazards to the marine ecosystem and humans. Prog. Earth Planet. Sci. 8 (1), 1–26. https://doi.org/10.1186/S40645-020-00405-4.

Andrady, A.L., Barnes, P.W., Bornman, J.F., Gouin, T., Madronich, S., White, C.C., Zepp, R.G., Jansen, M.A.K., 2022. Oxidation and fragmentation of plastics in a changing environment; from UV-radiation to biological degradation. Sci. Total Environ. 851, 158022 https://doi.org/10.1016/J.SCITOTENV.2022.158022.

Araujo, C., Nolasco, M., research, A.R.-W., & 2018, undefined. (n.d.). Identification of microplastics using Raman spectroscopy: Latest developments and future prospects. *Elsevier*. Retrieved March 10, 2023, from ⟨https://www.sciencedirect.com/science/article/pii/S0043135418304421⟩.

Arya, S.S., Kaimal, A.M., Chib, M., Sonawane, S.K., Show, P.L., 2019. Novel, energy efficient and green cloud point extraction: technology and applications in food processing. J. Food Sci. Technol. 56 (2), 524. https://doi.org/10.1007/S13197-018-3546-7.

Avazzadeh Samani, F., & Meunier, L. (2023). Interactions of microplastics with contaminants in freshwater systems: a review of characteristics, bioaccessibility, and environmental factors affecting sorption. Https://Doi.Org/10.1080/10934529.2023.2177458. https://doi.org/10.1080/10934529.2023.2177458.

Baeza-Martínez, C., Olmos, S., González-Pleiter, M., López-Castellanos, J., García-Pachón, E., Masiá-Canuto, M., Hernández-Blasco, L., Bayo, J., 2022. First evidence of microplastics isolated in European citizens' lower airway. J. Hazard. Mater. 438, 129439 https://doi.org/10.1016/J.JHAZMAT.2022.129439.

Bai, L., Kou, H., Kong, Z., 2022. Application of spectroscopy technology in nanomaterials in identification of Chinese paintings. J. Nanomater. 2022 https://doi.org/10.1155/2022/9393188.

Balasaraswathi, S.R., Rathinamoorthy, R., 2022. Synthetic textile and microplastic pollution. Anal. Environ. Health Impact 1–20. https://doi.org/10.1007/978-981-19-0530-8_1.

Banerjee, A., Shelver, W.L., 2021. Micro- and nanoplastic induced cellular toxicity in mammals: a review. Sci. Total Environ. 755, 142518 https://doi.org/10.1016/j.scitotenv.2020.142518.

Bank, M.S., Hansson, S. v, 2019. The plastic cycle: a novel and holistic paradigm for the anthropocene [News]. Environ. Sci. Technol. 53 (13), 7177–7179. https://doi.org/10.1021/acs.est.9b02942.

Bank Editor, M.S. (n.d.). *Environmental Contamination Remediation and Management Microplastic in the Environment: Pattern and Process*. Retrieved March 11, 2023, from http://www.springer.com/series/15836.

Barboza, L.G.A., Vieira, L.R., Branco, V., Figueiredo, N., Carvalho, F., Carvalho, C., Guilhermino, L., 2018. Microplastics cause neurotoxicity, oxidative damage and energy-related changes and interact with the bioaccumulation of mercury in the European seabass, Dicentrarchus labrax (Linnaeus, 1758). Aquat. Toxicol. 195 (December 2017), 49–57. https://doi.org/10.1016/j.aquatox.2017.12.008.

Bentrad, N., 2022. Polyvinyl Chloride (PVC), Chlorinated Polyethylene (cpe), Chlorinated Polyvinyl Chloride (CPVC), Chlorosulfonated Polyethylene (CSPE), Polychloroprene Rubber (CR)—chemistry, applications and ecological impacts—II. Ecol. Health Eff. Build. Mater. 53–66. https://doi.org/10.1007/978-3-030-76073-1_4.

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. Sci. Adv. 5 (8) https://doi.org/10.1126/SCIADV.AAX1157.

Bhat, M.A., Gedik, K., Gaga, E.O., 2023. Atmospheric micro (nano) plastics: future growing concerns for human health. Air Qual., Atmosphere Health 16 (2), 233–262. https://doi.org/10.1007/s11869-022-01272-2.

Bianco, A., Passananti, M., 2020. Atmospheric micro and nanoplastics: an enormous microscopic problem. Sustainability 12 (18), 7327. https://doi.org/10.3390/SU12187327.

Biswas, S., Bagchi, D., Ghosh, D., 2022. The effects of (micro and nano) plastics on the human body: nervous system, respiratory system, digestive system, placental barrier, skin, and excretory system. Assess. Eff. Emerg. Plast. Environ. Public Health 148–171. https://doi.org/10.4018/978-1-7998-9723-1.CH008.

Bogevik, A.S., Ytteborg, E., Madsen, A.K., Jordal, A.E.O., Karlsen, O.A., Rønnestad, I., 2023. PCB-126 spiked to polyethylene microplastic ingested by juvenile Atlantic cod (Gadus morhua) accumulates in liver and muscle tissues. Mar. Pollut. Bull. 187, 114528 https://doi.org/10.1016/J.MARPOLBUL.2022.114528.

Brahney, J., Mahowald, N., Prank, M., Cornwell, G., Klimont, Z., Matsui, H., Prather, K. A., 2021. Constraining the atmospheric limb of the plastic cycle. Proc. Natl. Acad. Sci. USA 118 (16), 1–10. https://doi.org/10.1073/pnas.2020719118.

de Bruin, C.R., de Rijke, E., van Wezel, A.P., Astefanei, A., 2022. Methodologies to characterize, identify and quantify nano- and sub-micron sized plastics in relevant media for human exposure: a critical review. Environ. Sci.: Adv. 1 (3), 238–258. https://doi.org/10.1039/D1VA00024A.

Brun, N.R., van Hage, P., Hunting, E.R., Haramis, A.P.G., Vink, S.C., Vijver, M.G., Schaaf, M.J.M., Tudorache, C., 2019. Polystyrene nanoplastics disrupt glucose metabolism and cortisol levels with a possible link to behavioural changes in larval zebrafish. Commun. Biol. 2 (1), 1–9. https://doi.org/10.1038/s42003-019-0629-6.

Burkhart, J., Jones, W., Porter, D.W., Washko, R.M., Eschenbacher, W.L., Castellan, R.M., 1999. Hazardous occupational exposure and lung disease among nylon flock workers. Am. J. Ind. Med. 36 (SUPPL. 1), 145–146. https://doi.org/10.1002/(SICI)1097-0274(199909)36:1+<145::AID-AJIM51>3.0.CO;2-F.

Cai, H., Xu, E.G., Du, F., Li, R., Liu, J., Shi, H., 2021. Analysis of environmental nanoplastics: progress and challenges. Chem. Eng. J. 410, 128208 https://doi.org/10.1016/j.cej.2020.128208.

Cai, L., Wang, J., Peng, J., Tan, Z., Zhan, Z., Tan, X., Chen, Q., 2017. Characteristic of microplastics in the atmospheric fallout from Dongguan city, China: preliminary research and first evidence. Environ. Sci. Pollut. Res. 24 (32), 24928–24935. https://doi.org/10.1007/S11356-017-0116-X.

Cai, L., Hu, L., Shi, H., Ye, J., Zhang, Y., Kim, H., 2018. Effects of inorganic ions and natural organic matter on the aggregation of nanoplastics. Chemosphere 197, 142–151. https://doi.org/10.1016/J.CHEMOSPHERE.2018.01.052.

Calderón-Garcidueñas, L., Ayala, A., 2022. Air pollution, ultrafine particles, and your brain: are combustion nanoparticle emissions and engineered nanoparticles causing preventable fatal neurodegenerative diseases and common neuropsychiatric outcomes? Environ. Sci. Technol. 56 (11), 6847–6856. https://doi.org/10.1021/ACS.EST.1C04706/ASSET/IMAGES/LARGE/ES1C04706_0001.JPEG.

Campanale, C., Massarelli, C., Savino, I., Locaputo, V., Uricchio, V.F., 2020. A detailed review study on potential effects of microplastics and additives of concern on human health. Int. J. Environ. Res. Public Health 17 (4). https://doi.org/10.3390/ijerph17041212.

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

Cao, J., Yang, Q., Jiang, J., Dalu, T., Kadushkin, A., Singh, J., Fakhrullin, R., Wang, F., Cai, X., Li, R., 2022. Coronas of micro/nano plastics: a key determinant in their risk assessments. Part. Fibre Toxicol. 19 (1), 1–25. https://doi.org/10.1186/S12989-022-00492-9.

Caputo, F., Vogel, R., Savage, J., Vella, G., Law, A., Della Camera, G., Hannon, G., Peacock, B., Mehn, D., Ponti, J., Geiss, O., Aubert, D., Prina-Mello, A., Calzolai, L., 2021. Measuring particle size distribution and mass concentration of nanoplastics and microplastics: addressing some analytical challenges in the sub-micron size range. J. Colloid Interface Sci. 588, 401–417. https://doi.org/10.1016/J.JCIS.2020.12.039.

Carlier, S., Nasser, M., Fort, E., Lamouroux, C., Si-Mohamed, S., Chalabreysse, L., Maury, J.M., Diesler, R., Cottin, V., Charbotel, B., 2022. Role of the occupational disease consultant in the multidisciplinary discussion of interstitial lung diseases. Respir. Res. 23 (1), 1–16. https://doi.org/10.1186/S12931-022-02257-6/TABLES/4.

Catarino, A., Macchia, V., … W. S.-E, & 2018, undefined. (n.d.). Low levels of microplastics (MP) in wild mussels indicate that MP ingestion by humans is minimal compared to exposure via household fibres fallout during a meal. *Elsevier*. Retrieved March 9, 2023, from ⟨https://www.sciencedirect.com/science/article/pii/S0269749117344445⟩.

Cerasa, M., Teodori, S., Pietrelli, L., 2021. Searching nanoplastics: from sampling to sample processing. Polymers 13 (21), 3658. https://doi.org/10.3390/POLYM13213658/S1.

Chamas, A., Moon, H., Zheng, J., Qiu, Y., Tabassum, T., Jang, J.H., Abu-Omar, M., Scott, S.L., Suh, S., 2020. Degradation rates of plastics in the environment. ACS Sustain. Chem. Eng. 8 (9), 3494–3511. https://doi.org/10.1021/ACSSUSCHEMENG.9B06635/ASSET/IMAGES/LARGE/SC9B06635_0009.JPEG.

