Health Implications of Microplastic Exposure: A Comprehensive Analysis of Physiological and Neurological Risks

Sufiya Khan 1*, Anjali Yadav 1, Urvashi Sharma 2, Naaz Parween 1, Tushar 1,

1 Department of Pharmacology, Ram-Eesh Institute of Vocational and Technical Education, Greater Noida, UP-201310

2 Ishan Ayurvedic Medical College and Research Centre, Greater Noida, UP-201310

*** Corresponding author: Sufiya Khan**, Email: (sufiyakhan12r3@gmail.com), Department of Pharmacology, Ram-Eesh Institute of Vocational and Technical Education, Greater Noida, UP - 201310, India.

Declarations

Ethical approval and consent to participate

Not Applicable

Consent of publication

Not Applicable

Competing interests

The authors declare no competing interests

Funding

No Funding

Abstract

Background
Microplastics (MPs) are particles of plastic less than 5 mm in diameter and have become ubiquitous pollutants. Their growing occurrence in food, air, and water causes serious concerns about human health effects, especially in relation to physiological and neurological systems.

Objectives
The purpose of conducting this review is to summarise existing data on the negative health impacts of exposure to microplastics. It concentrates on exposure pathways, cellular and molecular pathways of toxicity and accumulation by the tissue, with a special emphasis on the possible association with chronic diseases.

Methods
Systematic reviews of in vitro and in vivo and epidemiological investigations have been done to assess the biological impact of MPs. The focus was on pathways of exposures like ingestion, inhalation, and dermal absorption, and organ-specific distribution and mechanistic outcomes.

Results
Recent evidence shows that MPs cause oxidative stress, inflammatory reactions and cellular homeostasis disturbances. The build-up has been reported in the lungs, liver, kidneys and the brain. There is experimental evidence that nanoplastics may cross the biological barriers, such as,the blood-brain barrier, causing neuroinflammation and possible neurodegeneration. Metabolic disorders and cardiovascular complications have also been found to have associations with it.

Conclusions

The exposure to microplastics and nanoplastics has severe physiological and neurological toxicity via various pathways. There is a need to conduct further research to clarify long-term health outcomes, dose-response relationships, and molecular interaction mechanisms to inform preventive and regulatory policies.

Keywords: Microplastics, Nanoplastics, Human health, Neurotoxicity, Oxidative stress, Inflammation, Bioaccumulation

Introduction

Plastic manufacturing, which developed in the middle of the 20th century, has led to a massive amount of plastic waste in the environment that has never been observed previously. In 2023, the amount of plastic that was produced around the globe was higher than 400 million tons, and it is projected to grow further [1,2]. Larger plastic debris gets fragmented into microplastics (1–5000 μm) and nanoplastics (None), through degradation processes such as photodegradation, mechanical fragmentation, and biodegradation and has now occupied virtually all of the environmental compartments: air, water, soil, and food, subject to degradation [3].

Recent research has even found microplastics in the human blood, lung tissue, placenta, and stool, thus establishing that human beings continue to be exposed to the particles in various ways. On average, the estimated figure is 39,000-52,000 microplastic particles consumed in food and water every year, with inhalation being an additional to the previous exposure. These particles are small, and as a result, they permeate biological barriers and accumulate in tissues, and may cause different responses of pathophysiology.[4]

The problem of microplastic toxicity is not only a manifestation of the physical presence of the components but also relates to the chemical additives (plasticisers, flame retardants, and colourants) and the adsorption of environmental contaminants (heavy metals and persistent

organic pollutants). Such components of the plastic can be washed away and added to the toxic load. The present review is a discussion of the existing level of knowledge on the health effects of microplastic exposure, focusing on the examination of physiological and neurological threats recorded in recent literature. [5,6]

2. Pathways and Routes of Human Exposure.

2.1 Ingestion

The main path of exposure to microplastics is through diet. The contamination has been reported in various food types such as seafood, salt, honey, beer, bottled water, and fresh food. The feeding habits of marine life have led to significant deposits of microplastics, particularly in filter-feeders such as mussels and oysters.[7] One portion of mussels has the potential to have as many as 90 microplastic particles. Another important source of microplastics is the consumption of both tap and bottled water, with bottled water exhibiting the highest contamination rates, ranging from 10 to 6,000 parts per litre. Plastic packaging causes food contamination due to the migration of particles during storage, and in particular when it is subjected to heat or mechanical force.[8]

2.2 Inhalation

Textile fibres, tyre wear products, and degradation of plastic items, as well as industrial activities, are all sources of airborne microplastics. Microplastics generally have greater levels of concentration in indoor air than outdoors, with synthetic fabrics and carpeting being significant sources. Research approximates that human beings breathe 272 to 304 microplastic particles in houses every day.[9] The current rates of inhalation may be very high because of the occupational exposures in the textile, manufacturing, and waste management industries. The structure of the respiratory system enables particles that are less than 100 μm to move to the deep parts of the alveoli, where they could be translocated to the systemic circulation.[10]

2.3 Dermal Contact

Devoid of research, dermal exposure occurs via the use of personal care products containing microbeads, synthetic textiles, and environmental contact. The cosmetics contain microplastics, which can come in direct contact with skin and mucous membranes, especially facial scrubs and toothpastes. Most microplastics generally penetrate the intact skin barrier, but because of broken skin or inflamed skin, they can gain entry. Nanoplastics can enter healthy skin through hair follicles and sweat glands, but the penetration degree of this method is not well documented.[11]

Table 1: Major Sources and Estimated Daily Exposure to Microplastics

Exposure Route	Primary Sources	Estimated Daily Exposure	Particle Size Range
Ingestion	Drinking water, seafood, salt, packaged foods	106-142 particles/day	1-5000 μm
Inhalation	Indoor air, textile fibres, tyre particles	272-304 particles/day	0.1-100 μm
Dermal	Personal care products, textiles	Unknown (minimal)	5-500 μm

3. Mechanisms of Cellular Toxicity

3.1 Oxidative Stress

Microplastics have been seen to induce oxidative stress in various ways. Reactive oxygen species (ROS) generation is usually achieved through the interaction of particles and cells, mitochondrial electron transport chain perturbation, and inflammatory cell activation. The net effect of ROS accumulation is an overload of cellular defences against oxidants, which results in lipid peroxidation, protein oxidation, and DNA damage. In vitro experiments indicate that the microplastics in polystyrene cause a dose-related elevation of intracellular ROS in human epithelial and endothelial cell lines.[12] Depending on size, shape, and surface charge, the nature of the microplastics' surfaces determines the intensity of the oxidative stress response. Nanoplastics have a large surface area/volume ratio, and the ROS-generating potential is especially advantageous in this case.[13]

