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A Comprehensive Review of Environmental Microplastics: Food Web Transfer, Human Exposure, and Toxicological Implications

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Abstract

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Recent years have witnessed a rapid expansion of research on microplastics (MPs), driven by increasing recognition of their potential health implications. The opening section of this review addresses the environmental occurrence, distribution patterns, and quantification methodologies for MPs. These particles are transferred from environmental compartments to humans predominantly via inhalation, followed by ingestion, and to a lesser degree through dermal absorption. Regarding food web contamination, this review examines MP presence not only in extensively studied matrices such as seafood, potable water, and table salt, but also in other dietary sources including honey, sugar, milk, fruits, and various meats (chicken, beef, and pork). Collectively, the available literature indicates that human exposure to MPs through these pathways is substantial and warrants attention. Consequently, considerable scientific effort has focused on evaluating potential human health hazards. Toxicological investigations have progressed from aquatic organism models to experimental mammalian systems and human cell cultures.

1. Introduction

Plastic materials have become indispensable to modern life, permeating applications from food packaging and technological devices to disposable medical equipment. This pervasive integration, however, entails chronic human exposure to microscopic particulates generated through environmental degradation, potentially eliciting adverse physiological consequences over extended timescales. A substantial body of literature has been dedicated to characterizing microplastic transport across atmospheric, aquatic, and terrestrial compartments and their subsequent incorporation into biological food webs. Given their extraordinary environmental persistence, these particulate contaminants represent a significant toxicological concern for human populations (Cole et al., 2011). According to established definitions, plastic debris qualifies as microplastics (MPs) when particle dimensions fall below 5mm5mm in diameter. Microplastics are further categorized based on provenance: primary MPs denote particles deliberately manufactured at microscopic scales, whereas secondary MPs originate from the progressive disintegration of larger plastic artifacts.

Primary MPs are exemplified by microbeads and abrasive granules intentionally formulated into personal care commodities and household cleaning agents. Secondary MPs arise from the weathering, embrittlement, and mismanaged disposal of macroplastic materials such as packaging films, municipal refuse, atmospherically deposited particulates, and vehicular exhaust emissions (Wright et al., 2013). Notably, complex substances like paints can simultaneously contribute both categories, primary MPs while in liquid suspension and secondary MPs as fragments exfoliating from cured surfaces. Microplastics display remarkable morphological heterogeneity, occurring as fibers, irregular shards, spherical beads, planar films, thin flakes, cylindrical pellets, and porous foams. This structural diversity reflects the original conformation of the parent plastic, the specific degradation mechanisms operating at the particle surface, and the duration of environmental residence (Hidalgo-Ruz et al., 2012).

The propensity of MPs to inflict physical damage upon living organisms is intricately governed by both particle size and geometric configuration. Although larger MP fragments are typically precluded from assimilation by most terrestrial vegetation and soil-dwelling invertebrates, submicron and nanoscale particles can readily traverse biological membranes, thereby posing a distinct ecological risk. Empirical investigations indicate that fibrous MPs exert more pronounced toxicological effects on marine invertebrates than fragments or spheres fabricated from identical polymer compositions (Gray & Weinstein, 2017). Growing scholarly attention has been directed toward anthropogenic cellulosic fibers detected across diverse environmental settings, including abyssal oceanic sediments and fish specimens. Although these cellulosic materials are intrinsically biodegradable, the chemical adjuncts they contain may nonetheless confer toxicity upon aquatic biota (Woodall et al., 2014).

Arguably, the leachable constituents embedded within plastic formulations, encompassing organic and inorganic additives, unpolymerized monomer residues, and metallic species, constitute a more pernicious contamination source for human health than the inert polymeric scaffolds themselves. Endocrine-disrupting agents such as bisphenol A and various phthalate congeners are recurrently encountered in association with microplastics and present considerable hazards to human homeostatic regulation (Barboza et al., 2020). Additional environmental concerns derive from the demonstrated capacity of MPs to function as vectors for extraneous contaminants, including potential human microbial pathogens, persistent organic pollutants (POPs), and heavy metal species. The adsorption of POPs, chiefly polycyclic aromatic hydrocarbons, polychlorinated biphenyls, and polybrominated diphenyl ethers, onto MP surfaces has been extensively corroborated (Rodrigues et al., 2019).

