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Microplastics and Their Toxicological Impacts on Human Health: An Overview

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ABSTRACT

Microplastics (MPs) represent a pervasive and complex environmental contaminant with far-reaching implications for ecosystem and human health. This literature review aims to synthesize current knowledge on the sources, environmental distribution, and toxicological impacts of microplastics on human health, with a particular focus on recent empirical findings, mechanistic insights, detection methodologies, and emerging research frontiers. The review also highlights methodological advances, policy implications, and future directions necessary for a comprehensive understanding of the risks posed by microplastic pollution to human populations.

Keywords: Microplastics, Plastic toxicity, Human health, Ecological health.

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1. INTRODUCTION

Since the advent of synthetic polymers in the early twentieth century, plastics have become ubiquitous, with global production exceeding 400 million tonnes annually [1, 18]. The very properties that make plastics useful—durability and resistance to degradation—have created a global crisis. Microplastics (MPs), defined as particles <5 mm, originate from primary manufacturing or the secondary fragmentation of larger debris [3, 19].

Over the past two decades, a growing body of research has focused on the environmental fate of microplastics, their accumulation in diverse ecosystems, and their potential impacts on biota and human health. Microplastics have been detected in marine and freshwater environments, sediments, soils, the atmosphere, and even within the tissues of living organisms, including humans. In India, the proliferation of MPs in Ganges river sediments and coastal regions of the Arabian Sea highlights a regional crisis with global implications [20, 21]. Concerns over their toxicological effects stem from their capacity to act as vectors for heavy metals and persistent organic pollutants (POPs), their intrinsic physical sharp edges, and their potential to disrupt biological processes at the molecular level [5, 22]. Despite these concerns, direct evidence of human health impacts remains nascent, necessitating a deep dive into mechanistic pathways [14, 23].

This literature review aims to synthesize current knowledge on the sources, environmental distribution, and toxicological impacts of microplastics on human health, with a particular focus on recent empirical findings, mechanistic insights, detection methodologies, and emerging research frontiers. Drawing on a corpus of recent studies, the review also highlights methodological advances, policy implications, and future directions necessary for a comprehensive understanding of the risks posed by microplastics to human populations.

2. METHODOLOGY

The present literature review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure transparency, replicability, and academic rigor in synthesizing the toxicological impacts of microplastics on human health.

2.1. Search Strategy and Information Sources

A systematic search of electronic databases was performed to identify relevant studies published between 2013-2025. The primary databases searched included: PubMed/MEDLINE, Web of Science (Core Collection), Scopus, ScienceDirect, Google Scholar (for gray literature and supplementary cross-referencing). The search strategy employed a combination of Medical Subject Headings (MeSH) terms and keywords using Boolean operators (AND, OR). The search string used was: (“microplastics” OR “nanoplastics” OR “plastic debris”) AND (“human health” OR “toxicology” OR “cytotoxicity” OR “oxidative stress”) AND (“exposure pathways” OR “ingestion” OR “inhalation”).

2.2. Eligibility Criteria

Studies were selected based on the following Inclusion (IC) and Exclusion (EC) criteria:

Inclusion Criteria:

- Peer-reviewed original research articles, systematic reviews, and meta-analyses.
- Studies focused on the detection of microplastics in human tissues (blood, placenta, lung, stool, etc.).
- In vitro studies using human cell lines or in vivo studies using mammalian models (mice/rats) to extrapolate human health risks.
- Studies examining the chemical additives or adsorbed pollutants (vectors) associated with microplastics.
- Articles published in the English language.

Exclusion Criteria:

- Studies exclusively focusing on macroplastics (>5mm).
- Research focused solely on marine ecology or environmental monitoring without a link to human exposure or toxicity.
- Conference abstracts, editorials, posters, and non-peer-reviewed commentaries.
- Studies published before 2010 (to maintain a focus on contemporary findings).

2.3. Study Selection and Data Extraction

The selection process was conducted in three distinct phases:

- Identification: Initial records were identified through database searches, and duplicates were removed using reference management software (e.g., Zotero/EndNote).
- Screening: Two independent reviewers screened titles and abstracts against the eligibility criteria.
- Eligibility: Full-text versions of the remaining articles were retrieved and assessed for their relevance to human toxicological mechanisms (e.g., inflammation, translocation, and cellular damage).