3.2 Inflammatory Response

Microplastics cause acute and chronic inflammatory reactions. Treatment with microplastics as foreign objects leads to activation of pattern recognition receptors and triggers inflammatory cascades of events via NF. This eliminates the need for NF-KB, MAPK, and the inflammasome, which are responsible for initiating inflammatory responses in astrocytes and microglia in the hippocampus to remove these particles.[14] Long-term exposure can result in long-term low-grade inflammation, which has been linked to many pathological actions such as metabolic syndrome, cardiovascular disease, and neurodegeneration. The inflammatory agent, especially NLRP3, is at the center of the inflammation caused by microplastic uptake. NLRP3 activation causes caspase-1 release and release of mature IL-18 and IL-1, not only stopping the inflammatory signal but also amplifying the effect of further propagation of the signal.[15]

3.3 Membrane Disturbance and Cytoplasmic uptake.

The interaction of microplastics and the cell membrane is determined by the nature of the particles and the type of cell. The main form of cellular internalization of microplastics is endocytosis, and several pathways are involved in this process, such as clathrin-mediated, caveolae-mediated, and macropinocytosis.[16] The smaller particles below 150 nm may enter the cells by clathrin-coated pits, and larger particles may enter the cells in different ways. After internalisation, microplastics are able to interfere with autophagy as well as lysosomal functioning and accumulation in intracytoplasmic compartments. Direct mechanical damage to membranes may also occur during physical contact with them, especially in the case of sharp or irregularly shaped particles. Disruption of membranes may cause ionic dysregulation, membrane potential loss, and, therefore, cell death.[17,18]

3.4 Genotoxicity

Microplastics demonstrate genotoxic effects, which include both direct and indirect effects. Oxidative damage of the DNA by ROS causes a break in strands, alteration of bases, and aberration of the chromosomes. Using comet analysis and micronucleus tests, studies have recorded DNA damage in human cell lines subjected to different types of microplastics. Furthermore, the microplastics may disrupt cell division, resulting in aneuploidy and chromosomal instability due to their physical presence.[19] The genotoxic chemicals may be delivered to the cells more easily through the adsorption of genotoxic chemicals to the surface of the microplastic, increasing the genotoxic effects. The long-term effects include a higher rate of mutation and a potential carcinogenic risk; however, no significant epidemiological data have been found so far.[20]

4. Physiological Health Implications

4.1 Gastrointestinal System

The major entry point for ingested microplastics is the gastrointestinal tract. It has been shown that microplastics have the potential to change the composition of intestinal microbiota, as well as disrupt the functioning of the intestinal barrier and cause a local inflammatory response. Chronic exposure to microplastics in animals causes dysbiosis; decreased diversity of the microbes and changes in the proportion of Firmicutes and Bacteroidetes. Breakage of the gut epithelial barrier, commonly known as leaky gut, promotes gut microplastic and bacterial endotoxin translocation into the circulatory mass.[21] This impaired basement membrane is associated with augmented intestinal permeability, tight junction protein breakdown, and a thin mucus layer. Possible clinical correlates include exacerbations of inflammatory bowel disease; however, direct evidence in humans is limited.[22]

4.2 Respiratory System

Exposure to microplastics is extremely dangerous to respiratory health. The manner of deposition is determined by the aerodynamic diameter of the particles, where particles smaller than 10 μm can reach the airways.[23] The fiber-shaped microplastics, especially with a high aspect ratio, are biopersistent and may cause the same local response in the body as asbestos fibres. Occupational exposure to asbestos as a chronic inhalation exposure through inhalation has been attributed to high prevalence of respiratory symptoms, impaired lung performance, and high pulmonary inflammatory markers.[24] Investigations in animals have shown that through inhalation of microplastics, pulmonary fibrosis, granuloma formation, and pathology characteristic of chronic obstructive pulmonary disease develop. Recent discoveries of microplastics in human lung tissue by various research groups demonstrate the clinical significance of respiratory exposure.[25]

4.3 Cardiovascular System

There is some emerging evidence of the cardiovascular impacts of exposure to microplastics. When microplastics are translocated out of the gut or the lung into the bloodstream, they are able to be distributed throughout the body and accumulate in cardiovascular tissues.[26] It has been reported that microplastics were found in human atherosclerotic plaques, and they may contribute to the formation or development of a plaque. Theorized pathways of microplastic-cardiovascular risk have been suggested to be endothelial dysfunction, stimulation of oxidative stress and inflammation, disruption of lipid metabolism, and possible prothrombotic effects. Testing on animals indicates that exposure to microplastics will make atherosclerosis worse, and vascular reactivity will also be compromised.[27] There is a high urgency to put epidemiological studies in place to deepen our comprehension of the links between cardiovascular disease outcomes and environmental microplastic exposure in humans.[28]

4.4 Hepatic System

The liver, which is the main organ of detoxification, is one of the main locations where microplastic accumulates after taking place in the system. [29,30] The lipid accumulation (steatosis), oxidative injury, inflammatory cellular infiltration, and fibrotic alterations are all examples of hepatic effects in animal models. Exposure to microplastics disrupts hepatic lipid metabolism, which causes the accumulation of triglycerides and even the pathology of non-alcoholic fatty liver disease.[31] Furthermore, the microplastics can interfere with xenobiotic metabolism through the influence on cytochrome P450 enzyme activity and the expression of cytochrome P450 enzymes. These disruptions may affect the absorption of the drugs and the elimination of other environmental pollutants. Exposure to hepatocyte damage is indicated by the high level of liver enzymes and the effects of histopathological changes in the exposed animals.[32]

4.5 Renal System

Excretion and renal filtration processes contact microplastics, which are circulating on the circuit. Although the large particles are not expected to go through glomerular filtration, nanoplastics can go past the filtration barrier and become deposited into the renal tubules. Research claims microplastics have nephrotoxicity as a result of tubular injury, glomerular damage, and interstitial fibrosis in animal study models.[33] These pathological changes are helped by the oxidative stress and inflammatory reactions of renal tissue. There is also the possibility of microplastics accumulating in the kidneys and reducing their functionality in the long term, which can cause chronic kidney disease.[34] Nevertheless, there is a lack of human data on the microplastic content of the kidney and related outcomes of its functions.[35]

Table 2: Organ-Specific Physiological Effects of Microplastic Exposure

Organ System	Primary Effects	Pathological Outcomes	Evidence Level	References
Gastrointestinal	Dysbiosis, barrier disruption	Inflammation, increased permeability	Animal/In vitro	[36,37]
Respiratory	Inflammation, fibrosis	Reduced lung function, COPD-like changes	Human/Animal	[37]
Cardiovascular	Endothelial dysfunction, plaque formation	Atherosclerosis, vascular impairment	Limited human	[38,39]
Hepatic	Steatosis, oxidative stress	Fatty liver disease, fibrosis	Animal/In vitro	[40,41]
Renal	Tubular damage, filtration impairment	Nephrotoxicity, fibrosis	Animal	[42,43]