Microplastics possess the capacity to bioaccumulate within human physiological compartments through diverse exposure modalities, encompassing the inhalation of resuspended dust and the direct consumption of MP-adulterated dietary items. Current estimates place maximum annual MP intake attributable to dust ingestion at approximately 1000 particles for adult individuals and 3000 particles for pediatric populations (Dehghani et al., 2017). Trace elemental characterization of MPs recovered from marine environments has confirmed the presence of aluminum, iron, chromium, zinc, nickel, manganese, lead, cobalt, and copper at milligram per kilogram concentrations, alongside arsenic, vanadium, rubidium, and cadmium at microgram per kilogram levels (Squadrone et al., 2021). These findings underscore the potential for MPs to serve as delivery vehicles for toxic metals into biological systems.

At present, scientific comprehension regarding MP-mediated toxicity and adverse human health sequelae remains markedly incomplete, thereby accentuating the imperative for investigations centered upon the trophic translocation of MPs through ecological food chains. This knowledge gap constitutes an essential prerequisite for devising efficacious contamination abatement strategies and evidence-based risk assessment frameworks. This comprehensive narrative review delineates the predominant environmental conduits, aquatic, atmospheric, and edaphic, by which MPs infiltrate biological food webs, scrutinizes their potential ramifications for human physiological well-being, and consolidates contemporary findings pertaining to their environmental distribution, ultimate fate, and behavioral dynamics (Pironti et al., 2021). The review is structured to articulate the mechanisms through which MPs interface with human organisms, evaluate their multifaceted impacts across environmental compartments, and ascertain contamination levels within water, soil, air, and alimentary products.

2. Methods

This study undertook an exhaustive examination of peer-reviewed literature concerning microplastics, noting that contemporary scholarship remains disproportionately oriented toward environmental contamination rather than the nexus between MPs and human physiological interactions. This review was structured according to a tripartite conceptual framework. First, it articulates the urgency of microplastic infiltration into food webs by delineating the mechanisms through which MPs interface with the human organism. Second, it evaluates the multifaceted impacts of MPs on the physicochemical properties of aquatic, atmospheric, and terrestrial compartments, alongside the latent hazards posed when these particulates are redistributed across environmental media and translocated along trophic cascades. Third, this review ascertains the extent of MP contamination within water bodies, soil matrices, atmospheric aerosols, and alimentary products, appraises particle-associated toxicity, and proffers prospective research trajectories predicated upon extant knowledge gaps.

To retrieve pertinent scholarly information, the following search terms were deployed, individually and in various Boolean combinations, across the Web of Science, Scopus, and Google Scholar databases: "microplastic," "environment," "food web," "human exposure," and "toxicological effects." Seminal literature published during the interval spanning 2004 through June 2021 was systematically collated and subjected to critical analysis.

Regarding analytical methodologies employed in the studies under review, sample collection and processing constitute pivotal steps in securing reliable MP quantification devoid of procedural contamination. Divergent sampling strategies are necessitated contingent upon the specific environmental matrix under investigation. For aquatic systems, predominant sampling modalities encompass sediment retrieval from benthic, littoral, and estuarine habitats; shoreline beachcombing; direct visual surveillance by divers; deployment of marine trawls for water column particle acquisition; and examination of plastic remnants ingested by marine biota (Hidalgo-Ruz et al., 2012). With respect to airborne MPs, the preponderance of investigations has utilized passive collection of deposited particulates, whereas comparatively fewer inquiries have adopted active sampling approaches. These two sampling paradigms yield distinct informational outputs:

passive samplers furnish estimates of MP deposition flux onto specific surface areas over defined temporal windows, whereas active devices enumerate MP abundance within air masses that may remain suspended rather than undergoing deposition (Zhang, Kang, et al., 2020).

