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Research Article

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Micro and Nano Plastics in the Food Chain: Challenges, Risks, and Future Directions

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Abstract

This review explores the pervasive presence of micro and nano plastics (MNPs) in the food chain, elucidating their diverse sources, distribution, and potential health impacts. MNPs, originating from macro plastic fragmentation, shedding of microfibers (MFs), and industrial activities, enter the food chain through soil and water contamination, affecting aquatic organisms and human health via food consumption. The article emphasizes MNPs' intricate interactions within the human gastrointestinal (GI) tract, outlining their absorption dynamics and highlighting potential health implications, particularly for vulnerable populations. Additionally, the release of chemicals from plastics during digestion raises concerns about endocrine disruption. Analytical techniques, including fourier-transform infrared spectroscopy (FTIR) and chromatographic methods, are discussed as crucial tools for addressing MNPs' impact on food safety. The review concludes by emphasizing the urgent need for comprehensive strategies to mitigate MNPs' environmental and health consequences, underscored by potential economic implications and the imperative for robust analytical frameworks.

Keywords

Microplastics, Nano plastics, Food chain, Health impact, Contamination

Introduction

Plastics have become ubiquitous, infiltrating various industries such as food, health, and textiles. In recent years, the emergence of MNPs has intensified environmental concerns, as they result from the continuous fragmentation of macro plastics [1]. Microplastics, defined as fragments smaller than 1 mm, and nano plastics, less than 1 μm in size, are increasingly prevalent in the environment, posing a significant threat to both ecosystems and human health. Various factors contribute to the formation of MNPs, including photooxidation, ultraviolet radiation-induced degradation, weathering, mechanical abrasion, and microbial degradation [2]. Despite their small size, these particles accumulate in water bodies, evading removal by conventional sewage and cleaning systems. The inefficiency of regular filtration systems exacerbates environmental contamination and biological uptake.

The introduction of MNPs into the food industry is notably influenced by packaging materials. During processing, storage, and transportation, direct contact with plastic packaging facilitates the transfer of plastic particles into food items [3]. The widespread use of single-use plastics, such as bottles and containers, amplifies this issue, contributing significantly to food contamination. Beyond the physical presence of plastic particles, the leaching of chemicals from plastics raises additional concerns. Plastics, composed of synthetic organic polymers and additives like plasticizers, antioxidants, heat stabilizers, and pigments, release these substances when exposed to heat or acidic environments. These additives, not chemically bound to the polymer, readily leach into substances packed in plastics, leading to human exposure through food consumption [4]. The chemicals leached from plastics have the potential to disrupt the endocrine system and induce adverse health effects.

MNPs are known to release toxic compounds such as polycyclic aromatic hydrocarbons, phthalates, bisphenols, and esters. These particles can be absorbed by aquatic organisms, causing acute poisoning [5]. Additionally, research suggests that MNPs can adsorb heavy metals and organic pollutants, posing a potential risk of contamination to aquatic organisms. The contamination of foods with MNPs, coupled with the leaching of chemicals, presents a complex and urgent challenge that requires immediate attention [6]. This review aims to discuss the sources of contamination, distribution, leaching, and adverse effects of MNPs in foods, shedding light on the multifaceted nature of this environmental and health issue.

MNPs: sources, and distribution

The key sources of MNPs include fragmentation of macro plastics, MF shedding, micro breads in personal care products, industrial and agricultural impacts, and waste management gaps [7, 8]. The disintegration of macro plastics including bottles, packaging materials, and synthetic textiles release MNPs into the environment catalyzed by mechanical forces, ultraviolet radiation, and fluctuating temperatures and pressures [9]. The use of synthetic textiles such as polyester (PES) and nylon sheds MFs during daily use and washing infiltrate into water bodies, and consequently the food chain [10]. The activities including tire wear on roads and fields, breakdown of plastic mulches also contribute to micro plastic contamination. Improper disposal of plastic waste, inadequate recycling, and waste treatment contribute to the MNPs contamination [11].