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

Chang, J., Fang, W., Liang, J., Zhang, P., Zhang, G., Zhang, H., Zhang, Y., Wang, Q., 2022. A critical review on interaction of microplastics with organic contaminants in soil and their ecological risks on soil organisms. Chemosphere 306, 135573. https://doi.org/10.1016/J.CHEMOSPHERE.2022.135573.

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

Chen, Q., Gundlach, M., Yang, S., Jiang, J., Velki, M., Yin, D., Hollert, H., 2017. Quantitative investigation of the mechanisms of microplastics and nanoplastics toward zebrafish larvae locomotor activity. *584–585* Sci. Total Environ. 1022–1031. https://doi.org/10.1016/J.SCITOTENV.2017.01.156.

Chen, Q., Gao, J., Yu, H., Su, H., Yang, Y., Cao, Y., Zhang, Q., Ren, Y., Hollert, H., Shi, H., Chen, C., Liu, H., 2022. An emerging role of microplastics in the etiology of lung ground glass nodules. Environ. Sci. Eur. 34 (1) https://doi.org/10.1186/s12302-022-00605-3.

Chen, X., Wang, Y., Zhang, X., Liu, C., 2021. Advances in super-resolution fluorescence microscopy for the study of nano–cell interactions. Biomater. Sci. 9 (16), 5484–5496. https://doi.org/10.1039/D1BM00676B.

Chen, X., Zhuang, J., Chen, Q., Xu, L., Yue, X., Qiao, D., 2022. Chronic exposure to polyvinyl chloride microplastics induces liver injury and gut microbiota dysbiosis based on the integration of liver transcriptome profiles and full-length 16S rRNA sequencing data. Sci. Total Environ. 839, 155984 https://doi.org/10.1016/J.SCITOTENV.2022.155984.

Chou, S.H., Chuang, Y.K., Lee, C.M., Chang, Y.S., Jhang, Y.J., Yeh, C.W., Wu, T.S., Chuang, C.Y., Hsiao, I.L., 2022. Visualization and (Semi-)quantification of submicrometer plastics through scanning electron microscopy and time-of-flight secondary ion mass spectrometry. Environ. Pollut. 300, 118964 https://doi.org/10.1016/J.ENVPOL.2022.118964.

Clayton, K.N., Salameh, J.W., Wereley, S.T., Kinzer-Ursem, T.L., 2016. Physical characterization of nanoparticle size and surface modification using particle scattering diffusometry. Biomicrofluidics 10 (5), 054107. https://doi.org/10.1063/1.4962992.

Cong, Y., Jin, F., Tian, M., Wang, J., Shi, H., Wang, Y., Mu, J., 2019. Ingestion, egestion and post-exposure effects of polystyrene microspheres on marine medaka (Oryzias melastigma). Chemosphere 228, 93–100. https://doi.org/10.1016/J.CHEMOSPHERE.2019.04.098.

Correia, M., Loeschner, K., 2018. Detection of nanoplastics in food by asymmetric flow field-flow fractionation coupled to multi-angle light scattering: possibilities, challenges and analytical limitations. Anal. Bioanal. Chem. 410 (22), 5603–5615. https://doi.org/10.1007/S00216-018-0919-8/METRICS.

Cox, K.D., Covernton, G.A., Davies, H.L., Dower, J.F., Juanes, F., Dudas, S.E., 2019. Human consumption of microplastics. Environ. Sci. Technol. 53 (12), 7068–7074. https://doi.org/10.1021/ACS.EST.9B01517.

Cunsolo, S., Williams, J., Hale, M., Read, D.S., Couceiro, F., 2021. Optimising sample preparation for FTIR-based microplastic analysis in wastewater and sludge samples: multiple digestions. Anal. Bioanal. Chem. 413 (14), 3789–3799. https://doi.org/10.1007/S00216-021-03331-6/TABLES/2.

da Costa, J.P., Santos, P.S.M., Duarte, A.C., Rocha-Santos, T., 2016. (Nano)plastics in the environment - sources, fates and effects. Sci. Total Environ. 566–567, 15–26. https://doi.org/10.1016/j.scitotenv.2016.05.041.

Dash, S., Das, T., Patel, P., Panda, P.K., Suar, M., Verma, S.K., 2022. Emerging trends in the nanomedicine applications of functionalized magnetic nanoparticles as novel therapies for acute and chronic diseases. J. Nanobiotechnol. 20 (1), 393. https://doi.org/10.1186/s12951-022-01595-3.

Dehghani, S., Moore, F., and, R. A.-E. S, & 2017, undefined. (2017). Microplastic pollution in deposited urban dust, Tehran metropolis, Iran. *Springer*, *24*(25), 20360–20371. ⟨https://doi.org/10.1007/s11356–017-9674–1⟩.

Deng, Y., Zhang, Y., Lemos, B., Ren, H., 2017. Tissue accumulation of microplastics in mice and biomarker responses suggest widespread health risks of exposure. Sci. Rep. 7 (April), 1–10. https://doi.org/10.1038/srep46687.

Deng, Y., Zhang, Y., Qiao, R., Bonilla, M.M., Yang, X., Ren, H., Lemos, B., 2018. Evidence that microplastics aggravate the toxicity of organophosphorus flame retardants in mice (Mus musculus). J. Hazard. Mater. 357, 348–354. https://doi.org/10.1016/J.JHAZMAT.2018.06.017.

Diaz-Basantes, M.F., Conesa, J.A., Fullana, A., 2020. Microplastics in honey, beer, milk and refreshments in ecuador as emerging contaminants. Sustainability 12 (14), 5514. https://doi.org/10.3390/SU12145514.

Dong, C. di, Chen, C.W., Chen, Y.C., Chen, H.H., Lee, J.S., Lin, C.H., 2020. Polystyrene microplastic particles: In vitro pulmonary toxicity assessment. J. Hazard. Mater. 385, 121575 https://doi.org/10.1016/J.JHAZMAT.2019.121575.

Dong, M., Zhang, Q., Xing, X., Chen, W., She, Z., Luo, Z., 2020. Raman spectra and surface changes of microplastics weathered under natural environments. Sci. Total Environ. *739*.

Donkers, J.M., Höppener, E.M., Grigoriev, I., Will, L., Melgert, B.N., van der Zaan, B., van de Steeg, E., Kooter, I.M., 2022. Advanced epithelial lung and gut barrier models demonstrate passage of microplastic particles. Micro Nanoplastics 2 (1), 1–18. https://doi.org/10.1186/S43591-021-00024-W.

Dris, R., Gasperi, J., Mirande, C., … C. M.-E, & 2017n.d). A first overview of textile fibers, including microplastics, in indoor and outdoor environments. *Elsevier*. Retrieved March 8, 2023, from ⟨https://www.sciencedirect.com/science/article/pii/S0269749116312325⟩.

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. Environ. Chem. 12 (5), 592–599. https://doi.org/10.1071/EN14167.

Dris, R., Gasperi, J., Saad, M., Mirande, C., Tassin, B., 2016. Synthetic fibers in atmospheric fallout: a source of microplastics in the environment? Mar. Pollut. Bull. 104 (1–2), 290–293. https://doi.org/10.1016/j.marpolbul.2016.01.006.

Du, F., Cai, H., Zhang, Q., Chen, Q., Shi, H., 2020. Microplastics in take-out food containers. J. Hazard. Mater. 399 https://doi.org/10.1016/J.JHAZMAT.2020.122969.

Du, T., Yu, X., Shao, S., Li, T., Xu, S., Wu, L., 2023. Aging of nanoplastics significantly affects protein corona composition thus enhancing macrophage uptake. Environ. Sci. Technol. 57 (8), 3206–3217. https://doi.org/10.1021/acs.est.2c05772.

Duan, J., Li, Y., Gao, J., Cao, R., Shang, E., Zhang, W., 2022. ROS-mediated photoaging pathways of nano- and micro-plastic particles under UV irradiation. Water Res. 216, 118320 https://doi.org/10.1016/J.WATRES.2022.118320.

Duarte, C., Sarathana, D., Winijkul, E., 2022. Concentrations of airborne microplastics during the dry season at five locations in Bangkok Metropolitan Region, Thailand. Atmosphere 14 (1), 28. https://doi.org/10.3390/ATMOS14010028.

Dümichen, E., Barthel, A., Braun, U., research, C.B.-W., & 2015, undefined. (n.d.). Analysis of polyethylene microplastics in environmental samples, using a thermal decomposition method. *Elsevier*. Retrieved March 9, 2023, from ⟨https://www.sciencedirect.com/science/article/pii/S0043135415302141⟩.

Ekvall, M.T., Lundqvist, M., Kelpsiene, E., Šileikis, E., Gunnarsson, S.B., Cedervall, T., 2019. Nanoplastics formed during the mechanical breakdown of daily-use polystyrene products. Nanoscale Adv. 1 (3), 1055–1061. https://doi.org/10.1039/c8na00210j.

Elert, A.M., Becker, R., Duemichen, E., Eisentraut, P., Falkenhagen, J., Sturm, H., Braun, U., 2017. Comparison of different methods for MP detection: What can we learn from them, and why asking the right question before measurements matters? Environ. Pollut. 231, 1256–1264. https://doi.org/10.1016/j.envpol.2017.08.074.

Enyoh, C.E., Verla, A.W., Verla, E.N., Ibe, F.C., Amaobi, C.E., 2019. Airborne microplastics: a review study on method for analysis, occurrence, movement and risks. Environ. Monit. Assess. 191 (11) https://doi.org/10.1007/s10661-019-7842-0.

Enyoh, C.E., Wang, Q., Chowdhury, T., Wang, W., Lu, S., Xiao, K., Chowdhury, M.A.H., 2021. New analytical approaches for effective quantification and identification of nanoplastics in environmental samples. Processes 9 (11), 2086. https://doi.org/10.3390/PR9112086.

Eram, R., Kumari, P., Panda, P., Singh, S., Sarkar, B., Mallick, M., Verma, S., 2021. Cellular investigations on mechanistic biocompatibility of green synthesized calcium oxide nanoparticles with Danio rerio. J. Nanotheranostics 2 (1), 51–62. https://doi.org/10.3390/jnt2010004.

Facciolà, A., Visalli, G., Ciarello, M.P., di Pietro, A., 2021. Newly emerging airborne pollutants: current knowledge of health impact of micro and nanoplastics. Int. J. Environ. Res. Public Health 18 (6), 1–17. https://doi.org/10.3390/ijerph18062997.

Filipe, V., Hawe, A., Jiskoot, W., 2010. Critical evaluation of nanoparticle Tracking Analysis (NTA) by nanosight for the measurement of nanoparticles and protein aggregates. Pharm. Res. 27 (5), 796–810. https://doi.org/10.1007/s11095-010-0073-2.