Following sample acquisition, MP analysis proceeds through sequential stages of separation, identification, and quantification. Initial particle segregation is conventionally accomplished via sieving apparatuses featuring mesh apertures spanning 0.038 to 4.75mm4.75mm, coupled with filtration membranes possessing nominal pore sizes in the range of 0.02−5μm0.02−5μm (Li, Liu, & Chen, 2018). For submicron particles, studies have documented the application of field-flow fractionation and hydrodynamic chromatography. Visual inspection, encompassing assessment of chromatic attributes, morphological characteristics, and optical transmission properties, is indispensable for discriminating MPs from non-plastic extraneous debris such as biogenic shell fragments and siliceous sand grains (Song et al., 2015). Advanced instrumentation, exemplified by scanning electron microscopy integrated with energy-dispersive X-ray spectroscopy (SEM-EDS), has been increasingly reported for morphological characterization of diminutive plastic particles. Ultimately, chemical compositional elucidation, specifically polymer identification, is predominantly achieved through Fourier transform infrared (FT-IR) spectroscopy and Raman microspectroscopy. These vibrational spectroscopic modalities are complementary in nature: functional groups exhibiting robust IR absorption typically manifest attenuated Raman scattering, and conversely (Baruah et al., 2021). Despite continual advancements in analytical sophistication, FT-IR and

Raman spectroscopies remain the preeminent techniques for polymer identification, routinely augmented by optical microscopy-based morphological documentation.

3. Results and Discussion

3.1. Detection, Distribution, and Quantification of Microplastics in Aquatic, Atmospheric, and Terrestrial Systems

The phenomenon of microplastic pollution was initially documented within marine environments. As early as the 1970s, researchers reported the presence of spherules, disks, and pellets adrift on the surface waters of the Sargasso Sea, strewn along the New England coastline, and dispersed throughout the surface strata of both the Atlantic and Pacific Oceans (Carpenter & Smith, 1972; Carpenter et al., 1972; Colton et al., 1974). In more recent decades, scholarly attention has progressively shifted toward inland aquatic systems, encompassing wastewater effluents, fluvial channels, and lacustrine basins (Eerkes-Medrano et al., 2015). Concomitant with this expanding interest, numerous investigations have endeavored to provide consolidated overviews of MP occurrence across global water matrices, the analytical methodologies employed for their identification, and the potential ramifications for human well-being. The ubiquity of MPs in aquatic settings has been comprehensively addressed in previously published reviews, which emphasize their relative abundance across disparate water matrices and their worldwide geographical dissemination.

With respect to the provenance of MP contamination in aqueous milieus, the predominant sources are improperly managed plastic refuse originating from terrestrial activities and, to a substantially lesser degree, debris derived from maritime operations, including the fishing industry's extensive reliance on plastic-based equipment (Andrady, 2017). The progressive fragmentation of plastic detritus within water columns facilitates the contamination of aquatic organisms through both active and passive uptake mechanisms, thereby enabling subsequent transfers throughout the intricate architecture of the food web. More recently, microplastics have garnered recognition as a distinct class of airborne contaminants, warranting regular surveillance alongside other atmospheric constituents to safeguard human health (Gasperi et al., 2018). Accumulating evidence indicates that airborne MP particulates can be conveyed to geographically remote regions via atmospheric transport phenomena, including aeolian processes and oceanic circulation patterns.

Airborne MPs may ultimately be deposited onto aquatic surfaces and terrestrial landscapes through either dry gravitational settling or wet depositional events, engendering pronounced spatial heterogeneity and temporal fluctuations in their environmental abundance (Dris et al., 2015). As a direct corollary, MPs have been detected even in some of the planet's most isolated and ostensibly pristine locales, including the Antarctic continent and the remote expanses of the South Indian Ocean. The estimated annual influx of plastic materials into pedological systems substantially exceeds the corresponding flux into oceanic reservoirs, thereby positioning the terrestrial environment as a critically important yet historically underappreciated sink for MP accumulation (Horton et al., 2017). Despite its significance, MP contamination within soil matrices languished in relative obscurity for numerous years, only beginning to attract meaningful research attention around 2012 (Rillig, 2012).