MNPs accumulate in the soil through contaminated irrigation water, which leads to the uptake of microplastics by plants. The water bodies such as rivers, lakes, and oceans contaminated with plastics act as reservoirs for microplastics [12]. Aquatic organisms, such as fish and shellfish, ingest microplastics directly or indirectly through consumption of contaminated prey. MNPs are ingested by aquatic organisms, from zooplankton to large marine animals and incorporate them into the food chain. MNPs can adsorb harmful contaminants and pollutants that magnify the toxicological effect throughout the food chain [13]. Smaller organisms such as planktonic species ingest MNPs suspended in water, and as the larger species feed on smaller organisms MNPs are biomagnified reaching higher concentration in predators through bioaccumulation [13].

The plastic materials used during food processing shed the MNPs into food products and their migration into foods is influenced by temperature and contact time [14]. Seafood such as shrimp and fish, as well as other meats like chicken, pork, and various plant-based meat alternatives, are significant sources of protein for humans. However, these foods are increasingly being contaminated with microplastics. These microplastics can enter the human body through diet, posing potential health risks [15]. MNPs also enter the atmosphere through wind dispersion, industrial emissions, and atmospheric fallout [6]. The airborne MNPs travel through the wind and deposit onto land and water surfaces potentially impacting the environment. The occurrence of MNPs in different foods are shown in table 1.

Beverages ranging from bottled water to soft drinks have become the carriers of MNPs. Plastic bottles caps and water used in manufacturing the beverages can introduce the MNPs into final products [20]. Salt is one of the major products that are getting contaminated with MNPs. As the production of salt involves evaporation of seawater it concentrates the MNPs that contaminate the food materials added with salt containing MNPs. Distribution of MNPs in the ecosystems ultimately lead to the potential human exposure through various pathways. Consumption of seafood, contaminated water, and foods contaminated with MNPs contributes to the ingestion of MNPs into humans [21]. Figure 1 illustrates the potential routes of plastic contamination and their entry into the food chain.

The widespread distribution of MNPs across ecosystems highlights their profound impact on both environmental integrity and human health. MNPs, originating from various sources including plastic fragmentation and industrial pro-

Table 1: Occurrence of microplastics in foods and analytical techniques.

Type of food	Microplastics concentration (Particles/L or kg)	Analytical technique	Type of plastic	Ref.
Drinking water	193	Micro-Raman spectroscopy	PET and PP	[16]
Table salt	550 - 681	Stereo microscope μ-FTIR	PET, PES, and PE	[17]
Honey	440 - 660	Dissection microscope, FTIR, and Raman spectroscopy	PE and PP	[5]
Packaged meat	10 - 221	FTIR	PS	[18]
Skim milk	34 - 254	10X lens inverted microscope and FTIR	PE, PP, and Polyamide (PA)	[16]
Industrial honey	20 - 166			
Refreshing beverage	10 - 144			
Industrial beer	18 - 98			
Canned fish	2 - 128	Epifluorescence microscope and Micro-Raman	PET, PE, PP, and Polyvinyl chloride (PVC)	[1]
Vinegar	4.9 - 21.2 mg/kg	Stereo microscope and FTIR	PE	[19]

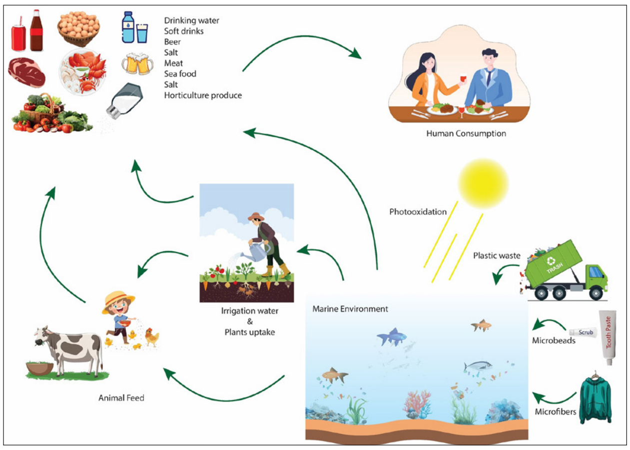

Figure 1: Potential routes of MNPs contamination and entry into food chain.

cesses, contaminate food chains and accumulate in organisms, posing significant risks through dietary intake. Their ability to absorb toxic pollutants exacerbates these risks, threatening biodiversity and ecosystem stability. Effective mitigation strategies are urgently needed, focusing on enhanced waste management, sustainable practices, and innovation in materials to curb the pervasive influence of MNPs on our planet and future generations.