5. Neurological and Neurodevelopmental Risks

5.1 Blood-Brain Barrier Penetration

Various chemical substances can penetrate the physical barrier of the blood-brain barrier (Barley, 2007). The most important aspect of neurotoxicity with microplastics is that they can

pass across the blood-brain barrier (BBB). Recent research has shown that nanoplastics (particles smaller than 100 nm) can compromise the BBB in several different ways, such as transcytosis, breaking of tight junctions, and the utilization of nutrient transport systems.[44] These particles are able to build up in neural tissue and cause inflammatory and oxidative stress once in the brain. Another issue is the Trojan horse phenomenon, in which the microplastics adsorb and carry other neurotoxic substances across the BBB. Direct or oral polystyrene lectures have been studied in animals with preferential accumulation of the nanoplastics in the brains, with portions such as the hippocampus, cortex, and hypothalamus.[45]

5.2. Neuroinflammation and Neurotoxicity

Microglial activation and neuroinflammation are the initial pathways of neurotoxicity in microplastics. Interaction with microplastics triggers microglia stimulation, resulting in the release of pro-inflammatory mediators and neurotoxic factors. The chronic neuroinflammation has several mediators of neuronal dysfunction and death, among which are excitotoxicity, oxidative damage, and disruption of synapses. [46,47] The rodent model studies demonstrate that exposure to microplastics can result in behavior changes such as anxiety-like behavior, depression-like behavior, and cognitive impairment. Such changes in behavior are associated with molecular evidence of neuroinflammation and oxidative stress, as well as changes in the levels of neurotransmitters. Dopaminergic and cholinergic neurons are the ones that seem especially susceptible to exposure to microplastics.[48]

5.3 Neurodegenerative Disease

There is some new evidence of a possible relationship between exposure to microplastics and neurodegenerative diseases. Microplastics' ability to cause chronic neuroinflammation, oxidative stress, and protein aggregation makes inroads into their application in the development of disorders like Alzheimer's, Parkinson's, and amyotrophic lateral sclerosis. Among other effects, microplastics were reported to foster aggregation of amyloid-beta and alpha-synuclein proteins in vitro, and these effects can accelerate the pathological process.[49] Furthermore, microplastics can disrupt autophagy and proteasomal degradation machineries, which could interfere with the clearance of misfolded proteins. Although direct causal relationships were not established in human beings, there is the potential biological plausibility that needs to be taken seriously and further investigated.[50]

5.4 Neurodevelopmental Effects

The human brain is particularly more sensitive to environmental toxicants, such as microplastics, in the developmental stage. In animal models, exposure to microplastics during pregnancy and the early postnatal stage causes neurodevelopmental abnormalities, including abnormal brain morphology, impaired neurogenesis, and abnormal synaptic development.[51] The behavioral effects experienced in children include hyperactivity, poor learning and memory, and disturbed social behavior. The effects could continue in adulthood, meaning that they could have a long-lasting effect on neurodevelopment. The presence of microplastics in

the human placenta confirms the exposure of foetuses to these chemicals, underscoring the pressing need to identify neurodevelopmental risks.[52] There are possible parallels in one way or another with other developmental neurotoxicants, implying that microplastics may also be a contributing factor to the increased prevalence of neurodevelopmental disorders, which is currently not supported by epidemiological evidence.[53]

Figure 1a: Pathways of Microplastic-Induced Neurotoxicity

1

BBB Penetration: Nanoplastics cross blood-brain barrier via transcytosis and tight junction disruption [89].

2

Microglial Activation: Recognition of particles triggers inflammatory response and cytokine release [90]

3

Oxidative Stress: ROS generation leads to neuronal damage and mitochondrial dysfunction [91].

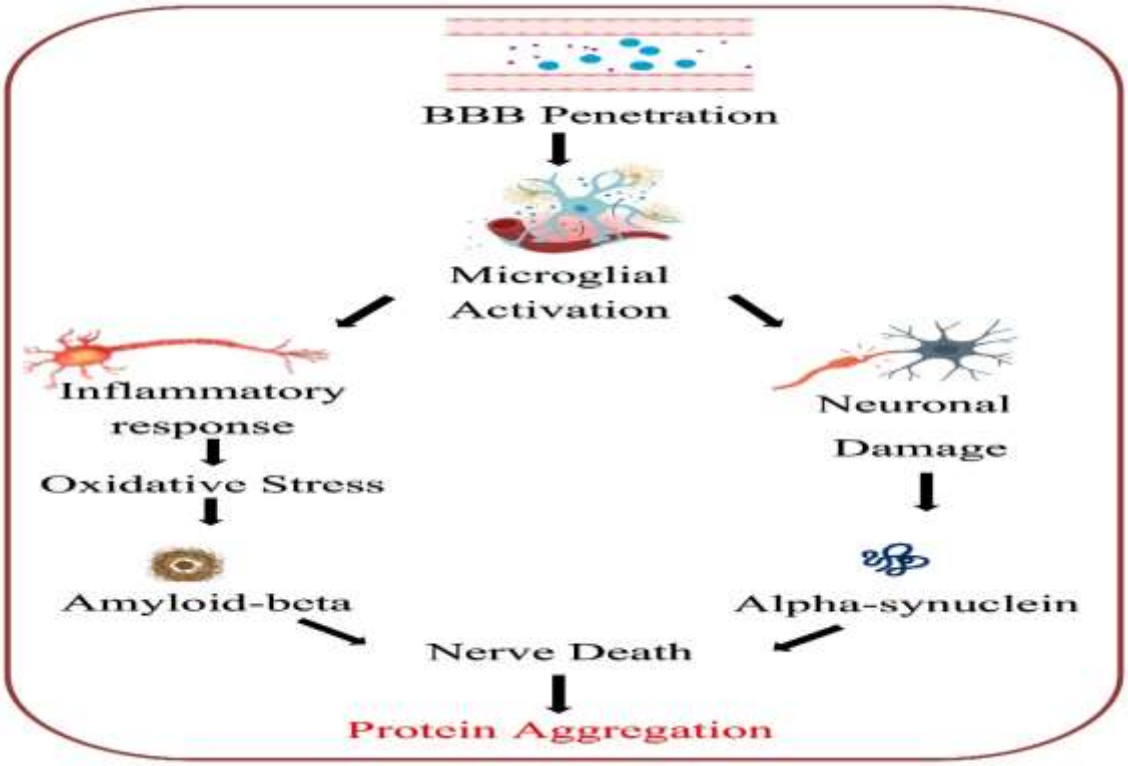
4

Protein Aggregation: Promotion of amyloid-beta and alpha-synuclein accumulation [92].