Principal vectors for MP introduction into agricultural and natural soils include the application of plastic mulch films, the incorporation of compost and municipal solid waste amendments, the land disposal of biosolids such as sewage residuals, irrigation with treated or untreated wastewaters, atmospheric depositional inputs, and the utilization of plastic-coated fertilizer formulations (Blasing & Amelung, 2018). The acquisition and subsequent processing of environmental samples constitute the most critical stages in ensuring a robust and contamination-free determination of MP pollution. Distinct sampling methodologies are mandated contingent upon the specific environmental compartment under scrutiny. For aquatic environments, predominant sampling approaches encompass benthic sediment retrieval from seabeds and shorelines, direct visual observation by divers, the deployment of marine trawling apparatus, and the forensic examination of plastic remnants recovered from the digestive tracts of marine fauna (Hidalgo-Ruz et al., 2012).

With regard to the analysis of atmospheric MPs, the majority of published investigations have relied upon passive sampling of gravitationally settled material, whereas comparatively fewer studies have employed active air sampling methodologies. These two sampling paradigms furnish complementary yet distinct informational outputs: passive samplers yield estimations of MP depositional flux onto designated surface areas over specified temporal intervals, whereas active sampling devices quantify the concentration of MPs entrained within air masses that may remain suspended rather than undergoing depositional clearance (Zhang, Kang, et al., 2020). Following sample collection, MP analytical workflows proceed through a sequential cascade of separation, identification, and quantification steps. Initial particle segregation is routinely accomplished via sieving apparatuses and filtration membranes of varying pore dimensions. Visual examination, incorporating assessments of chromatic properties, morphological attributes, and optical transmission characteristics, is essential for discriminating authentic MPs from non-plastic extraneous debris (Song et al., 2015).

Definitive chemical compositional elucidation, specifically the identification of polymer types, is predominantly accomplished through Fourier transform infrared (FT-IR) spectroscopy and Raman microspectroscopy. These vibrational spectroscopic techniques are fundamentally complementary: functional groups exhibiting pronounced IR absorption typically demonstrate correspondingly attenuated Raman scattering, and vice versa. By way of illustration, polar carbonyl functionalities are optimally resolved via IR spectroscopy, whereas aromatic moieties and olefinic double bonds are more effectively discerned through Raman methodologies (Baruah et al., 2021). The analytical methodologies delineated within this section are universally applicable to MP identification across all environmental compartments. Notwithstanding the advent of progressively more accurate and sophisticated analytical instrumentation, FT-IR and Raman spectroscopies persist as the most widely adopted techniques for ascertaining the polymeric composition of microplastics, routinely augmented by morphological documentation derived from optical microscopy.

3.2. Trophic Transfer of Microplastics and Associated Human Dietary Exposure across Diverse Food Categories

Microplastics migrate through environmental compartments and enter biological food webs, ultimately reaching human consumers via ingestion of contaminated dietary items. This section critically examines peer-reviewed literature documenting MP contamination in edible marine species, as well as in a diverse array of food commodities including table salt, granulated sugar, honey, dairy milk, various fruits, carbonated soft drinks, and potable water (Barboza et al., 2018). Notably, the pretreatment of food and beverage specimens is an indispensable prerequisite to circumvent substantial analytical inaccuracies. Drinking water samples undergo parallel filtration through stainless steel assemblies with flowmeter quantification, followed by ethanolic preservation at −20∘C−20∘C (Kirstein et al., 2021). Salt specimens may be digested with hydrogen peroxide to eliminate potential organic interferences. Fish specimens are typically captured, conveyed on ice, and subsequently stored at −20∘C−20∘C in advance of laboratory analysis.

The marine environment constitutes the most intensively investigated system with respect to MP contamination, and products derived from the sea represent a principal dietary staple for substantial segments of the global human population. A considerable corpus of research has been devoted to elucidating MP occurrence and abundance in marine biota, with MP concentrations conventionally expressed as particle counts per gram of tissue or per individual organism (Walkinshaw et al., 2020). Two distinct mechanistic pathways have been proposed to account for the accumulation of MPs within piscine tissues. MPs may be actively captured through mistaken identification as prey items, passively acquired via branchial water filtration, or assimilated through the consumption of prey organisms already burdened with MP contamination. Shellfish, encompassing both decapod crustaceans and bivalve mollusks, alongside various teleost species, are recurrently found to harbor microplastic particulates.