Behavior of MNPs in human tract

The behavior of MNPs within the human GI tract is a critical concern given their widespread presence in various consumables. The oral route serves as a primary gateway for MNPs' entry into the human body, with sources including seafood, drinking water, beverages, pickled products, and salt. Remarkably, humans ingest an estimated annual load of 39,000 to 52,000 MNPs through food consumption alone, underscoring the urgency of comprehending their dynamics within the GI tract [22]. Notably, MNPs readily develop a protein corona upon entry into the GI environment, influencing their interactions and potential impacts. Research conducted by Luo et al. [23] examined protein-coated polystyrene (PS) microplastics, revealing that aggregated microplastics augment accumulation and residence time in the intestine. Distinct effects on lipid digestion were demonstrated by Tan et al. [24] particularly with PS microplastics, which hindered free fatty acid release and altered droplet sizes, thereby affecting nutrient absorption, and potentially impacting human health.

The effects of 50 nm and 250 nm PS MPs on mice stomachs was studied [25]. Exposure to these MPs disrupted gastric secretion, reduced mucus secretion, and damaged the gastric barrier. In gastric cells, MPs inhibited cell viability, increased reactive oxygen species (ROS), and induced mitochondria-dependent apoptosis. The P62/Keap1/Nrf2 oxidative stress pathway was activated, decreasing antioxidant enzyme expression. The ROS scavenger N-acetylcysteine (NAC) partially alleviated the damage. The study suggests ROS-related pathways as potential targets for intervention. Paul et al. [26] examined how GI conditions affect polylactic acid (PLA), polymethylmethacrylate, and melamine formaldehyde particles of various sizes (micro, submicro, and nano). It was found that digestion reduces the interaction of these plastic particles with cells and enhances their transport across the intestinal barrier. Additionally, the interaction with organic matter in the digestive system causes the particles to agglomerate, altering their size and surface properties. Overall, the digestive process impacts the characteristics of the particles and their interactions with the intestinal barrier. The GI environment also significantly shapes MNPs' absorption. The uptake of differently sized carboxylated PS particles by Caco-2 cell layers was reduced when incubated with substances like bovine serum albumin (BSA) and casein [2]. Exposure to meat extract increased the uptake of 20 nm nanoparticles. After contact with saliva, functionalized MNPs significantly agglomerated triggered by multivalent anions, such as PO_4^{3-}, SO_4^{2-}, and CO_3^{2-} leading to reduced absorption. Particle size, deformation, degradation, and protein corona formation emerge as key factors influencing MNPs' bioavailability, uptake rate, toxicological impacts, and health risks. While polyethylene glycol-coated PS particles exhibited diffuse mobility through physiological mucus, larger particles encountered a restricted diffusion, influenced by ionization and hydrophobic traits. Importantly, the release of additives from plastics under physiological conditions enhances complexities [10]. MNPs can leach numerous chemicals, such as bisphenol A, phthalates and alkylphenols, during digestion, with potential endocrine disruption effects. The implications of these chemicals, especially in combination, necessitate further risk assessment. In light of these considerations, a comprehensive understanding of MNPs' behavior within the GI tract is indispensable for assessing their impact on human health and fostering food safety and sustainability.

The intricate dynamics of MNPs within the human GI tract underscore their complex interaction with physiological processes and potential health implications. From their initial entry through dietary sources to the formation of protein coronas and interactions with digestive enzymes and mucosal barriers, MNPs exhibit varied behaviors that impact their bioavailability and toxicological effects. The release of chemical additives from MNPs further complicates the risk landscape, necessitating continued research into their cumulative effects and regulatory measures to mitigate human exposure. A thorough understanding of MNPs' behavior in the GI tract is essential for informing policies on food safety, environmental sustainability, and public health protection in the face of increasing plastic pollution.