5

Neuronal Death: Combined effects result in apoptosis and neurodegeneration [93]

Figure 1b: Proposed mechanism of neurodegeneration



6. Bioaccumulation and Organ Selectivity.

After their ingestion in the body, microplastics are distributed to other body organs and tissues. The distribution pattern is also dependent on various factors such as particle size, shape, and surface chemistry, as well as polymer type. The experimental studies of fluorescently labelled microplastics present in the animal models show that they accumulate in the liver, spleen, kidneys, lungs, brain, and even reproductive organs.[54] Smaller-sized particles, such as nanoplastics, have higher tissue penetration and distribution rates than larger, micro-sized plastics. Blood circulation is the main pathway to systemic distribution when it has been translocated across epithelial cells.[55]

Bio-porosity is a very important property of microplastics. Synthetic polymers do not degrade biologically (as organic molecules do), and so the residence time of the tissue increases. The dwelling period of microplastics in different organs is under-characterised in humans, but animal research indicates that the dwellings could take days to months with regard to the characteristics of particles and type of tissues, among other factors.[56] Lifelong exposure can accumulate to large body burdens, especially on organs whose clearance is limited. The existence of microplastics in the human autopsy samples will confirm the long-term retention in tissues.[57]

Food chains, Trophic transfer, and biomagnification of microplastics through food chains are other issues. Although conventional biomagnification of persistent organic pollutants leads to higher and higher concentrations with increases in trophic levels, microplastic actions in the food webs are still a puzzle.[58] The results of some evidence indicate that there is biodilution (reducing concentration with rising trophic level) because of selective feeding or removal, whereas some other studies demonstrate accumulation. The health and ecological effects of microplastics on trophic transfer issues need further study.[59]

7. Vulnerable Populations and Special Considerations

7.1 Infants and Children

Children face a disproportionate exposure to microplastics, putting them at risk. The high intake levels are caused by the use of plastic bottles to prepare infant formulas and exposure to plastic toys through the use of measuring spoons to suck them. Research has determined that babies who are fed in polypropylene bottles could consume more than 1.5 million microplastic particles each day.[60] The physiological systems of children are in the process of development, and such factors as immature blood-brain barriers, developing immune systems, and continuous neurodevelopment make children more susceptible to adverse effects. Furthermore, children have an increased respiration rate and hand-to-mouth activities, which increase exposure. This population has critical developmental windows in infancy and childhood that deserve priority for risk assessment due to microplastics.[61]

7.2 Pregnant Women and Fetal Development

Mother-to-child exposure to microplastics is dangerous to the mother and the growing unborn baby. In humans, microplastics have been identified in the placental tissue, which is a clear indication of the transplacental transfer and exposes the fetus to the particles at the most crucial stages of development.[62] The animal research indicates that prenatal exposure to microplastics can result in developmental abnormalities, low birth weight, and the development of organs. The placental barrier seems partially permeable to smaller microplastics and nanoplastics; thus, they expose the fetus. Possible outcomes include developmental toxicity, endocrine disruption that affects fetal programming, and long-term health outcomes that may manifest later. The pregnancy is a risky phase that ought to be taken care of to reduce exposure.[63,64]

7.3 Occupationally Exposed Workers

Workers in the plastic sector, textile industries, and waste management and recycling industries face high levels of microplastic exposure, particularly through inhalation. Workplace health investigations have found that there are more symptoms related to respiration, less lung capacity, and inflammatory indicators in the exposed workers.[65,66] The workers have proven to have higher rates of respiratory infections, such as chronic bronchitis and interstitial lung disease, based on the historical cohorts of the workers who have had exposure to plastic dust and fibers. The contemporary workplace may present similar risks; however, formal risk evaluations and health surveillance are still inadequate in many instances. Better working safety measures and exposure checks would protect workers' health.[67]

7.4 Pre-existing Conditions

The health status of the population having compromised health conditions can be more vulnerable to the toxicity of microplastic. Exposure to microplastics is likely to aggravate conditions in people with inflammatory bowel disorders, respiratory disorders, cardiovascular disorders, or immune dysfunction.[68] The additive or synergistic effect of microplastics on the already existing pathology might increase disease progression. Moreover, having a lifetime exposure and possibly hampered clearance ability, elderly people might have the heaviest burden of microplastics. Individual risk evaluation based on personal health conditions is a significant way to go in the future.[69]

8. Current Detection Methods and Challenges

8.1 Analytical Techniques

The molecular identification and profiling of microplastics in biosamples pose serious analytical problems. Existing techniques involve visual identification of samples by microanalysis and spectroscopic methods (Fourier-transform infrared spectroscopy, Raman

spectroscopy, pyrolysis-gas chromatography-mass spectrometry, and matrix-assisted laser desorption/ionization time-of-flight mass spectrometry, among others).[70] All techniques have their unique merits and drawbacks based on the limit of detection, throughput, and capacity to describe the characteristics of particles (size, shape, polymer type, and additives). Sample preparation is a very important procedure that must involve the digestion of biological material while maintaining the integrity of microplastics.[71] Digestion by enzymes, alkaline digestion and oxidative digestion are used, although either may partially degrade some forms of polymer. The contamination throughout the entire process of sample collection, processing, and analysis must not be overlooked, as ubiquitous microplastics in the environment can introduce artifacts. Similarity of procedures is one of the pressing requirements to provide a chance to compare the studies and to quantify the human exposure and tissue burdens reliably.[72]

8.2 Biomonitoring and Exposure Assessment

Biomarkers of exposure to microplastics would be useful in supporting epidemiological research. Currently, the most effective method for identifying microplastics in bio-products (such as blood, urine, and stool) is through direct methods; however, these methods have low sensitivity and can be influenced by contamination.[73] Other methods in development include the quantification of the chemicals in biospecimens of plastic derivation or the biological signature of exposure to microplastics (e.g., the presence of typical inflammatory findings, the presence of an oxidative stress response, or a metabolomic signature). Bringing together the environmental exposure assessment with the biomonitoring data will prove critical in the establishment of the exposure-response relationships in a human population.[74]

Table 3: Analytical Methods for Microplastic Detection in Biological Samples

Method	Detection Limit	Advantages	Limitations	References
Visual/Microscopy	>50 μm	Simple, morphological data	Subjective, no chemical ID	[75,76]
FTIR Spectroscopy	>10 μm	Polymer identification	Time-consuming, size limit	[77]
Raman Spectroscopy	>1 μm	High resolution, polymer ID	Fluorescence interference	[78]
Py-GC-MS	ng/g range	Sensitive, quantitative	Destructive, no morphology	[79,80]
SEM-EDS	>1 μm	Morphology, elemental analysis	Limited polymer ID	[81]