MPs have been documented in 25 of the species that contribute most substantially to global marine fisheries landings, including Atlantic cod (*Gadus morhua*), European hake (*Merluccius merluccius*), and red mullet (*Mullus barbatus*) (Barboza et al., 2018). Scientific inquiries have extended to the analysis of MP bioaccumulation in additional taxa, including *Dicentrarchus labrax*, *Trachurus trachurus*, and *Scomber colias* specimens procured from Portuguese coastal waters. Within the Persian Gulf, a diverse assemblage of pelagic and demersal organisms was scrutinized, with MPs localized within the muscular tissues and branchial structures of sampled individuals. The sequestration of MPs within edible muscle tissue carries profound toxicological significance, as such particles are positioned for direct transfer to successive trophic echelons, including human consumers (Akhbarizadeh et al., 2019).

Microplastic fibers have recently been identified both on the exterior integument and within the gastrointestinal lumina of clupeid fishes from the Mediterranean Sea. Given that these small pelagic clupeids constitute a foundational forage base for numerous marine predators, these observations engender substantial apprehension regarding the potential for MP translocation throughout the marine trophic architecture. The physicochemical properties of the aqueous medium, particularly salinity, have been shown to modulate MP uptake dynamics. An investigation of fishes inhabiting the Saudi Exclusive Economic Zone of the Arabian Gulf revealed that merely 5.71%5.71% of sampled specimens had ingested MPs, a diminished prevalence hypothesized to reflect preferential accumulation of MPs within the sea surface microlayer, thereby reducing bioavailability for ingestion by ichthyofauna (Baalkhuyur et al., 2020).

MP contamination is not confined to wild-caught marine stocks; this phenomenon portends significant implications for freshwater capture fisheries and the expanding aquaculture sector. The potential for cultured organisms to encounter elevated MP concentrations is substantiated by the analysis of fish meals sourced from commercial Malaysian brands, wherein 64.3%64.3% of isolated particles were positively identified as MPs, with polyethylene constituting the most prevalent polymer (Karbalaei et al., 2020). Stable isotope analysis has emerged as a powerful and instructive tool for quantifying the magnitude of MP contamination within freshwater trophic webs. This analytical approach quantifies the relative abundances of stable isotopic variants, yielding isotopic ratios that furnish valuable insights concerning the provenance and trophic positioning of a given specimen (Garcia et al., 2021).

Over the past several years, a burgeoning body of literature has addressed the issue of MP contamination in edible salts destined for human consumption. MPs have been documented in commercial salt products encompassing 128 distinct brands derived from 38 disparate sources spanning five continents (Peixoto et al., 2019). The relative abundance of MPs in table salt exhibits pronounced international variability: the lowest concentrations were recorded in China (600 particles/kg) and the United States (800 particles/kg), whereas substantially elevated values were reported in Italy (8,000 particles/kg) and Croatia (20,000 particles/kg). The particulate contaminants identified in sea salt encompassed a diverse array of polymeric species, including polyethylene, polypropylene, polyethylene terephthalate, and polyvinyl chloride. A meta-analytical synthesis confirmed that the MP content of salt is strongly contingent upon its geographical provenance.

Freshwater reservoirs constitute the predominant source of potable water for human consumption across the globe. A growing corpus of scientific literature has implicated drinking water as a plausible and potentially significant vector for MP exposure. Freshwater samples have been demonstrated to contain polyethylene and polypropylene, which together may constitute upwards of 90%90% of the total MP burden in drinking water (Zhang, Xu, et al., 2020). German potable water investigations documented mean concentrations of 700 particles per liter, with identified polymers including polyester, polyvinyl chloride, and epoxy resin (Mintenig et al., 2019). Bottled water analyses revealed substantially elevated MP abundance in reusable polyethylene terephthalate containers relative to single-use bottles. The World Health Organization estimates that tap water contains approximately 5 particles per liter, corresponding to a daily MP dose of approximately 10 particles per capita (Cox et al., 2019).