Fournier, S.B., D'Errico, J.N., Adler, D.S., et al., 2020. Nanopolystyrene translocation and fetal deposition after acute lung exposure during late-stage pregnancy. Part Fibre Toxicol 17, 55. https://doi.org/10.1186/s12989-020-00385-9.

Frias, J.P.G.L., Nash, R., 2019. Microplastics: Finding a consensus on the definition. Mar. Pollut. Bull. 138 (November 2018), 145–147. https://doi.org/10.1016/j.marpolbul.2018.11.022.

Gambino, I., Bagordo, F., Grassi, T., Panico, A., De Donno, A., 2022. Occurrence of microplastics in tap and bottled water: current knowledge. Int. J. Environ. Res. Public Health 19 (9), 5283. https://doi.org/10.3390/IJERPH19095283.

Gao, N., Huang, Z., Xing, J., Zhang, S., Hou, J., 2021. Impact and molecular mechanism of microplastics on zebrafish in the presence and absence of copper nanoparticles. Front. Mar. Sci. 8, 1479. https://doi.org/10.3389/FMARS.2021.762530/BIBTEX.

García Rellán, A., Vázquez Ares, D., Vázquez Brea, C., Francisco López, A., Bello Bugallo, P.M., 2023. Sources, sinks and transformations of plastics in our oceans: Review, management strategies and modelling. Sci. Total Environ. 854, 158745 https://doi.org/10.1016/j.scitotenv.2022.158745.

García-Muñoz, P., Robert, D., Ruppert, A., & Keller, N. (2023). Microplastics (MPs) and nanoplastics (NPs): Introduction (pp. 1–32). https://doi.org/10.1016/B978–0-323–99908-3.00013–0.

Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Sci. Adv. 3 (7), 3–8. https://doi.org/10.1126/sciadv.1700782.

Giddings, J.C., 1993. Field-flow fractionation: analysis of macromolecular, colloidal, and particulate materials. Science 260 (5113), 1456–1465. https://doi.org/10.1126/science.8502990.

Gigault, J., Halle, A. ter, Baudrimont, M., Pascal, P.Y., Gauffre, F., Phi, T.L., el Hadri, H., Grassl, B., Reynaud, S., 2018. Current opinion: What is a nanoplastic? Environ. Pollut. 235, 1030–1034. https://doi.org/10.1016/j.envpol.2018.01.024.

Gong, J., Xie, P., 2020. Research progress in sources, analytical methods, eco-environmental effects, and control measures of microplastics. Chemosphere 254, 126790. https://doi.org/10.1016/j.chemosphere.2020.126790.

González-Acedo, A., García-Recio, E., Illescas-Montes, R., Ramos-Torrecillas, J., Melguizo-Rodríguez, L., Costela-Ruiz, V.J., 2021. Evidence from in vitro and in vivo studies on the potential health repercussions of micro- and nanoplastics. Chemosphere 280, 130826. https://doi.org/10.1016/j.chemosphere.2021.130826.

Greven, A.C., Merk, T., Karagöz, F., Mohr, K., Klapper, M., Jovanović, B., Palić, D., 2016. Polycarbonate and polystyrene nanoplastic particles act as stressors to the innate immune system of fathead minnow (Pimephales promelas). Environ. Toxicol. Chem. 35 (12), 3093–3100. https://doi.org/10.1002/ETC.3501.

Habibi, N., Uddin, S., Fowler, S.W., Behbehani, M., 2022a. Microplastics in the atmosphere: a review. J. Environ. Expo. Assess. https://doi.org/10.20517/jeea.2021.07.

Habibi, N., Uddin, S., Fowler, S.W., Behbehani, M., 2022b. Microplastics in the atmosphere: a review. J. Environ. Expo. Assess. 1 (1), 6. https://doi.org/10.20517/JEEA.2021.07.

Hæggernes, E. (2022). *Microplastic in naturally exposed cod from a plastic polluted coastal ecosystem-An investigation of the evidence of microplastic bioaccumulation.* ⟨https://bora.uib.no/bora-xmlui/bitstream/handle/11250/3045547/Microplastic-in-naturally-exposed-cod-from-a-plastic-polluted-coastal-ecosystem–An-investigation-of-the-evidence-of-microplastic-bioaccumulation-EH-.pdf?sequence=1⟩.

He, H., Wu, T., Chen, Y.F., Yang, Z., 2023. A pore-scale investigation of microplastics migration and deposition during unsaturated flow in porous media. Sci. Total Environ. 858, 159934 https://doi.org/10.1016/J.SCITOTENV.2022.159934.

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. Environ. Sci. Technol. 46 (6), 3060–3075. https://doi.org/10.1021/es2031505.

Hildebrandt, L., Voigt, N., Zimmermann, T., Reese, A., Proefrock, D., 2019. Evaluation of continuous flow centrifugation as an alternative technique to sample microplastic from water bodies. Mar. Environ. Res. 151 (July), 104768 https://doi.org/10.1016/j.marenvres.2019.104768.

Hoellein, T.J., Rochman, C.M., 2021. The "plastic cycle": a watershed-scale model of plastic pools and fluxes. Front. Ecol. Environ. 19 (3), 176–183. https://doi.org/10.1002/FEE.2294.

Hojjati-Najafabadi, A., Mansoorianfar, M., Liang, T., Shahin, K., Karimi-Maleh, H., 2022. A review on magnetic sensors for monitoring of hazardous pollutants in water resources. Sci. Total Environ. 824, 153844 https://doi.org/10.1016/j.scitotenv.2022.153844.

Horton, A.A., Dixon, S.J., 2018a. Microplastics: an introduction to environmental transport processes. WIREs Water 5 (2), 1–10. https://doi.org/10.1002/wat2.1268.

Horton, A.A., Dixon, S.J., 2018b. Microplastics: an introduction to environmental transport processes. WIREs Water 5 (2). https://doi.org/10.1002/wat2.1268.

Hu, T., Shen, M., Tang, W., 2022. Wet wipes and disposable surgical masks are becoming new sources of fiber microplastic pollution during global COVID-19. Environ. Sci. Pollut. Res. 29 (1), 284–292. https://doi.org/10.1007/S11356-021-17408-3/FIGURES/3.

Hua, X., Wang, D., 2022. Cellular uptake, transport, and organelle response after exposure to microplastics and nanoplastics: current knowledge and perspectives for environmental and health risks. Rev. Environ. Contam. Toxicol. 260 (1), 1–24. https://doi.org/10.1007/S44169-022-00013-X.

Huang, D., Chen, H., Shen, M., Tao, J., Chen, S., Yin, L., Zhou, W., Wang, X., Xiao, R., Li, R., 2022. Recent advances on the transport of microplastics/nanoplastics in abiotic and biotic compartments. J. Hazard. Mater. 438, 129515 https://doi.org/10.1016/J.JHAZMAT.2022.129515.

Huang, Y., Qing, X., Wang, W., Han, G., Wang, J., 2020. Mini-review on current studies of airborne microplastics: analytical methods, occurrence, sources, fate and potential risk to human beings. TrAC - Trends Anal. Chem. 125, 115821 https://doi.org/10.1016/j.trac.2020.115821.

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. J. Hazard. Mater. 416 (April), 126168 https://doi.org/10.1016/j.jhazmat.2021.126168.

Husain, S., Verma, S.K., Yasin, D., Hemlata, A., Rizvi, M.M., Fatma, T., 2021. Facile green bio-fabricated silver nanoparticles from Microchaete infer dose-dependent antioxidant and anti-proliferative activity to mediate cellular apoptosis. Bioorg. Chem. 107, 104535 https://doi.org/10.1016/j.bioorg.2020.104535.

Hwang, J., Choi, D., Han, S., Choi, J., Hong, J., 2019. An assessment of the toxicity of polypropylene microplastics in human derived cells. Sci. Total Environ. 684, 657–669. https://doi.org/10.1016/J.SCITOTENV.2019.05.071.

Ivleva, N.P., Wiesheu, A.C., Niessner, R., 2017. Microplastic in Aquatic Ecosystems. Angewandte Chemie 56 (7), 1720–1739. https://doi.org/10.1002/anie.201606957.

Jakubauskas, D., Mortensen, K., Jensen, P.E., Kirkensgaard, J.J.K., 2021. Small-angle X-ray and neutron scattering on photosynthetic membranes. Front. Chem. 9 https://doi.org/10.3389/fchem.2021.631370.

Jakubowicz, I., Enebro, J., Yarahmadi, N., 2021. Challenges in the search for nanoplastics in the environment—a critical review from the polymer science perspective. Polym. Test. 93, 106953 https://doi.org/10.1016/J.POLYMERTESTING.2020.106953.

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L., 2015. Plastic waste inputs from land into the ocean. Science 347 (6223), 768–771. https://doi.org/10.1126/SCIENCE.1260352/SUPPL_FILE/JAMBECK.SM.PDF.

Jenner, L.C., Rotchell, J.M., Bennett, R.T., Cowen, M., Tentzeris, V., Sadofsky, L.R., 2022. Detection of microplastics in human lung tissue using μFTIR spectroscopy. Sci. Total Environ. 831, 154907 https://doi.org/10.1016/J.SCITOTENV.2022.154907.

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). Environ. Sci. Technol. 50 (16), 8849–8857. https://doi.org/10.1021/acs.est.6b01441.

Ji, Y., Wang, Y., Shen, D., Kang, Q., Chen, L., 2021. Mucin corona delays intracellular trafficking and alleviates cytotoxicity of nanoplastic-benzopyrene combined contaminant. J. Hazard. Mater. 406, 124306 https://doi.org/10.1016/j.jhazmat.2020.124306.

Jiao, R., Sun, H., Xu, S., He, Y., Xu, H., Wang, D., 2022. Aggregation, settling characteristics and destabilization mechanisms of nano-particles under different conditions. Sci. Total Environ. 827, 154228 https://doi.org/10.1016/J.SCITOTENV.2022.154228.

Jiménez-Skrzypek, G., Ortega-Zamora, C., González-Sálamo, J., Hernández-Sánchez, C., Hernández-Borges, J., 2021. The current role of chromatography in microplastic research: plastics chemical characterization and sorption of contaminants. J. Chromatogr. Open 1, 100001. https://doi.org/10.1016/J.JCOA.2021.100001.

Jin, Y., Lu, L., Tu, W., Luo, T., Fu, Z., 2019. Impacts of polystyrene microplastic on the gut barrier, microbiota and metabolism of mice. Sci. Total Environ. 649, 308–317. https://doi.org/10.1016/J.SCITOTENV.2018.08.353.