2.4. Data Abstraction and Synthesis

Data from the selected studies were extracted into a standardized matrix. Key information recorded included:

- Study Characteristics: Author, year, and geographic location.
- Microplastic Characteristics: Polymer type (e.g., PE, PET, PS), size (µm/nm), and morphology (fibers, fragments, beads).
- Exposure Route: Ingestion, inhalation, or dermal contact.
- Toxicological Endpoints: Cell viability, reactive oxygen species (ROS) generation, inflammatory cytokines, and histological changes.

2.5. Quality Assessment

The quality of the included studies was appraised using the OHAT (Office of Health Assessment and Translation) Risk of Bias Tool for Human and Animal Studies, adapted for environmental health research. This ensured that the synthesis prioritized studies with robust methodologies, appropriate control groups, and validated detection techniques (e.g., μ-FTIR, Raman spectroscopy, or Py-GC/MS).

3. THE UBIQUITY AND SOURCES OF MICROPLASTICS

3.1. Historical Context and Production Trends

Plastics production has risen exponentially since their introduction in the early 1900s, reaching approximately 400 million tons in 2022, with packaging constituting nearly 40 percent of this total [1, 24]. The durability and resistance to natural degradation processes mean that most plastic waste persists in the environment for decades or longer. Recycling rates remain low, with estimates suggesting that less than 30 percent of plastic products are effectively recycled, leaving the majority to accumulate in landfills or leak into natural environments [2, 25] .This massive and poorly managed waste stream underpins the global proliferation of microplastics. In emerging economies like India, mismanaged plastic waste serves as a primary source for secondary MP formation through photo-oxidative degradation [26].

3.2. Classification and Environmental Entry Points

Microplastics are generally categorized as either primary or secondary. Primary microplastics are manufactured at small sizes for use in products such as cosmetics, cleaning agents, and industrial abrasives. Secondary microplastics, by contrast, result from the breakdown of larger plastic items via photodegradation, physical abrasion, and biological activity [3, 27]. Synthetic textiles are a major contributor; a single laundry cycle can release over 700,000 microfibers into wastewater [28].

The pathways by which microplastics enter environmental compartments are diverse. Land-based sources dominate, accounting for around 80 percent of microplastics in the marine environment [4, 29]. These include urban runoff, sewage effluent, atmospheric deposition, agricultural runoff, and direct littering. Notably, the use of agricultural plastic mulch, organic fertilizers, and sewage sludge in farming practices introduces significant quantities of microplastics into soils [5]. Ocean-based sources, such as lost fishing gear, shipping, and aquaculture, account for the remaining share [4].

Rivers and wastewater treatment plants act as important conduits, transporting microplastics from terrestrial sources into aquatic systems. Even advanced wastewater treatment plants are unable to fully retain microplastic particles, with small facilities releasing billions of particles per day [5, 30]. Extreme weather events, such as heavy rainfall and hurricanes, can further exacerbate the transfer of plastics from land to water bodies [1,6].

3.3. Accumulation in Environmental Compartments

The persistence and mobility of microplastics have led to their detection in virtually all environmental matrices. In aquatic systems, microplastics have been observed in remote oceanic gyres, deep-sea sediments, and freshwater bodies [7, 8]. Soil environments, initially overlooked, are now recognized as significant sinks for microplastics, with agricultural soils potentially accumulating more microplastics than oceanic environments due to inputs from plastic mulching, fertilizers, and irrigation [5, 9].

Atmospheric transport and deposition further amplify the ubiquity of microplastics, allowing particles to be distributed across vast distances and even inhaled by terrestrial organisms, including humans [10]. Beaches, acting as interfaces between land and sea, serve as accumulation zones, where microplastics are deposited by tidal action, wind, and human activity [11].