Beyond drinking water, MPs have been documented in a broader spectrum of commercially available beverages. An analysis of samples encompassing soft drinks, cold teas, and energy beverages procured from Mexico City revealed MP contamination across all product categories, with polymers including polyamide and polyethylene terephthalate (Shruti et al., 2020). Dairy milk contamination raises particular concern given infant consumption patterns. MPs were detected in every milk sample examined from Mexican brands, with thermoplastic sulfone polymers, materials employed in ultrafiltration membranes, constituting predominant contaminants. Infant polypropylene feeding bottles release substantial MP quantities during formula preparation, with estimated daily infant MP ingestion averaging approximately 1,580,000 particles per capita, representing exposure levels approximately 3,000 times those of adults (Li, Shi, et al., 2020).

Honey, sugar, fruits, and vegetables exhibit varying MP contamination levels. Honey samples from diverse origins contain elevated MP concentrations, with contamination most likely attributable to atmospheric depositional fluxes during production and processing (Liebezeit & Liebezeit, 2013). Sugar samples averaged 217±123217±123 fibers per kilogram and 32±732±7 fragments per kilogram. Notably, MPs have been detected in edible fruits and vegetables, with concentrations spanning 52,600−307,75052,600−307,750 particles per gram in fruits and 72,175−130,50072,175−130,500 particles per gram in vegetables. Apples and carrots were identified as the most heavily contaminated matrices (Oliveri Conti et al., 2020). Estimated daily intakes range from 2.96×1042.96×104 to 1.41×1061.41×106 particles per kilogram of body weight.

Terrestrial food animals accumulate MPs through environmental and processing pathways. Mexican home garden investigations documented MP transfer from soil to earthworm casts to chicken feces, with gizzards containing 10.2±13.810.2±13.8 particles per gram (Huerta Lwanga et al., 2017). South Chinese livestock farms revealed polypropylene and polyethylene as predominant polymers in pig, poultry, and cattle manure. MPs resist digestive degradation, persisting through gastrointestinal transit and accumulating in fecal matter subsequently utilized as agricultural compost. Meat packaging constitutes an additional vector, with extruded polystyrene contaminating products at 4–18.74–18.7 particles per kilogram (Kedzierski et al., 2020). Collectively, the evidence substantiates non-negligible human MP ingestion through dietary pathways. Salt contributes minimal MP exposure, whereas infant formula confers extraordinarily elevated burdens. Further toxicological investigations are imperative to elucidate health consequences of chronic dietary MP exposure.

4. Conclusion

The progressive accumulation of microplastic particulates within environmental matrices imposes considerable stress upon ecosystem integrity and function. This comprehensive review has synthesized current scholarly literature pertaining to microplastic occurrence across environmental compartments and alimentary products, the principal exposure pathways through which these contaminants reach human receptors, and the associated toxicological ramifications. A disproportionately larger body of research has been directed toward characterizing contamination in marine-derived foodstuffs, drinking water, edible salts, and select commodities such as honey, fruits, and poultry products. The collective weight of evidence unequivocally indicates that human ingestion of microplastic particles through dietary consumption is far from negligible and warrants serious consideration as an emerging public health concern. Multiple toxicological effects associated with ingested microplastics have been documented in experimental systems, predominantly manifesting under elevated concentrations that substantially exceed typical human environmental exposures.

Future research endeavors must be directed toward evaluating the authentic health consequences of microplastic contamination at environmentally relevant, low-level concentrations and under conditions of protracted, chronic exposure. The growing recognition of potential risks posed to human physiological integrity has not been paralleled by commensurate investigative efforts aimed at establishing causal linkages between environmental microplastic abundance and *in vivo* human health outcomes. This discrepancy is largely attributable to the persistent absence of standardized sampling methodologies and harmonized analytical protocols for microplastic separation, detection, and quantification across disparate matrices. This review is intended to serve as a foundational resource for subsequent researchers, fostering deeper mechanistic inquiries into the processes governing microplastic uptake, translocation, and bioaccumulation, elucidating the underlying molecular and cellular mechanisms of toxicity, and ultimately informing the development of evidence-based risk assessment frameworks and preventive health guidelines.

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