9. Regulatory Perspectives and Risk Assessment

9.1 Current Regulatory Framework

The governments of various countries have regulatory frameworks in the infantile phase of development regarding microplastic contamination of food, water, and consumer products. Personal care products containing microbeads have been banned in the jurisdictions of some jurisdictions, which form the first steps in regulation. However, no comprehensive regulations exist to control the amount of microplastics in drinking water, food products, or indoor/outdoor air. Although no safety levels have been defined, the European Food Safety Authority (EFSA) has recognised microplastics as a major concern and has started work on the risk assessment. Such efforts are currently being undertaken in other parts of the world, yet control efforts are hindered by the lack of knowledge with respect to the levels of exposure, toxicity, and dose-response relationships. [82,83]

9.2 Risk Assessment Challenges

There are a few complications related to conducting an extensive risk assessment of microplastics. This is because microplastics are heterogeneous (they exist in various polymer types, sizes, shapes, and additives), and thus, they cannot be measured singularly. An old paradigm of toxicology centred upon chemical toxicity might not be very useful in understanding the effects that particles cause.[84] There are other complexities in determining the relevant exposure situations, choosing the right animal models, and extrapolating the findings to the human population. The fact that there may exist low doses and lifetime exposures with a long-term effect necessitates long-term studies, which are resource-intensive and time-consuming. Also, contact between microplastics and co-contaminants (adsorbed chemicals, biological agents) makes it difficult to characterise the hazards.[85]

9.3 Precautionary Approaches

Given the significant uncertainty surrounding the long-term health effects, it is justifiable to implement precautionary measures to reduce exposure. Strategies comprise the task of lowering single-use plastics, enhancing waste management and recycling frameworks, producing biodegradable substitutes, filtering microplastics in drinking water system sources, and raising awareness of consumers on the best fit of sources of exposure. [86,87] Public health agencies especially advise precautionary measures for vulnerable groups. The industry should mobilize to prevent the release of microplastics from textiles, tires, and other products. Effective mitigation requires a multi-stakeholder approach to regulation, industry, researchers, and civil society.[88]

10. Conclusions and Future Directions

10.1 Summary of Key Findings

The reviewed evidence shows that exposure to microplastics can have plausible risks for human health in various organ systems. The main preliminaries include (1) ubiquitous human exposure to microplastics happening by ingestion, inhalation, and possibly dermal paths; (2) the capability of microplastics to cause cellular toxicity by producing oxidative stress, inflammation, membrane disruption, and genotoxicity; (3) accumulation in essential body organs such as those of the lungs, liver, kidney and brain; (4) pathophysiological effects on the gastrointestinal, respiratory, and cardiovascular.

10.2 Knowledge Gaps and Research Priorities

Despite growing research attention, substantial knowledge gaps remain. Priority areas for future investigation include:
1. Human epidemiological research: Studies should be done in large prospective cohort studies to determine the relationship between exposure to microplastics and health in human populations.
2. Dose-response correlations: the definitive establishment of threshold values for adverse effects and the determination of health guidance values.
3. Long-term health effects: Evaluation of the damage of chronic and lifetime exposures, such as cancer risk, neurodegenerative disease, and reproductive effects.
4. Vulnerable populations: Specialized research on infants, children, and pregnant women to define the risk at the most critical development stages.
5. Mechanistic insights: The explanation of molecular processes that mediate the toxicity of microplastics to establish possible therapeutic sites.
6. Mixture toxicity: Investigation of the effects of microplastic-adsorbed chemical agonists when combined with microplastics that contain adsorbed chemicals and biological contaminants.
7. Standardisation: Formulation of standardised protocols of exposure assessment, analytical detection, and toxicity testing.
8. Mitigation measures: Intervention assessment to diminish the exposure and effectiveness of removal technologies.

10.3 Public Health Implications

The ubiquitous character of the microplastic contamination and the increasing evidence of the health risk require concerted efforts for the population's health. Although the exact cause of human disease from environmental microplastic exposure has not yet been established, the biological plausibility of harm, existing evidence from experimental research, and the presence of microplastics in human tissues provide sufficient reasons to take precautionary action. Public health intervention must focus on minimising exposure, especially to the vulnerable segments;

further monitoring of the level of environmental and human contamination; and research to provide knowledge on how to make evidence-based policies.

10.4 Concluding Remarks

The microplastics can be discussed as a new category of environmental pollutants with the possibility of large-scale exposure of the whole population and negative health consequences of microplastic presence. The nature of microplastic pollution and its versatility, both in terms of the types of polymer, particle sizes, and chemical compositions, pose some special difficulties to the risk assessment and management process. Increasing evidence, although largely based on in vitro and animal research, suggests a sound reason to be concerned about the consequences of such activity on human health. The fact that microplastics are in human blood, organs, and tissues proves the exposure that is associated with internal dosage. The concept of health risk will keep on changing as the ability to analyse and epidemiological studies becomes more elaborate. In the meantime, active precautions in the reduction of the production, release, and exposure to microplastics are considered wise methods of safeguarding human health in the context of this emerging threat. The issue of microplastics finally needs systemic solutions for the whole lifecycle of plastic materials, including production and utilisation as well as disposal and environmental destiny.

Key Takeaway Messages

Microplastics are ubiquitous and have proven to be environmental contaminants that humans have encountered.
Various biological processes suggest the possibility of having negative health outcomes.
Multi-organ toxicity and neuro-threats have been proven through experimental evidence.
We should prioritise vulnerable groups and ensure their safety.
We urgently require standardised techniques and human epidemiological information.
Precautionary steps of exposure reduction can be justified by existing evidence.

References

1. Gilani IE, Sayadi S, Zouari N, Al-Ghouti MA. Plastic waste impact and biotechnology: Exploring polymer degradation, microbial role, and sustainable development implications. Bioresource Technology Reports. 2023 Dec 1;24:101606.
2. Fayshal MA, Dhara FT, Hasan MM, Adnan HM, Mizan T. Global plastic waste scenario: A review on production, fate and future prospects. InProceedings of the Waste Safe 2023—8th International Conference on Integrated Solid Waste and Faecal Sludge Management 2023.
3. Amobonye A, Bhagwat P, Raveendran S, Singh S, Pillai S. Environmental impacts of microplastics and nanoplastics: a current overview. Frontiers in microbiology. 2021 Dec 15;12:768297.

4. Roslan NS, Lee YY, Ibrahim YS, Anuar ST, Yusof KM, Lai LA, Brentnall T. Detection of microplastics in human tissues and organs: A scoping review. Journal of Global Health. 2024 Aug 23;14:04179.

5. Li M, Ma W, Fang JK, Mo J, Li L, Pan M, Li R, Zeng X, Lai KP. A review on the combined toxicological effects of microplastics and their attached pollutants. Emerging Contaminants. 2025 Feb 26:100486.