4. DETECTION AND MONITORING OF MICROPLASTICS

4.1. Analytical Challenges

Detecting MPs in complex biological matrices requires high precision. While traditional sieving and density separation are common, spectroscopic techniques like Fourier Transform Infrared (FTIR) and Raman spectroscopy are now the gold standard for polymer identification [11, 31]. Recent advances include Pyrolysis-Gas Chromatography-Mass Spectrometry (Py-GC-MS), which allows for the quantification of MP mass rather than just particle count, providing a more accurate dose-response metric for toxicological studies [32, 33].

4.2. Technological Innovations

Recent advances have improved the spatial and temporal resolution of microplastics monitoring. Remote sensing technologies, such as space radar-based methods, now enable the detection of microplastics on the ocean surface by measuring the wind-dampening effects on surface roughness [1,12]. Autonomous robotic platforms equipped with cameras and near-infrared (NIR) spectrometers have been developed for *in situ* detection and chemical analysis of microplastics on beaches, allowing rapid mapping of concentration gradients and plastic types [11].

In the biological domain, the use of microscopic laser particles as optical barcodes has enabled non-invasive tracking of microplastic uptake, transport, and retention within live organisms, such as reef-building corals [13]. These innovations not only facilitate more comprehensive environmental surveys but also open new avenues for investigating exposure pathways and ecological impacts.

5. ENVIRONMENTAL FATE AND DYNAMICS OF MICROPLASTICS

5.1. Transport and Transformation

Once released into the environment, microplastics are subject to a complex array of physical, chemical, and biological processes that govern their transport, transformation, and ultimate fate. Ocean currents, wind patterns, and hydrological cycles distribute microplastics across local, regional, and global scales [1,14]. Biofouling by microorganisms and aggregation into marine snow can alter buoyancy, causing particles to sink and accumulate in sediments [14].

In soils, earthworm activity can promote the vertical movement of microplastics, facilitating their integration into deeper soil layers and potential entry into groundwater systems [5]. Atmospheric processes, including aerosolization via seawater evaporation, enable microplastics to become airborne and inhalable, with implications for both environmental and human health [1,10].

5.2. Microplastics as Vectors for Chemical Pollutants

A critical dimension of microplastics' environmental impact is their role as vectors for plastic-related organic pollutants (PROPs), including hydrophobic organic compounds, plastic additives, and persistent organic pollutants [14]. Microplastics have high sorptive capacities, enabling them to adsorb and concentrate environmental contaminants on their surfaces. During their environmental journey, microplastics can both uptake and release these chemicals, modulating local pollution profiles [14].

Numerical modeling approaches have elucidated the coupled dynamics of microplastics and associated pollutants, demonstrating that particle origin, source type, and environmental conditions significantly influence the extent of pollutant transport and fate [14]. These findings underscore the potential for microplastics to serve as mobile sources of hazardous chemicals, amplifying exposure risks for organisms and humans alike.

6. ECOLOGICAL AND ORGANISMAL EFFECTS

Microplastics have been shown to induce a spectrum of adverse effects across taxa. In marine environments, ingestion of microplastics has been linked to impaired feeding, oxidative stress, reproductive toxicity, and disruption of gut microbiota in organisms ranging from zooplankton to fish, bivalves, and corals [5,13,14]. For example, exposure of Mediterranean mussels to polyethylene microplastics resulted in oxidative damage and compromised antioxidant systems in digestive glands [5]. Common carp exposed to microplastics experienced alterations in gut microbial community structure and diminished functional diversity, though no significant effects on isotope or elemental composition were observed [5].

In soil systems, earthworms and nematodes have exhibited impaired growth, reproduction, and lifespan following microplastic exposure, mediated by mechanisms such as bioaccumulation, genotoxicity, metabolic disorders, and histopathological damage [5]. These impacts cascade to broader ecological processes, affecting litter decomposition, nutrient cycling, and energy flow.

6.1. Microplastics in the Human Food Chain

The potential for microplastics to enter the human body via the food chain has generated considerable concern. Human exposure occurs via ingestion, inhalation, and dermal contact [40]. MPs have been detected in bottled water, sea salt, honey, and commercial seafood, particularly bivalves [10, 41]. Inhalation is increasingly recognized as a significant route, with indoor air often containing higher concentrations of plastic microfibers than outdoor air [1, 42]. While studies have demonstrated the capacity for microplastics to accumulate in biological tissues, their bioavailability and retention within the human body, as well as their ultimate health consequences, remain inadequately characterized.