Kacprzak, S., Tijing, L.D., 2022. Microplastics in indoor environment: sources, mitigation and fate. J. Environ. Chem. Eng. 10 (2), 107359 https://doi.org/10.1016/J.JECE.2022.107359.

Karimi Estahbanati, M.R., Rostami, S., Ghasemian, M., Kiendrebeogo, M., Drogui, P., Tyagi, R.D., 2023. Quantitative and qualitative identification, characterization, and analysis of microplastics and nanoplastics in water. Curr. Dev. Biotechnol. Bioeng. 99–123. https://doi.org/10.1016/B978-0-323-99908-3.00020-8.

Kaya, A., Yurtsever, M., Bayraktar, S.Ç., 2018. Ubiquitous exposure to microfiber pollution in the air. European Physical Journal Plus 133 (11). https://doi.org/10.1140/epjp/i2018-12372-7.

Kedzierski, M., Lechat, B., Sire, O., Le Maguer, G., Le Tilly, V., Bruzaud, S., 2020. Microplastic contamination of packaged meat: occurrence and associated risks. Food Packag. Shelf Life 24, 100489. https://doi.org/10.1016/J.FPSL.2020.100489.

Kiran, B.R., Kopperi, H., Venkata Mohan, S., 2022. Micro/nano-plastics occurrence, identification, risk analysis and mitigation: challenges and perspectives. Rev. Environ. Sci. Biotechnol. 21 (1), 169–203. https://doi.org/10.1007/S11157-021-09609-6/TABLES/3.

Klein, M., Environment, E.F.-S. of the T., & 2019, undefined. (n.d.). Microplastic abundance in atmospheric deposition within the Metropolitan area of Hamburg, Germany. *Elsevier*. Retrieved March 9, 2023, from ⟨https://www.sciencedirect.com/science/article/pii/S0048969719324581⟩.

Koelmans, A.A., Mohamed Nor, N.H., Hermsen, E., Kooi, M., Mintenig, S.M., de France, J., 2019. Microplastics in freshwaters and drinking water: critical review and assessment of data quality. Water Res. 155, 410–422. https://doi.org/10.1016/J.WATRES.2019.02.054.

Kokalj, A.J., Hartmann, N.B., Drobne, D., Potthoff, A., Kühnel, D., 2021. Quality of nanoplastics and microplastics ecotoxicity studies: refining quality criteria for nanomaterial studies. J. Hazard. Mater. 415, 125751 https://doi.org/10.1016/J.JHAZMAT.2021.125751.

Koning, R.I., Vader, H., van Nugteren, M., Grocutt, P.A., Yang, W., Renault, L.L.R., Koster, A.J., Kamp, A.C.F., Schwertner, M., 2022. Automated vitrification of cryo-EM samples with controllable sample thickness using suction and real-time optical inspection. Nat. Commun. 13 (1), 1–10. https://doi.org/10.1038/s41467-022-30562-7.

Kristanti, R.A., Hadibarata, T., Wulandari, N.F., Sibero, M.T., Darmayati, Y., Hatmanti, A., 2022. Overview of microplastics in the environment: type, source, potential effects and removal strategies. Bioprocess Biosyst. Eng. 46 (3), 429–441. https://doi.org/10.1007/S00449-022-02784-Y/METRICS.

Kumar, R., Verma, A., Shome, A., Sinha, R., Sinha, S., Jha, P.K., Kumar, R., Kumar, P., Shubham, Das, S., Sharma, P., Prasad, P.V.V., 2021. Impacts of plastic pollution on ecosystem services, sustainable development goals, and need to focus on circular economy and policy interventions. Sustainability 13 (17), 9963. https://doi.org/10.3390/SU13179963.

Kumar, V., Singh, E., Singh, S., Pandey, A., Chaturvedi Bhargava, P., 2023. Micro- and nano-plastics (MNPs) as emerging pollutant in ground water: environmental impact, potential risks, limitations and way forward towards sustainable management. Chem. Eng. J. 459, 141568 https://doi.org/10.1016/J.CEJ.2023.141568.

Kusenberg, M., Roosen, M., Zayoud, A., Djokic, M.R., Dao Thi, H., de Meester, S., Ragaert, K., Kresovic, U., van Geem, K.M., 2022. Assessing the feasibility of chemical recycling via steam cracking of untreated plastic waste pyrolysis oils: feedstock impurities, product yields and coke formation. Waste Manag. 141, 104–114. https://doi.org/10.1016/j.wasman.2022.01.033.

Kutralam-Muniasamy, G., Pérez-Guevara, F., Shruti, V.C., 2022. A critical synthesis of current peer-reviewed literature on the environmental and human health impacts of COVID-19 PPE litter: new findings and next steps. J. Hazard. Mater. 422, 126945 https://doi.org/10.1016/J.JHAZMAT.2021.126945.

Kutralam-Muniasamy, G., Shruti, V.C., Pérez-Guevara, F., Roy, P.D., 2023. Microplastic diagnostics in humans: "the 3Ps" Progress, problems, and prospects. Sci. Total Environ. 856, 159164 https://doi.org/10.1016/J.SCITOTENV.2022.159164.

Lai, H., Liu, X., Qu, M., 2022. Nanoplastics and human health: hazard identification and biointerface. Nanomaterials 12 (8). https://doi.org/10.3390/NANO12081298.

Lai, Y., Dong, L., Li, Q., Li, P., Hao, Z., Yu, S., Liu, J., 2021. Counting nanoplastics in environmental waters by single particle inductively coupled plasma mass spectroscopy after cloud-point extraction and in situ labeling of gold nanoparticles. Environ. Sci. Technol. 55 (8), 4783–4791. https://doi.org/10.1021/ACS.EST.0C06839/SUPPL_FILE/ES0C06839_SI_001.PDF.

Lavoy, M., Crossman, J., 2021. A novel method for organic matter removal from samples containing microplastics. Environ. Pollut. 286, 117357 https://doi.org/10.1016/J.ENVPOL.2021.117357.

Lebreton, L., Andrady, A., 2019. Future scenarios of global plastic waste generation and disposal. *2019 5:1* Palgrave Commun. 5 (1), 1–11. https://doi.org/10.1057/s41599-018-0212-7.

Lehel, J., Murphy, S., 2021. Microplastics in the food chain: food safety and environmental aspects. Rev. Environ. Contam. Toxicol. 259, 1–49. https://doi.org/10.1007/398_2021_77/COVER.

LeMoine, C.M.R., Kelleher, B.M., Lagarde, R., Northam, C., Elebute, O.O., Cassone, B.J., 2018. Transcriptional effects of polyethylene microplastics ingestion in developing zebrafish (Danio rerio). Environ. Pollut. 243, 591–600. https://doi.org/10.1016/J.ENVPOL.2018.08.084.

Li, X., Zhang, T., Lv, W., Wang, H., Chen, H., Xu, Q., Cai, H., Dai, J., 2022. Intratracheal administration of polystyrene microplastics induces pulmonary fibrosis by activating oxidative stress and Wnt/β-catenin signaling pathway in mice. Ecotoxicol. Environ. Saf. 232, 113238 https://doi.org/10.1016/J.ECOENV.2022.113238.

Li, Y., Shao, L., Wang, W., Zhang, M., Feng, X., … W. L.-S. of the T, & 2020, undefined. (n.d.). Airborne fiber particles: types, size and concentration observed in Beijing. *Elsevier*. Retrieved March 9, 2023, from ⟨https://www.sciencedirect.com/science/article/pii/S0048969719359625⟩.

Li, Z., Zhu, S., Liu, Q., Wei, J., Jin, Y., Wang, X., Zhang, L., 2020a. Polystyrene microplastics cause cardiac fibrosis by activating Wnt/β-catenin signaling pathway and promoting cardiomyocyte apoptosis in rats. Environ. Pollut. 265, 115025 https://doi.org/10.1016/J.ENVPOL.2020.115025.

Li, Z., Zhu, S., Liu, Q., Wei, J., Jin, Y., Wang, X., Zhang, L., 2020b. Polystyrene microplastics cause cardiac fibrosis by activating Wnt/β-catenin signaling pathway and promoting cardiomyocyte apoptosis in rats. Environ. Pollut. 265, 115025 https://doi.org/10.1016/J.ENVPOL.2020.115025.

Lim, S.L., Ng, C.T., Zou, L., Lu, Y., Chen, J., Bay, B.H., Shen, H.M., Ong, C.N., 2019. Targeted metabolomics reveals differential biological effects of nanoplastics and nanoZnO in human lung cells. Nanotoxicology 13 (8), 1117–1132. https://doi.org/10.1080/17435390.2019.1640913.

Liu, K., Wang, X., Wei, N., Song, Z., international, D.L.-E., & 2019, undefined. (n.d.). Accurate quantification and transport estimation of suspended atmospheric microplastics in megacities: Implications for human health. *Elsevier*. Retrieved March 9, 2023, from ⟨https://www.sciencedirect.com/science/article/pii/S0160412019325206⟩.

Liu, K., Wu, T., Wang, X., Song, Z., Zong, C., Wei, N., Li, D., 2019b. Consistent transport of terrestrial microplastics to the ocean through atmosphere. Environ. Sci. Technol. 53 (18), 10612–10619. https://doi.org/10.1021/acs.est.9b03427.

Liu, L., Xu, K., Zhang, B., Ye, Y., Zhang, Q., Jiang, W., 2021. Cellular internalization and release of polystyrene microplastics and nanoplastics. Sci. Total Environ. 779, 146523 https://doi.org/10.1016/J.SCITOTENV.2021.146523.

Liu, N., Tang, M., Ding, J., 2020. The interaction between nanoparticles-protein corona complex and cells and its toxic effect on cells. Chemosphere 245, 125624. https://doi.org/10.1016/j.chemosphere.2019.125624.

Liu, Y., Lorenz, C., Vianello, A., Syberg, K., Nielsen, A.H., Nielsen, T.G., Vollertsen, J., 2023. Exploration of occurrence and sources of microplastics (>10 μm) in Danish marine waters. Sci. Total Environ. 865, 161255 https://doi.org/10.1016/J.SCITOTENV.2022.161255.

Löder, M.G.J., Gerdts, G., 2015. Methodology used for the detection and identification of microplastics—a critical appraisal. Mar. Anthropog. Litter 201–227. https://doi.org/10.1007/978-3-319-16510-3_8.