Health effect of MNPs from *in vivo* and *in vitro* studies

From various reports based on mice studies, the risks of MNPs on health include compromised mucus production, microbiota dysbiosis, local inflammation, oxidative stress, and metabolic disruptions. Certain population segments, such as infants, children, pregnant women, and the elderly, may be particularly vulnerable to the toxic effects of MNPs. MNPs traverse and reach remote tissues. Mussels and crabs accumulate microplastics in the intestines, showing translocation within the GI system. Studies reveal movement of MNPs into the circulatory system and distant organs following inhalation or ingestion in rats. Additional animal studies demonstrate MNPs' ability to cross biological barriers and accumulate in organs like the liver, kidneys, and spleen [27]. Prolonged exposure induces gene expression changes and histological abnormalities in organs. Inflammatory conditions elevate translocation frequency, with MNPs inducing histological changes, oxidative stress, and cytotoxicity.

Lin et al. [28] investigated the toxicity of nano polyethylene terephthalate (nPET) particles of different sizes in mice, revealing size-dependent effects. The median lethal dose (LD50) was 266 mg/kg for smaller nPET (S-nPET, 200 nm) and 523 mg/kg for larger nPET (B-nPET, 700 nm). A single oral exposure to 200 mg/kg S-nPET, but not B-nPET, caused significant weight loss, intestinal obstruction, organ damage, and 40% mortality in mice. S-nPET disrupted the gut microbiome, reducing bacteria involved in lipid metabolism and causing dysregulation of lipid metabolites. Serum analysis showed more severe lipid metabolism disorders, immune impairment, and neurological damage with S-nPET. Pathological examination revealed greater tissue damage in the liver, spleen, kidney, and brain with S-nPET. These findings highlight the increased health risks associated with smaller nano-sized plastic particles.

MF are tiny strands of plastic that often come from synthetic textiles, fishing gear, carpets, and car tires. On the other hand, microbeads (MBs) are small spherical pieces of plastic used in exfoliating scrubs, toothpaste, cosmetics, abrasive cleaners, and plastic resin pellets [29]. Notably, MF exhibits greater adverse effects than MB, inducing carapace and antenna deformities, and causing reduced reproductive output in freshwater zooplankton *Ceriodaphnia dubia* [13]. Ingestion of MF influences growth rates in the tropical house cricket *Gryllodes sigillatus* whereas MB does not exhibit the same impact. These findings emphasize intricate health implications of MNPs within the GI tract.

MNPs present significant health risks based on animal studies, including compromised mucus production, microbiota imbalance, inflammation, oxidative stress, and metabolic disruptions. Vulnerable groups like infants, children, pregnant women, and the elderly are particularly at risk. MNPs can traverse the GI system, reach distant organs, and induce histological abnormalities and oxidative stress. Different types of MNPs, such as MFs and MBs, exhibit varying impacts, with MFs showing more pronounced adverse effects in both aquatic and terrestrial organisms. Addressing these risks requires urgent research, regulatory action, and sustainable practices to safeguard human health and environmental integrity.

Leaching of plastics, a potential concern

Leaching and migration of plastics and their constituents is one of the major concerns in food safety. Migration of compounds depends on various factors such as contact surface area, nature of migrant, kinetics and thermodynamics of migration process, nature of food material, temperature, and duration of contact [30]. Plastics that come in contact with food materials contain several chemicals that undergo several chemical transformations that migrate into the foods. Application of high temperatures and irradiation during processing induces chemical transformations, production of several compounds and migrate into foods [31]. Various additives, dyes, monomers, oligomers, and degradation products are known to leach into the food materials. The chemicals bisphenol A and di-(2-ethylhexyl) phthalate are authorized to be used in plastics that are being leached into foods. Several other chemicals associated with plastics are known to be carcinogenic, reprotoxic, persistent, mutagenic, and endocrine disrupting. These hazardous chemicals migrate into the food and become a major source of chemical contamination in foods [32].

The release of chemicals from plastics occurs through diffusion, desorption, and erosion. Phthalates and flame retardants such as polybrominated diphenyl ethers (PDBEs) are known to release through diffusion mechanism from higher to lower concentration. The additives added to plastics to enhance the plastics properties are released from the surface to surrounding medium through desorption process [18]. The release of these additives is facilitated by acidic pH especially in the gut of animals. Erosion is another process through which additives, phenols, and aldehydes and pollutants such as heavy meatal ions and pesticide residues are released. Recent studies suggested that ingestion of plastics along with food components such as lipids will accelerate the leaching of plastics. The gut microflora is also known to biodegrade plastics and release various hazardous chemicals.