6. Weis JS, Alava JJ. (Micro) plastics are toxic pollutants. Toxics. 2023 Nov 17;11(11):935.

7. Giri S, Lamichhane G, Khadka D, Devkota HP. Microplastics contamination in food products: Occurrence, analytical techniques and potential impacts on human health. Current Research in Biotechnology. 2024 Jan 1;7:100190.

8. Exposito N, Rovira J, Sierra J, Gimenez G, Domingo JL, Schuhmacher M. Levels of microplastics and their characteristics in molluscs from North-West Mediterranean Sea: Human intake. Marine pollution bulletin. 2022 Aug 1;181:113843.

9. Noorimotlagh Z, Hopke PK, Mirzaee SA. A systematic review of airborne microplastics emissions as emerging contaminants in outdoor and indoor air environments. Emerging Contaminants. 2024 Dec 1;10(4):100372.

10. Ahmad M, Chen J, Khan MT, Yu Q, Phairuang W, Furuuchi M, Ali SW, Nawab A, Panyametheekul S. Sources, analysis, and health implications of atmospheric microplastics. Emerging Contaminants. 2023 Sep;9(3):100233.

11. Lin YD, Huang PH, Chen YW, Hsieh CW, Tain YL, Lee BH, Hou CY, Shih MK. Sources, degradation, ingestion and effects of microplastics on humans: a review. Toxics. 2023 Sep 1;11(9):747.

12. Kadac-Czapska K, Ośko J, Knez E, Grembecka M. Microplastics and oxidative stress—current problems and prospects. Antioxidants. 2024 May 8;13(5):579.

13. Sunil M, Mithun N, Xavier M, Nayak G, Kalthur G, Chidangil S, Kumar S, Lukose J. Exploring the detrimental effects of nanoplastics on ecosystems and human health. Journal of Hazardous Materials Advances. 2025 Jul 17:100831.

14. Wang Z, Wang Y, Zhang J, Feng G, Miao S, Lu R, Tian X, Ye Y. Antioxidant Intervention Against Microplastic Hazards. Antioxidants. 2025 Jun 27;14(7):797.

15. Wang Z, Wang Y, Zhang J, Feng G, Miao S, Lu R, Tian X, Ye Y. Antioxidant Intervention Against Microplastic Hazards. Antioxidants. 2025 Jun 27;14(7):797.

16. Liu L, Xu K, Zhang B, Ye Y, Zhang Q, Jiang W. Cellular internalization and release of polystyrene microplastics and nanoplastics. Science of the Total Environment. 2021 Jul 20;779:146523.

17. Rejman J, Oberle V, Zuhorn IS, Hoekstra D. Size-dependent internalization of particles via the pathways of clathrin-and caveolae-mediated endocytosis. Biochemical journal. 2004 Jan 1;377(1):159-69.

18. Liu L, Xu K, Zhang B, Ye Y, Zhang Q, Jiang W. Cellular internalization and release of polystyrene microplastics and nanoplastics. Science of the Total Environment. 2021 Jul 20;779:146523.

19. Gutleb AC, Murugadoss S, Stępnik M, SenGupta T, El Yamani N, Longhin EM, Olsen AK, Wyrzykowska E, Jagiello K, Judzinska B, Cambier S. New Approach Methods (NAMs) for genotoxicity assessment of nano-and advanced materials; Advantages and

challenges. Mutation Research-Genetic Toxicology and Environmental Mutagenesis. 2025 May 1;904:503867.

20. Alijagic A, Kotlyar O, Larsson M, Salihovic S, Hedbrant A, Eriksson U, Karlsson P, Persson A, Scherbak N, Färnlund K, Engwall M. Immunotoxic, genotoxic, and endocrine disrupting impacts of polyamide microplastic particles and chemicals. Environment international. 2024 Jan 1;183:108412.

21. de Souza-Silva TG, Oliveira IA, da Silva GG, Giusti FC, Novaes RD, de Almeida Paula HA. Impact of microplastics on the intestinal microbiota: A systematic review of preclinical evidence. Life sciences. 2022 Apr 1;294:120366.

22. Barbara G, Barbaro MR, Fuschi D, Palombo M, Falangone F, Cremon C, Marasco G, Stanghellini V. Inflammatory and microbiota-related regulation of the intestinal epithelial barrier. Frontiers in nutrition. 2021 Sep 13;8:718356.

23. Saha SC, Saha G. Effect of microplastics deposition on human lung airways: A review with computational benefits and challenges. Heliyon. 2024 Jan 30;10(2).

24. Sanchez VC, Pietruska JR, Miselis NR, Hurt RH, Kane AB. Biopersistence and potential adverse health impacts of fibrous nanomaterials: what have we learned from asbestos?. Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology. 2009 Sep;1(5):511-29.

25. Lu K, Zhan D, Fang Y, Li L, Chen G, Chen S, Wang L. Microplastics, potential threat to patients with lung diseases. Frontiers in toxicology. 2022 Sep 28;4:958414.

26. Chen Q, Gao J, Yu H, Su H, Yang Y, Cao Y, Zhang Q, Ren Y, Hollert H, Shi H, Chen C. An emerging role of microplastics in the etiology of lung ground glass nodules. Environmental Sciences Europe. 2022 Dec;34(1):25.

27. Yang Y, Zhang F, Jiang Z, Du Z, Liu S, Zhang M, Jin Y, Qin Y, Yang X, Wang C, Gao H. Microplastics are associated with elevated atherosclerotic risk and increased vascular complexity in acute coronary syndrome patients. Particle and fibre toxicology. 2024 Aug 21;21(1):34.

28. Nawab A, Ahmad M, Khan MT, Nafees M, Khan I, Ihsanullah I. Human exposure to microplastics: A review on exposure routes and public health impacts. Journal of Hazardous Materials Advances. 2024 Nov 1;16:100487.

29. Wang X, Deng K, Zhang P, Chen Q, Magnuson JT, Qiu W, Zhou Y. Microplastic-mediated new mechanism of liver damage: From the perspective of the gut-liver axis. Science of the Total Environment. 2024 Apr 1;919:170962.

30. Wang T, Hu M, Xu G, Shi H, Leung JY, Wang Y. Microplastic accumulation via trophic transfer: can a predatory crab counter the adverse effects of microplastics by body defence?. Science of the Total Environment. 2021 Feb 1;754:142099.

31. Yue S, Chen S, Zhang Y, Chen B, Xu T. Emerging threat of environmental microplastics: A comprehensive analysis of hepatic metabolic dysregulation and hepatocellular damage. International Journal of Molecular Medicine. 2025 Jul 14;56(4):144.

32. Ghosh T. Microplastics bioaccumulation in fish: its potential toxic effects on hematology, immune response, neurotoxicity, oxidative stress, growth and reproductive dysfunction. Toxicology Reports. 2024 Dec 9:101854.