Lombardo, D., Calandra, P., Kiselev, M.A., 2020. Structural characterization of biomaterials by means of small angle X-rays and neutron scattering (SAXS and SANS), and light scattering experiments. Molecules 25 (23), 5624. https://doi.org/10.3390/molecules25235624.

Londoño, O.M., Tancredi, P., Rivas, P., Muraca, D., Socolovsky, L.M., Knobel, M., 2018. Small-angle X-ray scattering to analyze the morphological properties of nanoparticulated systems. Handbook of Materials Characterization. Springer International Publishing, pp. 37–75. https://doi.org/10.1007/978-3-319-92955-2_2.

Lu, L., Wan, Z., Luo, T., Fu, Z., Jin, Y., 2018. Polystyrene microplastics induce gut microbiota dysbiosis and hepatic lipid metabolism disorder in mice. *631–632* Sci. Total Environ. 449–458. https://doi.org/10.1016/J.SCITOTENV.2018.03.051.

Lu, S., Zhu, K., Song, W., Song, G., Chen, D., Hayat, T., Alharbi, N.S., Chen, C., Sun, Y., 2018. Impact of water chemistry on surface charge and aggregation of polystyrene microspheres suspensions. Sci. Total Environ. 630, 951–959. https://doi.org/10.1016/j.scitotenv.2018.02.296.

Lu, Y., Zhang, Y., Deng, Y., Jiang, W., Zhao, Y., Geng, J., Ding, L., Ren, H., 2016. Uptake and accumulation of polystyrene microplastics in zebrafish (Danio rerio) and toxic effects in liver. Environ. Sci. Technol. 50 (7), 4054–4060. https://doi.org/10.1021/ACS.EST.6B00183.

Luo, T., Zhang, Y., Wang, C., Wang, X., Zhou, J., Shen, M., Zhao, Y., Fu, Z., Jin, Y., 2019. Maternal exposure to different sizes of polystyrene microplastics during gestation causes metabolic disorders in their offspring. Environ. Pollut. 255, 113122 https://doi.org/10.1016/J.ENVPOL.2019.113122.

Lv, L., He, L., Jiang, S., Chen, J., Zhou, C., Qu, J., Lu, Y., Hong, P., Sun, S., Li, C., 2020. In situ surface-enhanced Raman spectroscopy for detecting microplastics and nanoplastics in aquatic environments. Sci. Total Environ. 728, 138449 https://doi.org/10.1016/j.scitotenv.2020.138449.

Ma, J., Chen, F., Xu, H., Jiang, H., Liu, J., Li, P., Chen, C.C., Pan, K., 2021a. Face masks as a source of nanoplastics and microplastics in the environment: quantification, characterization, and potential for bioaccumulation. Environ. Pollut. 288, 117748 https://doi.org/10.1016/j.envpol.2021.117748.

Ma, J., Chen, F., Xu, H., Jiang, H., Liu, J., Li, P., Chen, C.C., Pan, K., 2021b. Face masks as a source of nanoplastics and microplastics in the environment: quantification, characterization, and potential for bioaccumulation. Environ. Pollut. 288 (July), 117748 https://doi.org/10.1016/j.envpol.2021.117748.

MacLeod, M., Arp, H.P.H., Tekman, M.B., Jahnke, A., 2021. The global threat from plastic pollution. Science 373 (6550), 61–65. https://doi.org/10.1126/SCIENCE.ABG5433.

Magrì, D., Sánchez-Moreno, P., Caputo, G., Gatto, F., Veronesi, M., Bardi, G., Catelani, T., Guarnieri, D., Athanassiou, A., Pompa, P.P., & Fragouli, D. (n.d.). *Laser Ablation as a Versatile Tool to Mimic Polyethylene Terephthalate Nanoplastic Pollutants: Characterization and Toxicology Assessment.*

Mak, C., Yeung, K., safety, K.C.-E. and environmental, & 2019, undefined. (n.d.). Acute toxic effects of polyethylene microplastic on adult zebrafish. *Elsevier.* Retrieved March 8, 2023, from ⟨https://www.sciencedirect.com/science/article/pii/S0147651319307730⟩.

Makhdoumi, P., Hossini, H., Pirsaheb, M., 2022. A review of microplastic pollution in commercial fish for human consumption. Rev. Environ. Health 38 (1), 97–109. https://doi.org/10.1515/REVEH-2021-0103/ASSET/GRAPHIC/J_REVEH-2021-0103_FIG_001.JPG.

Makkar, H., Verma, S.K., Panda, P.K., Jha, E., Das, B., Mukherjee, K., Suar, M., 2018. In vivo molecular toxicity profile of dental bioceramics in embryonic Zebrafish (*Danio rerio*). Chem. Res. Toxicol. 31 (9), 914–923. https://doi.org/10.1021/acs.chemrestox.8b00129.

Makkar, H., Verma, S.K., Panda, P.K., Pramanik, N., Jha, E., Suar, M., 2018. Molecular insight to size and dose-dependent cellular toxicity exhibited by a green synthesized bioceramic nanohybrid with macrophages for dental applications. Toxicol. Res. 7 (5), 959–969. https://doi.org/10.1039/C8TX00112J.

Malloy, A., Carr, B., 2006. NanoParticle tracking analysis - the Halo™ System. Part. Part. Syst. Charact. 23 (2), 197–204. https://doi.org/10.1002/ppsc.200601031.

Manzoor, S., Naqash, N., Rashid, G., Singh, R., 2022. Plastic material degradation and formation of microplastic in the environment: a review. Mater. Today.: Proc. 56, 3254–3260. https://doi.org/10.1016/J.MATPR.2021.09.379.

Mariano, S., Tacconi, S., Fidaleo, M., Rossi, M., Dini, L., 2021. Micro and nanoplastics identification: classic methods and innovative detection techniques. Front. Toxicol. 3, 2. https://doi.org/10.3389/FTOX.2021.636640.

Mastrangelo, G., Fedeli, U., Fadda, E., Milan, G., Turato, A., Pavanello, S., 2003. Lung cancer risk in workers exposed to poly(vinyl chloride) dust: a nested case-referent study. Occup. Environ. Med. 60 (6), 423–428. https://doi.org/10.1136/oem.60.6.423.

Materić, D., Peacock, M., Dean, J., Futter, M., Maximov, T., Moldan, F., Röckmann, T., & Holzinger, R. (2021). Presence of nanoplastics in rural and remote surface waters. 1–21.

Mattsson, K., Ekvall, M.T., Hansson, L.A., Linse, S., Malmendal, A., Cedervall, T., 2015. Altered behavior, physiology, and metabolism in fish exposed to polystyrene nanoparticles. Environ. Sci. Technol. 49 (1), 553–561. https://doi.org/10.1021/ES5053655.

Mattsson, K., Johnson, E.V., Malmendal, A., Linse, S., Hansson, L.A., Cedervall, T., 2017. Brain damage and behavioural disorders in fish induced by plastic nanoparticles delivered through the food chain. Sci. Rep. 7 (1) https://doi.org/10.1038/S41598-017-10813-0.

Mintenig, S.M., Bäuerlein, P.S., Koelmans, A.A., Dekker, S.C., van Wezel, A.P., 2018. Closing the gap between small and smaller: towards a framework to analyse nano- and microplastics in aqueous environmental samples. Environ. Sci.: Nano 5 (7), 1640–1649. https://doi.org/10.1039/c8en00186c.

Molenaar, R., Chatterjee, S., Kamphuis, B., Segers-Nolten, I.M.J., Claessens, M.M.A.E., Blum, C., 2021. Nanoplastic sizes and numbers: quantification by single particle tracking. Environ. Sci.: Nano 8 (3), 723–730. https://doi.org/10.1039/d0en00951b.

Mortensen, N.P., Fennell, T.R., Johnson, L.M., 2021. Unintended human ingestion of nanoplastics and small microplastics through drinking water, beverages, and food sources. NanoImpact 21 (February), 100302. https://doi.org/10.1016/j.impact.2021.100302.

Moshood, T.D., Nawanir, G., Mahmud, F., Mohamad, F.B., Ahmad, M.S., Ghani, A.A., 2021. Expanding Policy for Biodegradable Plastic Products and Market Dynamics of Bio-Based Plastics: Challenges and Opportunities. Sustainability 13 (11), 6170. https://doi.org/10.3390/su13116170.

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. Sci. Total Environ. 822, 153339 https://doi.org/10.1016/J.SCITOTENV.2022.153339.

Nava, V., Frezzotti, M.L., & Leoni, B. (2021). Raman Spectroscopy for the Analysis of Microplastics in Aquatic Systems. ⟨Https://Doi.Org/10.1177/00037028211043119,⟩*75*(11), 1341–1357. https://doi.org/10.1177/00037028211043119.

Ng, T.P., Lee, H.S., Low, Y.M., Phoon, W.H., Ng, Y.L., 1991. Pulmonary effects of polyvinyl chloride dust exposure on compounding workers. Scand. J. Work, Environ. Health 17 (1), 53–59. https://doi.org/10.5271/SJWEH.1734.

Noventa, S., Boyles, M.S.P., Seifert, A., Belluco, S., Jiménez, A.S., Johnston, H.J., Tran, L., Fernandes, T.F., Mughini-Gras, L., Orsini, M., Corami, F., Castro, K., Mutinelli, F., Boldrin, M., Puntes, V., Sotoudeh, M., Mascarello, G., Tiozzo, B., McLean, P., Losasso, C., 2021. Paradigms to assess the human health risks of nano- and microplastics. *2021 1:1* Micro Nanoplastics 1 (1), 1–27. https://doi.org/10.1186/S43591-021-00011-1.

Okoye, C.O., Addey, C.I., Oderinde, O., Okoro, J.O., Uwamungu, J.Y., Ikechukwu, C.K., Okeke, E.S., Ejeromedoghene, O., Odii, E.C., 2022. Toxic chemicals and persistent organic pollutants associated with micro-and nanoplastics pollution. Chem. Eng. J. Adv. 11, 100310 https://doi.org/10.1016/j.ceja.2022.100310.

Panda, P.K., Verma, S.K., Suar, M., 2021. Nanoparticle–biological interactions: the renaissance of bionomics in the myriad nanomedical technologies. Nanomedicine 16 (25), 2249–2254. https://doi.org/10.2217/nnm-2021-0174.

Panda, P.K., Chavda, P., Neve, V., Mishra, K., Verma, S. K, S., Ahuja, R., 2022. COVID-19: lesson learnt from diagnostics to therapeutics. Microbial Engineering for Therapeutics. Springer Nature Singapore,, pp. 345–374. https://doi.org/10.1007/978-981-19-3979-2_16.