Abiotic factors such as sunlight, temperature and pH affect the leaching of chemicals from MNPs. Sunlight promotes photochemical degradation, produces ROS resulting in the release of Bisphenol A and phthalates. Exposure to ultraviolet radiation leads to the aging of plastics and promotes the release of toxic additives from plastics [17]. The pH also has a major effect on the leaching of plastics. Acidic compounds such as phthalates are easily soluble and leach under acidic conditions, and basic compounds leach under basic conditions. The change in pH will change the secondary interactions such as hydrogen bonding and electrostatic interactions and has an impact on surface charge. The magnitude of change in pH will influence surface charge and effects the leaching rate of chemicals. The lower pH also enhances the breakdown of microplastics leading to the increased release of chemicals [2]. At natural pH of water, the microplastics have tendency to aggregate and adsorption of organic pollutants increase. The common chemicals that are leaching from plastics and contaminate foods are given in table 2.

The migration of chemicals from plastics into food poses significant food safety concerns. Factors such as surface area, temperature, and chemical nature influence the release of hazardous compounds. Processes like high temperature and irradiation can accelerate chemical transformations, allowing additives and degradation products to migrate into food. Chemicals such as bisphenol A and phthalates, authorized for use in plastics, leach into food, posing risks like carcinogenicity and reproductive toxicity. The pH plays a critical role, with acidic conditions enhancing leaching. Abiotic factors like sunlight and temperature further promote chemical release from plastics. Effective regulation and innovative material design are essential to minimize these risks and ensure safer food production and consumption practices.

Table 2: Results of migration testing and analysis for identifying chemicals leaching from plastics.

Type of plastics	Food products packed	Analytical technique	Chemicals identified	Ref.
PS, PP, PE, and PLA	Drinking water, yogurt cups, and milk	UPLC-QTOF-MS	Mono(2-acryloyloxyethyl) succinate; Pentaethylene glycol; 12-Aminolauric acid; 6-Deoxy-D-mannono-4-lactone; Solketal; Laurolactam; and Hexanoyl fluoride.	[16, 17]
PET	Drinking water	GC-MS	Styrene; Ethyl benzene; Toluene; *p*-Xylene; 2-Phenyl propane; Propyl benzene; 1-ethyl 4-methyl benzene; α-methyl styrene; (1-methylethyl) benzene; 2-propenyl benzene; and 1-ethyl 3-methyl benzene.	[1]
PE, PET, and PP	Milk, drinking water, and juices	GC-MS	Cyclohexanone; Cyclohexanone, 3,3,5-trimethyl; Benzaldehyde, 4-methyl; 2-Butoxyethyl acetate; 2-Phenyl-2-propanol; Ethanol, 2-(2-ethoxyethoxy)-, acetate; 2,4-Dimethylbenzaldehyde; Butoxyethoxyethyl acetate; Hexanoic acid, 2-ethyl-, 2-ethylhexyl ester; Octadecanoic acid, methyl ester; Benzophenone, 4-phenyl-; and Octadecanoic acid, 2-hydroxy-1-(hydroxymethyl)ethyl ester.	[2, 3]
PET, PP, PS, and PE	Drinking water, carbonated beverages, and fruit juices	GC-MS	Phthalate esters, and bisphenol A.	[7, 9, 26]
PVC	Drinking water	UPLC-QTOF/MS	1-oleoyl-3-linoleoyl-rac-glycerol; Tetracosenamide; Docosanamide; 2-(2-hydroxyethyl-hexadecylamino)ethyl palmitate; and Bis(2-ethylhexyl) 2,2′ disulfanediyldiacetate.	[19]
Polyurethane	Fruit juices, milk, and sea food	UPLC–Q-TOF/MS	1,4,7-trioxacyclotridecane-8,13-dione; 1,6-dioxacyclododecane-7,12-dione dimer; 1,4-dioxacyclotridecane-5,13-dione; 1,4,14,19-tetraoxacyclopent acosene-5,13,20,25-tetra one and 1,4-dioxacyclotridecane-5,13-dione; 1,1-(Methanediyldibenzene-4,1-diyl)bis[3-(2-hydroxyethyl)urea]; 4-(7-acetoxy-5-methoxy-8,8-dimethyl-2-oxo-7,8-dihydro-2H,6H-pyrano[3,2-g]chromen-3-yl)-1,3-phenylene diace-tate; and Bis[2-(diethylamino)ethyl] 4,4′-[(2-methyl-1,3propanediyl) bis(oxycarbonylimino)] dibenzoate.	[26]