33. Cao Y, Jiang N, Zheng X, Zhang N. The detrimental effects of microplastic exposure on kidney function. Frontiers in Medicine. 2025 Sep 23;12:1620733.

34. Aditya MR, Muhammad AR, Adriansyah V, Samsu N, Sulistomo HW. Microplastic exposure and its consequences for renal and urinary health: systematic review of in vivo studies. All Life. 2025 Dec 31;18(1):2457760.

35. Wang T, Li N, Zhao Z, Zhang Y, Lin L, Ding Y, Feng R, Yang Z, Du W, Zeng Y. Microplastic contamination in kidney transplant donor tissues and its association with early post-transplant blood pressure changes in recipients: A multi-modal analytical study. Journal of Hazardous Materials. 2025 Sep 1:139728.

36. Jin Y, Lu L, Tu W, Luo T, Fu Z. Impacts of polystyrene microplastic on the gut barrier, microbiota and metabolism of mice. Sci Total Environ. 2019;649:308-317.

37. Deng Y, Zhang Y, Lemos B, Ren H. Tissue accumulation of microplastics in mice and biomarker responses suggest widespread health risks of exposure. Sci Rep. 2017;7:46687.

38. Prata JC, da Costa JP, Lopes I, Duarte AC, Rocha-Santos T. Environmental exposure to microplastics: An overview on possible human health effects. Sci Total Environ. 2020;702:134455.

39. Jenner LC, Rotchell JM, Bennett RT, Cowen M, Sadofsky LR, Wright SL. Detection of microplastics in human lung tissue. Environ Sci Technol. 2022;56(8):5037-5043.

40. Hou L, Kang D, Li Q, Liu J. Microplastics and cardiovascular diseases: Potential mechanisms and perspectives. Environ Pollut. 2022;308:119620.

41. Wright SL, Kelly FJ. Plastic and human health: A micro issue? Environ Sci Technol. 2017;51(12):6634-6647.

42. Yong CQY, Valiyaveetill S, Tang BL. Toxicity of microplastics and nanoplastics in mammalian systems. Int J Environ Res Public Health. 2020;17(5):1509.

43. Lim XC, Ong KS, Seng CG. Microplastics in the environment: Research gaps, toxicological mechanisms, and potential health risk assessment. Chemosphere. 2022;287(Pt 1):132307.

44. Kopatz V, Wen K, Kovács T, Keimowitz AS, Pichler V, Widder J, Vethaak AD, Hollóczki O, Kenner L. Micro-and nanoplastics breach the blood–brain barrier (BBB): Biomolecular corona's role revealed. Nanomaterials. 2023 Jan;13(8):1404.

45. Blackburn K, Green D. The potential effects of microplastics on human health: What is known and what is unknown. Ambio. 2022 Mar;51(3):518-30.

46. Wang Y, Leak RK, Cao G. Microglia-mediated neuroinflammation and neuroplasticity after stroke. Frontiers in cellular neuroscience. 2022 Aug 16;16:980722.

47. Gao C, Jiang J, Tan Y, Chen S. Microglia in neurodegenerative diseases: mechanism and potential therapeutic targets. Signal transduction and targeted therapy. 2023 Sep 22;8(1):359.

48. Gaspar L, Bartman S, Coppotelli G, Ross JM. Acute exposure to microplastics induced changes in behavior and inflammation in young and old mice. International Journal of Molecular Sciences. 2023 Aug 1;24(15):12308.

49. Radbakhsh S, Norouzzadeh R. Microplastic Neurotoxicity: Pathways, Mechanisms, and Implications for Neurodegenerative Disease. Personalized Medicine Journal. 2025 May 1;10(37):31-8.

50. Ghosh S, Sinha JK, Ghosh S, Vashisth K, Han S, Bhaskar R. Microplastics as an emerging threat to the global environment and human health. Sustainability. 2023 Jul 10;15(14):10821.

51. Zheng D, Wang D, Zhang S, Liu Y, Xi Q, Weng Y. Impact of urinary microplastic exposure on cognitive function in primary school children. Ecotoxicology and Environmental Safety. 2025 Sep 1;302:118532.

52. Amran NH, Zaid SS, Mokhtar MH, Manaf LA, Othman S. Exposure to microplastics during early developmental stage: review of current evidence. Toxics. 2022 Oct 10;10(10):597.

53. Li L, Yang J, Wang Y, Liu T, Yao C, Huang L, Zhou J, Yang Q, Chen C, Qu Z, Huang S. Environmental neurotoxicity revisited: Evaluating microplastics as a potential risk factor for autism spectrum disorder. The Innovation Medicine. 2025 Sep 2:100156-.

54. Yuan Z, Nag R, Cummins E. Human health concerns regarding microplastics in the aquatic environment-From marine to food systems. Science of the Total Environment. 2022 Jun 1;823:153730.

55. Bhardwaj G, Abdulkadhim M, Joshi K, Wankhede L, Das RK, Brar SK. Exposure Pathways, Systemic Distribution, and Health Implications of Micro-and Nanoplastics in Humans. Applied Sciences. 2025 Aug 9;15(16):8813.

56. Fan P, Yu H, Xi B, Tan W. A review on the occurrence and influence of biodegradable microplastics in soil ecosystems: are biodegradable plastics substitute or threat. Environ. Int. 2022 May 1;163(107244):10-16.

57. Nihart AJ, Garcia MA, El Hayek E, Liu R, Olewine M, Kingston JD, Castillo EF, Gullapalli RR, Howard T, Bleske B, Scott J. Bioaccumulation of microplastics in decedent human brains. Nature medicine. 2025 Apr;31(4):1114-9.

58. Gao S, Li Z, Zhang S. Trophic transfer and biomagnification of microplastics through food webs in coastal waters: A new perspective from a mass balance model. Marine Pollution Bulletin. 2024 Mar 1;200:116082.

59. Varg JE, Outomuro D, Kunce W, Kuehrer L, Svanbäck R, Johansson F. Microplastic exposure across trophic levels: effects on the host–microbiota of freshwater organisms. Environmental Microbiome. 2022 Jul 6;17(1):36.

60. Mišľanová C, Valachovičová M, Slezáková Z. An overview of the possible exposure of infants to Microplastics. Life. 2024 Mar 12;14(3):371.

61. Bergdolt L, Dunaevsky A. Brain changes in a maternal immune activation model of neurodevelopmental brain disorders. Progress in neurobiology. 2019 Apr 1;175:1-9.

62. Zurub RE, Cariaco Y, Wade MG, Bainbridge SA. Microplastics exposure: implications for human fertility, pregnancy and child health. Frontiers in Endocrinology. 2024 Jan 4;14:1330396.