Panda, P.K., Kumari, P., Patel, P., Samal, S.K., Mishra, S., Tambuwala, M.M., Dutt, A., Hilscherová, K., Mishra, Y.K., Varma, R.S., Suar, M., Ahuja, R., Verma, S.K., 2022. Molecular nanoinformatics approach assessing the biocompatibility of biogenic silver nanoparticles with channelized intrinsic steatosis and apoptosis. Green. Chem. 24 (3), 1190–1210. https://doi.org/10.1039/D1GC04103G.

Patel, P., Nandi, A., Jha, E., Sinha, A., Mohanty, S., Panda, P.K., Mishra, S., Verma, S.K., Suar, M., 2021. Magnetic nanoparticles: fabrication, characterization, properties, and application for environment sustainability. Magnetic Nanoparticle-Based Hybrid Materials. Elsevier, pp. 33–64. https://doi.org/10.1016/B978-0-12-823688-8.00017-X.

Patil, S.M., Rane, N.R., Bankole, P.O., Krishnaiah, P., Ahn, Y., Park, Y.K., Yadav, K.K., Amin, M.A., Jeon, B.H., 2022. An assessment of micro- and nanoplastics in the biosphere: a review of detection, monitoring, and remediation technology. Chem. Eng. J. 430, 132913 https://doi.org/10.1016/J.CEJ.2021.132913.

Paul, M., Stock, V., Cara-Carmona, J., … E. L.-N, & 2020, undefined. (n.d.). Micro-and nanoplastics–current state of knowledge with the focus on oral uptake and toxicity. *Pubs.Rsc.Org*. Retrieved March 9, 2023, from ⟨https://pubs.rsc.org/en/content/articlehtml/2020/na/d0na00539h⟩.

Pearson, R.M., Juettner, V.V., Hong, S., 2014. Biomolecular corona on nanoparticles: a survey of recent literature and its implications in targeted drug delivery. Front. Chem. 2 https://doi.org/10.3389/fchem.2014.00108.

Pereao, O., Opeolu, B.O., Fatoki, O.S., 2020. Microplastics in aquatic environment: characterization, ecotoxicological effect, implications for ecosystems and developments in South Africa. Environmental Science and Pollution Research 27 (18), 22271–22291. https://doi.org/10.1007/s11356-020-08688-2.

Perera, K., Ziajahromi, S., Bengtson Nash, S., Manage, P.M., Leusch, F.D.L., 2022. Airborne microplastics in indoor and outdoor environments of a developing country in south asia: abundance, distribution, morphology, and possible sources. Environ. Sci. Technol. 56 (23), 16676–16685. https://doi.org/10.1021/ACS.EST.2C05885.

Pfeiffer, F., Fischer, E.K., 2020. Various digestion protocols within microplastic sample processing—evaluating the resistance of different synthetic polymers and the efficiency of biogenic organic matter destruction. Front. Environ. Sci. 8, 263. https://doi.org/10.3389/FENVS.2020.572424/BIBTEX.

Pfohl, P., Wagner, M., Meyer, L., Domercq, P., Praetorius, A., Hüffer, T., Hofmann, T., Wohlleben, W., 2022. Environmental degradation of microplastics: how to measure fragmentation rates to secondary micro- and nanoplastic fragments and dissociation into dissolved organics. Environ. Sci. Technol. 56 (16), 11323–11334. https://doi.org/10.1021/ACS.EST.2C01228/SUPPL_FILE/ES2C01228_SI_001.PDF.

Picó, Y., & Barceló, D. (2020). Journal Pre-proof Pyrolysis gas chromatography-mass spectrometry in environmental analysis: focus on organic matter and microplastics. https://doi.org/10.1016/j.trac.2020.115964.

Pitt, J.A., Kozal, J.S., Jayasundara, N., Massarsky, A., Trevisan, R., Geitner, N., Wiesner, M., Levin, E.D., Di Giulio, R.T., 2018. Uptake, tissue distribution, and toxicity of polystyrene nanoparticles in developing zebrafish (Danio rerio). Aquat. Toxicol. (Amst., Neth.) 194, 185–194. https://doi.org/10.1016/J.AQUATOX.2017.11.017.

Pitt, J.A., Trevisan, R., Massarsky, A., Kozal, J.S., Levin, E.D., Di Giulio, R.T., 2018. Maternal transfer of nanoplastics to offspring in zebrafish (Danio rerio): a case study with nanopolystyrene. Sci. Total Environ. 643, 324–334. https://doi.org/10.1016/J.SCITOTENV.2018.06.186.

Plastic production worldwide 2021 | Statista. (n.d.). Retrieved March 4, 2023, from ⟨https://www.statista.com/statistics/282732/global-production-of-plastics-since-1950/⟩.

Poma, A., Vecchiotti, G., Colafarina, S., Zarivi, O., Aloisi, M., Arrizza, L., Chichiriccò, G., Di Carlo, P., 2019. In vitro genotoxicity of polystyrene nanoparticles on the human fibroblast Hs27 cell line. Nanomaterials 9 (9). https://doi.org/10.3390/NANO9091299.

Porter, D.W., Castranova, V., Robinson, V. a, Hubbs, A.F., Mercer, R.R., Scabilloni, J., Goldsmith, T., Schwegler-berry, D., Battelli, L., Washko, R., Burkhart, J., Piacitelli, C., Whitmer, M., Jones, W., Virginia, W., 1999. Acute inflammatory reaction in rats after intratracheal instillation of material collected from a nylon flocking plant occupational interstitial lung disease (ILD) can result from exposure to various agents in the workplace, including crystalline silic. Toxicology 25–45.

Prata, J.C., 2018. Airborne microplastics: Consequences to human health? Environ. Pollut. 234, 115–126. https://doi.org/10.1016/j.envpol.2017.11.043.

Prata, J.C., Da Costa, Lopes, I., 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.

Prietl, B., Meindl, C., Roblegg, E., Pieber, T.R., Lanzer, G., Fröhlich, E., 2014. Nano-sized and micro-sized polystyrene particles affect phagocyte function. Cell Biol. Toxicol. 30 (1), 1–16. https://doi.org/10.1007/S10565-013-9265-Y.

Primpke, S., Booth, A.M., Gerdts, G., Gomiero, A., Kögel, T., Lusher, A., Strand, J., Scholz-Böttcher, B.M., Galgani, F., Provencher, J., Aliani, S., Patankar, S., & Vorkamp, K. (2022). Monitoring of microplastic pollution in the Arctic: recent developments in polymer identification, quality assurance and control, and data reporting. Https://Doi.Org/10.1139/as-2022–0006, 00, 1–22. https://doi.org/10.1139/AS-2022–0006.

Qiao, R., Sheng, C., Lu, Y., Zhang, Y., Ren, H., Lemos, B., 2019. Microplastics induce intestinal inflammation, oxidative stress, and disorders of metabolome and microbiome in zebrafish. Sci. Total Environ. 662, 246–253. https://doi.org/10.1016/J.SCITOTENV.2019.01.245.

Quattrini, F., Berrecoso, G., Crecente-Campo, J., Alonso, M.J., 2021. Asymmetric flow field-flow fractionation as a multifunctional technique for the characterization of polymeric nanocarriers. Drug Deliv. Transl. Res. 11 (2), 373. https://doi.org/10.1007/S13346-021-00918-5.

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. Sci. Total Environ. 757, 143872 https://doi.org/10.1016/j.scitotenv.2020.143872.

Ramsperger, A.F.R.M., Bergamaschi, E., Panizzolo, M., Fenoglio, I., Barbero, F., Peters, R., Undas, A., Purker, S., Giese, B., Lalyer, C.R., Tamargo, A., Moreno-Arribas, M.V., Grossart, H.P., Kühnel, D., Dietrich, J., Paulsen, F., Afanou, A.K., Zienolddiny-Narui, S., Eriksen Hammer, S., Laforsch, C., 2023. Nano- and microplastics: a comprehensive review on their exposure routes, translocation, and fate in humans. NanoImpact 29, 100441. https://doi.org/10.1016/J.IMPACT.2022.100441.

Reichel, J., Grabmann, J., Knoop, O., Drewes, J.E., Letzel, T., 2021. Organic contaminants and interactions with micro- and nano-plastics in the aqueous environment: review of analytical methods. Molecules 26 (4). https://doi.org/10.3390/MOLECULES26041164.

Reponen, T., Grinshpun, S.A., Conwell, K.L., Wiest, J., Anderson, M., 2001. Aerodynamic versus physical size of spores: measurement and implication for respiratory deposition. Grana 40 (3), 119–125. https://doi.org/10.1080/00173130152625851.

Revel, M., Châtel, A., Mouneyrac, C., 2018. Micro(nano)plastics: a threat to human health? Curr. Opin. Environ. Sci. Health 1, 17–23. https://doi.org/10.1016/j.coesh.2017.10.003.

Rhodes, C.J., 2019. Solving the plastic problem: From cradle to grave, to reincarnation. Science Progress 102 (3), 218–248. https://doi.org/10.1177/0036850419867204.

Rosenboom, J.G., Langer, R., Traverso, G., 2022. Bioplastics for a circular economy. Nat. Rev. Mater. 7 (2), 117–137. https://doi.org/10.1038/s41578-021-00407-8.

Rout, P.R., Mohanty, A., Aastha, Sharma, A., Miglani, M., Liu, D., Varjani, S., 2022. Micro- and nanoplastics removal mechanisms in wastewater treatment plants: A review. J. Hazard. Mater. Adv. 6, 100070 https://doi.org/10.1016/J.HAZADV.2022.100070.

Rubio, L., Marcos, R., Hernández, A., 2020. Potential adverse health effects of ingested micro- and nanoplastics on humans. Lessons learned from in vivo and in vitro mammalian models. J. Toxicol. Environ. Health - Part B: Crit. Rev. 23 (2), 51–68. https://doi.org/10.1080/10937404.2019.1700598.

Sajid, M., 2022. Advances in on-site analytical sample preparation for analysis of environmental waters: a review. Trends Environ. Anal. Chem. 36, e00175 https://doi.org/10.1016/J.TEAC.2022.E00175.

Samanta, P., Dey, S., Kundu, D., Dutta, D., Jambulkar, R., Mishra, R., Ghosh, A.R., Kumar, S., 2022. An insight on sampling, identification, quantification and characteristics of microplastics in solid wastes. Trends Environ. Anal. Chem. 36, e00181 https://doi.org/10.1016/J.TEAC.2022.E00181.