Notably, research into the trophic transfer and bioaccumulation of microplastics has revealed that contaminated food vectors can substantially increase the retention time of microplastics within organisms, as observed in reef-building corals ingesting microplastic-laden *Artemia nauplii* [13]. Such findings highlight the importance of indirect exposure pathways and the potential for chronic internal exposure to microplastics and their associated contaminants.

7. HUMAN HEALTH IMPLICATIONS

7.1. Epidemiological Evidence

Despite decades of investigation into microplastics as an environmental pollutant, direct empirical evidence linking microplastics exposure to adverse human health outcomes has only recently begun to emerge. A landmark study provided the first link between MP exposure and adverse birth outcomes, attributing over 200,000 cases of low birth weight annually to MP-laden aerosol inhalation [1]. Analyzing a dataset of 3 million births across 15 coastal countries and merging it with remote-sensing measurements of marine microplastic concentrations, the study found that prenatal exposure, particularly during the third trimester, significantly increased the likelihood of low birth weight (LBW). A doubling of microplastic exposure raised the hazard of LBW by 0.37 per 1,000 births, implying that over 205,000 cases per year globally could be attributed to microplastic exposure [1].

Strikingly, this effect was not mediated by seafood consumption—a traditional focus of microplastics exposure risk—but rather by atmospheric pathways. The study demonstrated that aerosolization of microplastics via seawater evaporation leads to airborne particles that can be inhaled, with implications for population-wide exposure [1]. MPs have also been identified in human blood (mean concentration of 1.6 μg/mL), lung tissue, and the placenta, suggesting they can translocate across biological barriers [16, 43, 44].

8. TOXICOLOGICAL MECHANISMS AND BIOLOGICAL IMPACTS

8.1. Physical and Chemical Hazards

The toxicological effects of microplastics arise from both their physical characteristics and chemical interactions. Physically, microplastics can cause mechanical blockages, reduced nutrition, and tissue damage in organisms following ingestion or inhalation [14, 15]. Their small size enables translocation across biological barriers, leading to accumulation in tissues and organs [14, 16].

Chemically, microplastics are composed of diverse polymers and additives, some of which are intrinsically toxic. They leach additives like phthalates and Bisphenol A (BPA), which are known endocrine disruptors [34]. Furthermore, their high surface-to-volume ratio allows them to adsorb co-contaminants such as lead, mercury, and organochlorine pesticides, increasing their bioavailability to organisms [5, 35]. Upon entry into biological systems, microplastics can desorb these chemicals, leading to localized exposure and potentially synergistic toxic effects [14, 17].

8.2. Cellular and Molecular Effects

In vitro studies using human cell lines (e.g., Caco-2, A549) have demonstrated that microplastics can induce the overproduction of reactive oxygen species (ROS) [36]. This oxidative stress leads to lipid peroxidation, protein carbonylation, and DNA damage [37]. Earlier studies have emphasized that MP exposure can trigger the NF-κB signaling pathway, leading to the release of pro-inflammatory cytokines like interleukin-6 (IL-6) and tumor-necrosis factor-α (TNF-α) [38, 39].

Beyond general oxidative stress, MPs interfere with specific molecular defense mechanisms. Research on marine organisms has highlighted the activation of the MAPK/Nrf2 pathway as a key response to MP-induced toxicity, suggesting that cells attempt to upregulate antioxidant enzymes to maintain redox homeostasis [37]. However, prolonged exposure can overwhelm these defenses, leading to mitochondrial dysfunction and triggering apoptosis [38]. The molecular impact of MPs is further complicated by their ability to enter systemic circulation. The detection of plastic particles in human blood [43] and lung tissue [44] suggests that MPs can interact directly with plasma proteins and alveolar cells. In the human placenta, the presence of MPs (the "Plasticenta" phenomenon) raises concerns regarding the disruption of maternal-fetal molecular exchange and potential interference with placental signaling molecules [16].