Analytical techniques to identify the MNPs and associated chemicals

Analytical techniques for the identification of MNPs in food have become principal in addressing concerns related to food safety and environmental contamination. The ubiquitous presence of these small plastic particles in various food products has raised significant health and environmental issues [16]. The identification of MNPs in food involves a multifaceted approach, starting with sample preparation and extraction techniques that aim to isolate these particles from complex matrices. FTIR and Raman spectroscopy emerge as pivotal techniques for their ability to characterize the chemical composition of the plastic particles, shedding light on the types of polymers present. Thermal analytical techniques including differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA) can be employed for identification of MNPs based on their thermal stability. DSC depends on changes occurring in sample in response to change in temperature and TGA is based on mass degradation of sample with increase in temperature. The quantification of MNPs is based on peak position and area under the peak.

The physical analysis of MNPs can be carried out using various microscopic techniques, including light microscopy, optical microscopy, scanning electron microscopy (SEM), and transmission electron microscopy (TEM), enable researchers to visualize and measure the size and morphology of these particles [1]. The light and optical microscopy are limited to identification and visual sorting of microplastics. They do not provide any chemical information leading to false positive results and nano sized particles cannot be identified. SEM in combination with energy-dispersive X-ray spectroscopy (EDX) can provide elemental composition and surface morphology of MNPs.

Chromatographic techniques, such as gas chromatography (GC) and liquid chromatography (LC), coupled with mass spectrometry (MS), offer high sensitivity and specificity in detecting and quantifying plastic additives and associated chemicals [16]. Additionally, emerging technologies like micro-FTIR imaging and nanoparticle tracking analysis (NTA) contribute to the evolving environment of analytical methods for MNPs identification. Apart from these conventional analytical techniques electrochemical based methods are being developed including voltammetry, potentiometry, chronoamperometry, and electrochemical impedance spectroscopy. These methods are fast, cost-effective, portable, and ecofriendly techniques for identification of MNPs. Pollard et al. [33] developed a three-dimensional printed microfluidic resistive pulse sensor that can identify the microplastics of 2 - 30 µm in size shed from tea bags. The device is stable and can measure at salt concentrations of 2.5×10^{-4} - 0.1 M at a flow rate of 1 mL/min. Impedance spectroscopy is another technique gaining attention for detecting MNPs that works based on electrical properties of individual particles. The study conducted by Colson and Michel [34] reported that impedance spectroscopy was effective in differentiating microplastics from biological samples and detected microplastics of 300 - 1000 µm in size with ≥ 90% recovery rate at an average flow rate of 103 ± 8 mL/min.

Challenges remain, including the need for standardized methods and the exploration of non-invasive techniques for *in-situ* analysis. As research progresses, the development of a robust analytical framework will not only enhance our understanding of the prevalence of MNPs in the food chain but will also facilitate the implementation of strategies to mitigate their potential impact on human health and the environment.

Potential health, environment, and economic impacts

The infiltration of MNPs into the global food supply chain has raised significant concerns about their potential health impacts on consumers. These tiny plastic particles have gained attention due to their widespread distribution within ecosystems and their potential to enter the human body through the consumption of contaminated food [27]. The primary pathway through which MNPs in food may affect human health is ingestion. When individuals consume food containing MNPs, these particles have the potential to be absorbed through the GI tract. The small size of nano plastics raises concerns about their ability to cross intestinal barriers and enter systemic circulation [19]. While the extent of absorption is still being investigated, studies have demonstrated that MNPs can interact with cells in the digestive system, which may have implications for nutrient absorption and overall gut health.