Sana, S.S., Dogiparthi, L.K., Gangadhar, L., Chakravorty, A., Abhishek, N., 2020. Effects of microplastics and nanoplastics on marine environment and human health. Environ. Sci. Pollut. Res. 27 (36), 44743–44756. https://doi.org/10.1007/s11356-020-10573-x.

Saravia, J., You, D., Thevenot, P., Lee, G.I., Shrestha, B., Lomnicki, S., Cormier, S.A., 2014. Early-life exposure to combustion-derived particulate matter causes pulmonary immunosuppression. Mucosal Immunol. 7 (3), 694–704. https://doi.org/10.1038/mi.2013.88.

Schrank, I., Möller, J.N., Imhof, H.K., Hauenstein, O., Zielke, F., Agarwal, S., Löder, M.G. J., Greiner, A., Laforsch, C., 2022. Microplastic sample purification methods - Assessing detrimental effects of purification procedures on specific plastic types. Sci. Total Environ. 833, 154824 https://doi.org/10.1016/J.SCITOTENV.2022.154824.

Schwaferts, C., Niessner, R., Elsner, M., Ivleva, N.P., 2019. Methods for the analysis of submicrometer- and nanoplastic particles in the environment. TrAC - Trends Anal. Chem. 112, 52–65. https://doi.org/10.1016/j.trac.2018.12.014.

Shanmugam, V., Das, O., Khorasani, S.N., Babu, K., Singh, S., Hedenqvist, M.S., Berto, F., Ramakrishna, S., 2020. Polymer Recycling in Additive Manufacturing: an Opportunity for the Circular Economy. Materials Circular Economy 2 (1). https://doi.org/10.1007/s42824-020-00012-0.

Shen, J., Liang, B., Zhang, D., Li, Y., Tang, H., Zhong, L., Xu, Y., 2021. Effects of PET microplastics on the physiology of Drosophila. Chemosphere 283, 131289. https://doi.org/10.1016/j.chemosphere.2021.131289.

Shi, Q., Tang, J., Liu, R., Wang, L., 2022. Toxicity in vitro reveals potential impacts of microplastics and nanoplastics on human health: a review. Crit. Rev. Environ. Sci. Technol. 52 (21), 3863–3895. https://doi.org/10.1080/10643389.2021.1951528.

Shi, Q., Tang, J., Wang, L., Liu, R., Giesy, J.P., 2021. Combined cytotoxicity of polystyrene nanoplastics and phthalate esters on human lung epithelial A549 cells and its mechanism. Ecotoxicology and Environmental Safety 213, 112041. https://doi.org/10.1016/j.ecoenv.2021.112041.

Shim, W.J., Hong, S.H., Eo, S.E., 2017. Identification methods in microplastic analysis: a review. Anal. Methods 9 (9), 1384–1391. https://doi.org/10.1039/c6ay02558g.

Shruti, V.C., Pérez-Guevara, F., Elizalde-Martínez, I., Kutralam-Muniasamy, G., 2021. Toward a unified framework for investigating micro(nano)plastics in packaged beverages intended for human consumption. Environ. Pollut. 268, 115811 https://doi.org/10.1016/J.ENVPOL.2020.115811.

Soong, Y.H.V., Sobkowicz, M.J., Xie, D., 2022. Recent advances in biological recycling of polyethylene terephthalate (PET) plastic wastes, 2022, Vol. 9, 98 Bioengineering 9 (3), 98. https://doi.org/10.3390/BIOENGINEERING9030098.

Stanton, T., Johnson, M., … P. N.-S. of the total, & 2019, undefined. (n.d.). Freshwater and airborne textile fibre populations are dominated by "natural", not microplastic, fibres. Elsevier. Retrieved March 9, 2023, from ⟨https://www.sciencedirect.com/science/article/pii/S0048969719307764⟩.

Stapleton, P.A., 2021. Microplastic and nanoplastic transfer, accumulation, and toxicity in humans. Current Opinion in Toxicology 28, 62–69. https://doi.org/10.1016/j.cotox.2021.10.001.

Stock, V., Böhmert, L., Lisicki, E., Block, R., Cara-Carmona, J., Pack, L.K., Selb, R., Lichtenstein, D., Voss, L., Henderson, C.J., Zabinsky, E., Sieg, H., Braeuning, A., Lampen, A., 2019. Uptake and effects of orally ingested polystyrene microplastic particles in vitro and in vivo. Arch. Toxicol. 93 (7), 1817–1833. https://doi.org/10.1007/S00204-019-02478-7/METRICS.

Sun, C., Yin, N., Wen, R., Liu, W., Jia, Y., Hu, L., Zhou, Q., Jiang, G., 2016. Silver nanoparticles induced neurotoxicity through oxidative stress in rat cerebral astrocytes is distinct from the effects of silver ions. NeuroToxicology 52, 210–221. https://doi.org/10.1016/j.neuro.2015.09.007.

Sun, M., Ding, R., Ma, Y., Sun, Q., Ren, X., Sun, Z., Duan, J., 2021. Cardiovascular toxicity assessment of polyethylene nanoplastics on developing zebrafish embryos. Chemosphere 282, 131124. https://doi.org/10.1016/J.CHEMOSPHERE.2021.131124.

Syafei, A., Nurasrin, N., … A. A.-C. W, & 2019, undefined. (n.d.). Microplastic pollution in the ambient air of Surabaya, Indonesia. Ailsa.Com. Retrieved March 9, 2023, from ⟨https://www.a-i-l-s-a.com/pdf/vol14no2/Vol14_No2_p_290–298.pdf⟩.

Tagorti, G., Kaya, B., 2022. Genotoxic effect of microplastics and COVID-19: the hidden threat. Chemosphere 286 (P3), 131898. https://doi.org/10.1016/j.chemosphere.2021.131898.

Taib, N.-A.A.B., Rahman, M.R., Huda, D., Kuok, K.K., Hamdan, S., Bakri, M.K. bin, Julaihi, M.R.M. bin, Khan, A., 2023. A review on poly lactic acid (PLA) as a biodegradable polymer. Polym. Bull. 80 (2), 1179–1213. https://doi.org/10.1007/s00289-022-04160-y.

Tenzer, S., Docter, D., Kuharev, J., Musyanovych, A., Fetz, V., Hecht, R., Schlenk, F., Fischer, D., Kiouptsi, K., Reinhardt, C., Landfester, K., Schild, H., Maskos, M., Knauer, S.K., Stauber, R.H., 2013. Rapid formation of plasma protein corona critically affects nanoparticle pathophysiology. Nat. Nanotechnol. 8 (10), 772–781. https://doi.org/10.1038/nnano.2013.181.

Ter Halle, A., Jeanneau, L., Martignac, M., Jardé, E., Pedrono, B., Brach, L., Gigault, J., 2017. Nanoplastic in the North Atlantic Subtropical Gyre. Environ. Sci. Technol. 51 (23), 13689–13697. https://doi.org/10.1021/ACS.EST.7B03667/SUPPL_FILE/ES7B03667_SI_001.PDF.

Tong, H., Zhong, X., Duan, Z., Yi, X., Cheng, F., Xu, W., Yang, X., 2022. Micro- and nanoplastics released from biodegradable and conventional plastics during degradation: formation, aging factors, and toxicity. Sci. Total Environ. 833, 155275 https://doi.org/10.1016/J.SCITOTENV.2022.155275.

Trevisan, R., Voy, C., Chen, S., di Giulio, R.T., 2019. Nanoplastics decrease the toxicity of a complex PAH mixture but impair mitochondrial energy production in developing zebrafish. Environ. Sci. Technol. 53 (14), 8405. https://doi.org/10.1021/ACS.EST.9B02003.

Uddin, S., Fowler, S.W., Habibi, N., Behbehani, M., 2022. Micro-nano plastic in the aquatic environment: methodological problems and challenges. Animals 12 (3), 297. https://doi.org/10.3390/ANI12030297/S1.

Valic, F., & Zuskin, E. (1977). Respiratory-function changes in textile workers exposed to synthetic fibres. December, 283–287.

Valsesia, A., Parot, J., Ponti, J., Mehn, D., Marino, R., Melillo, D., Muramoto, S., Verkouteren, M., Hackley, V.A., Colpo, P., 2021. Detection, counting and characterization of nanoplastics in marine bioindicators: a proof of principle study. *2021 1:1* Micro Nanoplastics 1 (1), 1–13. https://doi.org/10.1186/S43591-021-00005-Z.

van Pinxteren, M., Robinson, T.B., Zeppenfeld, S., Gong, X., Bahlmann, E., Fomba, K.W., Triesch, N., Stratmann, F., Wurl, O., Engel, A., Wex, H., Herrmann, H., 2022. High number concentrations of transparent exopolymer particles in ambient aerosol particles and cloud water - a case study at the tropical Atlantic Ocean. Atmos. Chem. Phys. 22 (8), 5725–5742. https://doi.org/10.5194/ACP-22-5725-2022.

Verma, S.K., Nandi, A., Sinha, A., Patel, P., Jha, E., Mohanty, S., Panda, P.K., Ahuja, R., Mishra, Y.K., Suar, M., 2021. Zebrafish (Danio rerio) as an ecotoxicological model for nanomaterial induced toxicity profiling. Precis. Nanomed. 4 (1) https://doi.org/10.33218/001c.21978.

Verma, S.K., Mishra, A.K., Suar, M., & Parashar, S.K. S. (2017). In vivo assessment of impact of titanium oxide nanoparticle on zebrafish embryo. 040030. https://doi.org/10.1063/1.4980232.

Vianello, A., Jensen, R.L., Liu, L., Vollertsen, J., 2019. Simulating human exposure to indoor airborne microplastics using a Breathing Thermal Manikin. Sci. Rep. 9 (1), 1–11. https://doi.org/10.1038/s41598-019-45054-w.

Vidal, C., Pasquini, C., 2021. A comprehensive and fast microplastics identification based on near-infrared hyperspectral imaging (HSI-NIR) and chemometrics. Environ. Pollut. 285, 117251 https://doi.org/10.1016/J.ENVPOL.2021.117251.

Vieira, Y., Lima, E.C., Foletto, E.L., Dotto, G.L., 2021. Microplastics physicochemical properties, specific adsorption modeling and their interaction with pharmaceuticals and other emerging contaminants. Sci. Total Environ. 753 https://doi.org/10.1016/J.SCITOTENV.2020.141981.

Vinyl Chloride - Cancer-Causing Substances - NCI . (n.d.). Retrieved March 8, 2023, from 〈https://www.cancer.gov/about-cancer/causes-prevention/risk/substances/vinyl-chloride〉.