63. Anifowoshe AT, Akhtar MN, Majeed A, Singh AS, Ismail TF, Nongthomba U. Microplastics: A threat to Fetoplacental unit and Reproductive systems. Toxicology Reports. 2025 Jan 30:101938.

64. Geng Y, Liu Z, Hu R, Huang Y, Li F, Ma W, Wu X, Dong H, Song K, Xu X, Zhang Z. Toxicity of microplastics and nanoplastics: invisible killers of female fertility and offspring health. Frontiers in physiology. 2023 Aug 28;14:1254886.

65. Lalrinfela P, Vanlalsangi R, Lalrinzuali K, Babu PJ. Microplastics: Their effects on the environment, human health, and plant ecosystems. Environmental Pollution and Management. 2024 Nov 26.

66. Shahsavaripour M, Abbasi S, Mirzaee M, Amiri H. Human occupational exposure to microplastics: A cross-sectional study in a plastic products manufacturing plant. Science of The Total Environment. 2023 Jul 15;882:163576.

67. Lai PS, Christiani DC. Long-term respiratory health effects in textile workers. Current opinion in pulmonary medicine. 2013 Mar 1;19(2):152-7.

68. Bora SS, Gogoi R, Sharma MR, Borah MP, Deka P, Bora J, Naorem RS, Das J, Teli AB. Microplastics and human health: unveiling the gut microbiome disruption and chronic disease risks. Frontiers in Cellular and Infection Microbiology. 2024 Nov 25;14:1492759.

69. Lim X. Microplastics are everywhere—but are they harmful. Nature. 2021 May 6;593(7857):22-5.

70. Lenz R, Enders K, Stedmon CA, Mackenzie DM, Nielsen TG. A critical assessment of visual identification of marine microplastic using Raman spectroscopy for analysis improvement. Marine pollution bulletin. 2015 Nov 15;100(1):82-91.

71. Ivleva NP. Chemical analysis of microplastics and nanoplastics: challenges, advanced methods, and perspectives. Chemical reviews. 2021 Aug 26;121(19):11886-936.

72. Song J, Pashazadeh A, Wu S, Greene VR, Hallee KO, Tannehill AM, Saxon T, Potter M, Beneke Z. Advances in Microplastic Detection and Interception: A State-of-the-Art Review. Cleaner Water. 2025 Sep 30:100141.

73. Chalannavar RK, Kamble AA, Malabadi RB, Divakar MS, Swathi KK, Kolkar KP, Moramazi S, Munhoz AN, Castaño Coronado KV. Microplastics: Detection Methods—An Update. World J. Adv. Res. Rev. 2025;26:2809-24.

74. Noventa S, Boyles MS, Seifert A, Belluco S, Jiménez AS, Johnston HJ, Tran L, Fernandes TF, Mughini-Gras L, Orsini M, Corami F. Paradigms to assess the human health risks of nano-and microplastics. Microplastics and Nanoplastics. 2021 Jun 29;1(1):9.

75. Karlsson T, et al. Analytical methods for microplastics in the environment: a review. 2022 Sep 28. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC9521859/

76. Hidalgo-Ruz V, et al. Microplastics in the Marine Environment: A Review of the Methods Used for Identification. Mar Pollut Bull. 2012 Mar; Available from: https://pubs.acs.org/doi/10.1021/es2031505

77. Shim WJ, Hong SH, Eo SE. Identification methods in microplastic analysis: a review. Analytical methods. 2017;9(9):1384-91.

78. Vasudeva M, Warrier AK, Kartha VB, Unnikrishnan VK. Advances in microplastic characterization: Spectroscopic techniques and heavy metal adsorption insights. TrAC Trends in Analytical Chemistry. 2025 Feb 1;183:118111.

79. Ivleva NP, et al. Chemical Analysis of Microplastics and Nanoplastics. Chem Rev. 2021 Aug 25; Available from: https://pubs.acs.org/doi/10.1021/acs.chemrev.1c00178

80. Huang Z, Hu B, Wang H. Analytical methods for microplastics in the environment: a review. Environmental chemistry letters. 2023 Feb;21(1):383-401.

81. Dierkes G, et al. Quantitative detection of microplastics in sediments using Py-GC-MS. 2020. Available from: https://pubs.acs.org/doi/10.1021/acs.chemrev.1c00178

82. Mitrano DM, Wohlleben W. Microplastic regulation should be more precise to incentivize both innovation and environmental safety. Nature communications. 2020 Oct 21;11(1):5324.

83. EU. Protecting environment and health: Commission adopts measures to restrict intentionally added microplastics.

84. Lee Y, Cho J, Sohn J, Kim C. Health effects of microplastic exposures: current issues and perspectives in South Korea. Yonsei medical journal. 2023 Apr 20;64(5):301.

85. Marshall LJ, Bailey J, Cassotta M, Herrmann K, Pistollato F. Poor translatability of biomedical research using animals—a narrative review. Alternatives to Laboratory Animals. 2023 Mar;51(2):102-35.

86. Thompson RC, Moore CJ, Vom Saal FS, Swan SH. Plastics, the environment and human health: current consensus and future trends. Philosophical transactions of the royal society B: biological sciences. 2009 Jul 27;364(1526):2153-66.

87. Saini K. Microplastics in the environment: Current consensus and future trends. InMicroplastics in Environment 2024 Nov 15 (pp. 239-255). CRC Press.

88. Hettiarachchi H, Meegoda JN. Microplastic pollution prevention: the need for robust policy interventions to close the loopholes in current waste management practices. International journal of environmental research and public health. 2023 Jul 23;20(14):6434.

89. Shan S, Zhang Y, Zhao H, Zeng T, Zhao X. Polystyrene nanoplastics penetrate across the blood-brain barrier and induce activation of microglia in the brain of mice. Chemosphere. 2022 Jul 1;298:134261.

90. Kato H, Walz W. The initiation of the microglial response. Brain Pathology. 2000 Jan;10(1):137-43.

91. Bhat AH, Dar KB, Anees S, Zargar MA, Masood A, Sofi MA, Ganie SA. Oxidative stress, mitochondrial dysfunction and neurodegenerative diseases; a mechanistic insight. Biomedicine & Pharmacotherapy. 2015 Aug 1;74:101-10.

92. Han J, Fan Y, Wu P, Huang Z, Li X, Zhao L, Ji Y, Zhu M. Parkinson's disease dementia: synergistic effects of alpha-synuclein, tau, beta-amyloid, and iron. Frontiers in Aging Neuroscience. 2021 Oct 11;13:743754.

93. Kim DY, Park MK, Yang HW, Woo SY, Jung HH, Son DS, Choi BY, Suh SW. Effects of microplastic accumulation on neuronal death after global cerebral ischemia. Cells. 2025 Feb 7;14(4):241.