MNPs can absorb and accumulate a variety of chemicals from their environment, including persistent organic pollutants and heavy metals. When contaminated food is consumed, MNPs may act as carriers for these adsorbed chemicals, releasing them into the body upon ingestion. This introduces the potential for chronic exposure to toxic compounds that have been linked to adverse health outcomes, including endocrine disruption, neurotoxicity, and carcinogenicity [35]. MNPs' presence in the GI tract may trigger inflammatory responses. Research on PS microplastics and their effects on mice indicates that MNPs can cause oxidative stress and inflammation in the gut tissues. Chronic inflammation has been associated with a range of health issues, including gastrointestinal disorders and an increased risk of chronic diseases such as inflammatory bowel disease and cardiovascular diseases [2]. While the exact mechanisms are still under investigation, there is evidence to suggest that MNPs may translocate from the GI tract to other parts of the body. Studies in animal models have shown that nanoparticles, including MNPs, can cross biological barriers and accumulate in organs such as the liver, kidneys, and spleen. This raises concerns about the potential for systemic distribution of MNPs and their associated contaminants [24].

MNPs' potential to carry adsorbed pollutants and chemicals introduces complex toxicological considerations. The combination of the physical properties of MNPs and the chemicals they carry may result in synergistic or additive toxic effects. Moreover, MNPs' small size and large surface area could enhance their interaction with biological tissues and cells, potentially leading to cellular damage or disruption of normal cellular functions [36]. The bioaccumulation of MNPs and associated contaminants within the human body is an area of ongoing investigation. If MNPs accumulate over time, they may reach concentrations that exceed safe levels, particularly in organs with limited excretion capabilities. This could potentially lead to chronic health effects and long-term risks. Certain populations, such as infants, children, pregnant women, and the elderly, may be more vulnerable to the health effects of MNPs contamination in food. Developing bodies and compromised immune systems could heighten susceptibility to any potential adverse impacts [37]. Stringent regulatory responses to MNPs contamination may require industries to implement new practices, invest in technologies, and modify processes to ensure compliance. These changes can result in increased operational costs as businesses strive to meet evolving food safety standards.

MNPs have emerged as significant environmental pollutants, disrupted ecosystems and created a range of ecological challenges. These particles, which originate from the degradation of larger plastics and various industrial processes, infiltrate both terrestrial and aquatic environments. Their widespread presence leads to severe consequences for wildlife, impacting feeding behaviors, reproductive health, and overall ecosystem balance. The persistence and ubiquity of MNPs exacerbate their environmental impact, affecting water bodies, soil health, and biodiversity. For instance, marine surface waters can contain microplastics at concentrations ranging from 0.0005 to 16 particles per liter [38]. Soil has the potential to accumulate MNPs for extended periods, with approximately 430,000 tons being introduced into European farmland through sewage sludge [39]. MNPs can persist in the environment for ages, impacting plants and higher-level organisms. Soil, being a complex medium compared to aquatic environments, has varying impacts on the transport and bioavailability of these particles, which in turn affects the organisms living there. MNP contamination in soil notably impacts earthworms' mortality, subsequently affecting soil porosity.

Recent studies have investigated the effects of polyethylene microplastics (PE MPs) and zinc oxide (ZnO) nanoparticles on earthworms (*Eisenia fetida*) both individually and in combination [40]. Exposure to either PE MPs or ZnO nanoparticles alone resulted in increased weight loss and mortality among earthworms. However, combined exposure led to even greater weight loss and reduced mortality. ZnO nanoparticles significantly raised soil zinc content, while PE MPs altered zinc accumulation in earthworms. Both types of particles caused oxidative stress and tissue damage, with co-exposure resulting in more severe effects. These findings underscore the ecological risks associated with simultaneous contamination from PE MPs and ZnO nanoparticles.

Further research explored the impacts of microplastics made from polyethylene terephthalate (PET) and PLA on earthworms (*E. fetida*) over a 28-day period [41]. Earthworms were exposed to 0.1% and 1% concentrations of these microplastics in soil. The study employed a multi-level approach, including measurements of oxidative stress, histological analyses, and behavioral tests. PLA-microplastics led to changes in oxidative stress markers, such as increased glutathione peroxidase activity and a bell-shaped pattern of superoxide dismutase activity but did not result in oxidative damage or tissue changes. In contrast, PET-microplastics showed no adverse effects. These findings suggest that bioplastic microplastics, such as PLA, may be more toxic than fossil-based ones, potentially due to PLA's biodegradation and the release of degradation products. This highlights the need for further research on the long-term impacts of bioplastic microplastics in soil environments.