In addition to direct cellular toxicity, MPs act as molecular hotspots in aquatic ecosystems. They facilitate the formation of a "plastisphere"—a unique microbial biofilm that can enhance horizontal gene transfer [46]. This molecular-level interaction increases the exchange of antibiotic resistance genes among environmental bacteria, potentially creating indirect hazards to human health through the food chain [47]. Furthermore, at the neuro-molecular level, nanoplastics have been observed to cross the blood-brain barrier, inhibiting acetylcholinesterase (AChE) activity and leading to behavioral disorders and brain damage in aquatic models [45].

9. POLICY IMPLICATIONS AND DIRECTIONS FOR FUTURE RESEARCH

9.1. Global and Transboundary Nature of Microplastics Pollution

Evidences represented in this review highlights the global, transboundary nature of microplastics pollution. Microplastic particles traverse long distances via ocean currents, atmospheric transport, and food webs, rendering local interventions insufficient. Effective mitigation requires coordinated international efforts to regulate plastic production, improve waste management, and reduce emissions from both land-based and ocean-based sources [1,14].

9.2. Need for Comprehensive Risk Assessment

The multifaceted risks posed by microplastics—encompassing physical, chemical, and biological dimensions—demand comprehensive risk assessment frameworks. Current regulatory standards for particulate matter and chemical pollutants may not adequately capture the unique properties and hazards of microplastics [1,14]. An integrated approach, informed by mechanistic understanding and empirical evidence, is essential for protecting human health and ecological integrity.

9.3. Research Gaps and Methodological Priorities

Significant research gaps persist in the understanding of microplastics' toxicological impacts on human health. Key priorities include:

- Elucidating exposure pathways and bioavailability of microplastics in humans, including inhalation, ingestion, and dermal contact.
- Characterizing the fate, retention, and biological effects of microplastics in human tissues, with attention to particle size, shape, polymer type, and co-contaminants.
- Investigating vulnerable populations and critical windows of susceptibility, such as pregnancy and early childhood.
- Developing standardized methodologies for detection, quantification, and toxicological assessment of microplastics.
- Integrating big data, modeling, and automated monitoring to support large-scale epidemiological studies and policy development.

9.4. Innovations in Detection and Remediation

Continued innovation in detection technologies, such as confocal hyperspectral imaging, autonomous robotic surveying, and remote sensing, will be essential for advancing monitoring, source attribution, and remediation efforts [11,12,13]. The development of scalable, cost-effective, and non-invasive methods will facilitate more comprehensive assessments of environmental and human exposure.

Remediation strategies must target both the prevention of primary plastic emissions and the removal of existing microplastics from environmental compartments. Approaches may include improved waste management, bioremediation, and the design of biodegradable or less hazardous plastic materials.

9.5. Emerging Research Frontiers

Research is shifting toward “nanoplastics” (<1 μm), which possess higher translocation potential and can cross the blood-brain barrier [45]. Additionally, the “plastisphere"—the microbial community colonizing MP surfaces—is being investigated for its role in spreading antibiotic-resistant genes (ARGs) [46, 47].

10. CONCLUSION

Microplastics represent a pervasive and complex environmental contaminant with far-reaching implications for ecosystem and human health. This paper demonstrates that microplastics are present in every major environmental compartment, act as vectors for hazardous chemicals, and can induce a range of toxicological effects across biological systems. Emerging epidemiological evidence links microplastics exposure to adverse human health outcomes, such as low birth weight, with atmospheric pathways playing a prominent role.

Technological advances in detection, monitoring, and modeling have expanded the frontiers of microplastics research, enabling more precise characterization of their sources, fate, and impacts. However, substantial knowledge gaps remain, particularly regarding the mechanisms and magnitude of human health risks.

Addressing the microplastics crisis requires a holistic, interdisciplinary approach that integrates scientific research, technological innovation, policy development, and international cooperation. Only through coordinated efforts can the downstream benefits of plastic waste management and reduction be fully realized, safeguarding both environmental and public health for future generations.

Conflict of interest

The author has no conflict of interest to declare.

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