Waldschläger, K., Brückner, M.Z.M., Carney Almroth, B., Hackney, C.R., Adyel, T.M., Alimi, O.S., Belontz, S.L., Cowger, W., Doyle, D., Gray, A., Kane, I., Kooi, M., Kramer, M., Lechthaler, S., Michie, L., Nordam, T., Pohl, F., Russell, C., Thit, A., Wu, N., 2022. Learning from natural sediments to tackle microplastics challenges: a multidisciplinary perspective. Earth-Sci. Rev. 228, 104021 https://doi.org/10.1016/J.EARSCIREV.2022.104021.

Wang, C., Zhao, J., Xing, B., 2021. Environmental source, fate, and toxicity of microplastics. J. Hazard. Mater. 407, 124357 https://doi.org/10.1016/j.jhazmat.2020.124357.

Wang, X., Li, C., Liu, K., Zhu, L., Song, Z., materials, D.L.-J. of hazardous, & 2020, undefined. (n.d.). Atmospheric microplastic over the South China Sea and East Indian Ocean: abundance, distribution and source. Elsevier. Retrieved March 9, 2023, from 〈https://www.sciencedirect.com/science/article/pii/S030438941931800X〉.

Wang, Y., Huang, J., Zhu, F., Zhou, S., 2021. Airborne microplastics: a review on the occurrence, migration and risks to humans. Bull. Environ. Contam. Toxicol. 107 (4), 657–664. https://doi.org/10.1007/s00128-021-03180-0.

Wieland, S., Balmes, A., Bender, J., Kitzinger, J., Meyer, F., Ramsperger, A.F., Roeder, F., Tengelmann, C., Wimmer, B.H., Laforsch, C., Kress, H., 2022. From properties to toxicity: comparing microplastics to other airborne microparticles. J. Hazard. Mater. 428, 128151 https://doi.org/10.1016/J.JHAZMAT.2021.128151.

Win-Shwe, T.T., Fujimaki, H., 2011. Nanoparticles and neurotoxicity. Int. J. Mol. Sci. 12 (9), 6267–6280. https://doi.org/10.3390/ijms12096267.

Wright, S.L., Ulke, J., Font, A., Chan, K.L.A., Kelly, F.J., 2020. Atmospheric microplastic deposition in an urban environment and an evaluation of transport. Environ. Int. 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. Micro Nanoplastics 1 (1), 1–18. https://doi.org/10.1186/s43591-021-00006-y.

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. J. Hazard. Mater. 437, 129361 https://doi.org/10.1016/J.JHAZMAT.2022.129361.

Xu, M., Halimu, G., Zhang, Q., Song, Y., Fu, X., Li, Y., Li, Y., Zhang, H., 2019. Internalization and toxicity: a preliminary study of effects of nanoplastic particles on human lung epithelial cell. Sci. Total Environ. 694, 133794 https://doi.org/10.1016/j.scitotenv.2019.133794.

Yakovenko, N., Carvalho, A., ter Halle, A., 2020. Emerging use thermo-analytical method coupled with mass spectrometry for the quantification of micro(nano)plastics in environmental samples. TrAC Trends Anal. Chem. 131, 115979 https://doi.org/10.1016/J.TRAC.2020.115979.

Yang, Y.F., Chen, C.Y., Lu, T.H., Liao, C.M., 2019. Toxicity-based toxicokinetic/toxicodynamic assessment for bioaccumulation of polystyrene microplastics in mice. J. Hazard. Mater. 366, 703–713. https://doi.org/10.1016/J.JHAZMAT.2018.12.048.

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. Environ. Sci.: Atmos. 2 (5), 921–942. https://doi.org/10.1039/D2EA00041E.

Yao, Y., Glamoclija, M., Murphy, A., Gao, Y., 2022. Characterization of microplastics in indoor and ambient air in northern New Jersey. Environ. Res. 207, 112142 https://doi.org/10.1016/j.envres.2021.112142.

Yee, M.S.L., Hii, L.W., Looi, C.K., Lim, W.M., Wong, S.F., Kok, Y.Y., Tan, B.K., Wong, C.Y., Leong, C.O., 2021. Impact of microplastics and nanoplastics on human health. Nanomaterials 11 (2), 1–23. https://doi.org/10.3390/NANO11020496.

Yong, C.Q.Y., Valiyaveettil, S., Tang, B.L., 2020. Toxicity of microplastics and nanoplastics in Mammalian systems. Int. J. Environ. Res. Public Health 17 (5). https://doi.org/10.3390/ijerph17051509.

Yousif, E., Ahmed, D., Zainulabdeen, K., Jawad, A., 2023. Photo-physical and morphological study of polymers: a review. Phys. Chem. Res. 11 (2), 409–424. https://doi.org/10.22036/PCR.2022.342751.2105.

Yu, Y., Chen, H., Hua, X., Dang, Y., Han, Y., Yu, Z., Chen, X., Ding, P., Li, H., 2020. Polystyrene microplastics (PS-MPs) toxicity induced oxidative stress and intestinal injury in nematode Caenorhabditis elegans. Sci. Total Environ. 726, 138679 https://doi.org/10.1016/j.scitotenv.2020.138679.

Yu, Y., Luan, Y., Dai, W., 2022. Time evolution of protein corona formed by polystyrene nanoplastics and urease. Int. J. Biol. Macromol. 218, 72–81. https://doi.org/10.1016/j.ijbiomac.2022.07.104.

Yu, Z. fu, Song, S., Xu, X., lu, Ma, Q., Lu, Y., 2021. Sources, migration, accumulation and influence of microplastics in terrestrial plant communities. Environ. Exp. Bot. 192, 104635 https://doi.org/10.1016/J.ENVEXPBOT.2021.104635.

Yuan, Z., Nag, R., Cummins, E., 2022. Human health concerns regarding microplastics in the aquatic environment - from marine to food systems. Sci. Total Environ. 823, 153730 https://doi.org/10.1016/J.SCITOTENV.2022.153730.

Yukioka, S., Tanaka, S., Nabetani, Y., Suzuki, Y., Ushijima, T., Fujii, S., Takada, H., van Tran, Q., Singh, S., 2020. Occurrence and characteristics of microplastics in surface road dust in Kusatsu (Japan), Da Nang (Vietnam), and Kathmandu (Nepal). Environ. Pollut. 256, 113447 https://doi.org/10.1016/j.envpol.2019.113447.

Zarreen Simnani, F., Singh, D., Patel, P., Choudhury, A., Sinha, A., Nandi, A., Kumar Samal, S., Verma, S.K., Kumar Panda, P., 2023. Nanocarrier vaccine therapeutics for global infectious and chronic diseases. Mater. Today. https://doi.org/10.1016/j.mattod.2023.04.008.

Zarus, G.M., Muianga, C., Hunter, C.M., Pappas, R.S., 2021. A review of data for quantifying human exposures to micro and nanoplastics and potential health risks. Sci. Total Environ. 756, 144010 https://doi.org/10.1016/j.scitotenv.2020.144010.

Zhang, M., Xu, L., 2022. Transport of micro- and nanoplastics in the environment: trojan-Horse effect for organic contaminants. Crit. Rev. Environ. Sci. Technol. 52 (5), 810–846. https://doi.org/10.1080/10643389.2020.1845531.

Zhang, Q., Xu, E.G., Li, J., Chen, Q., Ma, L., Zeng, E.Y., Shi, H., 2020. A review of microplastics in table salt, drinking water, and air: direct human exposure. Environ. Sci. Technol. 54 (7), 3740–3751. https://doi.org/10.1021/acs.est.9b04535.

Zhang, Q., Zhao, Y., Du, F., Cai, H., Wang, G., Shi, H., 2020. Microplastic fallout in different indoor environments. Environ. Sci. Technol. 54 (11), 6530–6539. https://doi.org/10.1021/acs.est.0c00087.

Zhang, Q., He, Y., Cheng, R., Li, Q., Qian, Z., Lin, X., 2022. Recent advances in toxicological research and potential health impact of microplastics and nanoplastics in vivo. Environ. Sci. Pollut. Res. 29 (27), 40415–40448. https://doi.org/10.1007/s11356-022-19745-3.

Zhang, Y., Kang, S., Allen, S., Allen, D., Gao, T., Sillanpää, M., 2020. Atmospheric microplastics: a review on current status and perspectives. Earth-Sci. Rev. 203, 103118 https://doi.org/10.1016/j.earscirev.2020.103118.

Zhao, S., Zettler, E.R., Bos, R.P., Lin, P., Amaral-Zettler, L.A., Mincer, T.J., 2022. Large quantities of small microplastics permeate the surface ocean to abyssal depths in the South Atlantic Gyre. Glob. Change Biol. 28 (9), 2991–3006. https://doi.org/10.1111/GCB.16089.

Zhao, T., Shen, L., Ye, X., Bai, G., Liao, C., Chen, Z., Peng, T., Li, X., Kang, X., An, G., 2023. Prenatal and postnatal exposure to polystyrene microplastics induces testis developmental disorder and affects male fertility in mice. J. Hazard. Mater. 445, 130544 https://doi.org/10.1016/J.JHAZMAT.2022.130544.

Zhou, X.X., Liu, R., Liu, J.F., 2014. Rapid chromatographic separation of dissoluble Ag(I) and silver-containing nanoparticles of 1-100 nanometer in antibacterial products and environmental waters. Environ. Sci. Technol. 48 (24), 14516–14524. https://doi.org/10.1021/es504088e.

Zhu, M., Chernick, M., Rittschof, D., Hinton, D.E., 2020. Chronic dietary exposure to polystyrene microplastics in maturing Japanese medaka (Oryzias latipes). Aquat. Toxicol. 220 https://doi.org/10.1016/J.AQUATOX.2019.105396.

Zhu, X., Wang, C., Duan, X., Liang, B., Genbo Xu, E., Huang, Z., 2023. Micro- and nanoplastics: a new cardiovascular risk factor? Environ. Int. 171, 107662 https://doi.org/10.1016/J.ENVINT.2022.107662.

Zuskin, E., Mustajbegovic, J., Schachter, E.N., Kern, J., Budak, A., Godnic-Cvar, J., 1998. Respiratory findings in synthetic textile workers. Am. J. Ind. Med. 33 (3), 263–273. https://doi.org/10.1002/(SICI)1097-0274(199803)33:3<263::AID-AJIM8>3.0.CO;2-X.

Zvekic, M., Richards, L.C., Tong, C.C., Krogh, E.T., 2022. Characterizing photochemical ageing processes of microplastic materials using multivariate analysis of infrared spectra. Environ. Sci.: Process. Impacts 24 (1), 52–61. https://doi.org/10.1039/D1EM00392E.