In soil ecosystems, microplastics can support biofilm formation by microorganisms capable of degrading plastics. Biofilms can become a food source for organisms like earthworms, leading to trophic transfer and potential accumulation of plastics in higher animals, including those consumed by humans. Additionally, biofilms can alter the properties of plastic particles, increasing their ingestion and bioaccumulation up the food chain. Ding et al. [42] investigated how soil aging affects the toxicity of polypropylene (PP) and tire wear particles (TP) microplastics to soil fauna. Aging slightly altered the surface properties and morphology of both types of MPs but significantly changed the release of additives, especially when aged in manure-amended soil. Aged MPs developed less diverse microbial communities compared to surrounding soil, with the type of MP influencing the biofilm composition. Exposure experiments revealed that aged MPs, particularly those in manure-amended soil, had a more pronounced impact on soil worm reproduction and gut microbiota compared to virgin MPs. This increased toxicity was linked to changes in biofilm profiles and additive leaching, with aged MPs releasing more toxic substances and transferring microbes to the worms' guts. This study emphasizes that aging MPs in soil can enhance their toxicity by altering their chemical properties and biofilm characteristics.

In aquatic environments MNPs with density sinking and pose toxicity to benthic environment. These particles travel from land to water via wind and runoff, reaching both freshwater and marine environments. Their presence in oceans is influenced by factors like rivers, human populations, and landfills. When ingested by aquatic life, MNPs can cause physical and nutritional issues, often worsened by plasticizers and toxic pollutants on their surfaces. Although consumer plastics initially float, they can become denser due to colonization by organisms and eventually sink.

The effect of various-sized PS MNPs on the freshwater microalgae *Chlamydomonas reinhardtii* was studied by Li et al. [43]. Smaller PS-MNPs and higher concentrations inhibited algal growth more than larger particles, with the effect becoming more pronounced over longer exposure. Smaller PS-MNPs caused more severe oxidative damage, as indicated by increased hydrogen peroxide, malondialdehyde, and altered superoxide dismutase activity. Proteomics analysis revealed that smaller PS-MNPs significantly suppressed proteins related to photosystem I, affecting photosynthesis. Additionally, smaller PS-MNPs reduced chlorophyll content and photosystem II efficiency more than larger particles. Microscopy and western blotting suggested that the size-dependent toxicity is due to impacts on protein expression in the photosynthesis pathway rather than physical effects. Overall, the study highlights the importance of particle size in influencing the biological effects of microplastics on microalgae.

The study conducted on effects of PS MNPs on *Arabidopsis thaliana* revealed that low concentrations of 1000 nm sized particles promoted plant growth, while higher concentrations of 50 nm and 100 nm sized particles inhibited it [44]. *A. thaliana* absorbed and accumulated PS particles from 50 - 1000 nm, with smaller particles (50 nm) being more readily absorbed and translocated. Exposure to these plastics affected gene expression related to growth, development, and stress responses, particularly in leaves and roots. The plastics also induced oxidative stress in the roots, increasing hydrogen peroxide levels and stimulating oxalic acid secretion. In summary, micro and nanoparticles pose significant environmental threats, impacting wildlife, soil health, and aquatic systems. Their persistence and interaction with organisms lead to oxidative stress and physiological damage, with potential differences in toxicity between bioplastic and fossil-based particles. Effective management and further research are crucial to understanding and mitigating these impacts.

Although the impacts of MNP contamination are not solely economic, the long-term environmental consequences can have significant indirect effects on economies [19]. Depleted marine resources, disruptions in aquatic ecosystems, and the need for environmental remediation efforts can strain economies that depend on healthy oceans and aquatic environments for industries such as fisheries, tourism, and coastal development.

According to the United Nations Environmental Programme (UNEP) about 1,000 rivers are responsible for 80% plastic emissions around the world accounting for 0.8 - 2.7 million tons per year [45]. Large concentrations of plastic debris in water bodies will have a significant effect on the seafood industry. MNPs contamination in water bodies killing more than 100, 000 marine species every year along the coastlines and in deep oceans. Marine debris has become a major problem for Scottish fishing vessels, with 86% of them catching less fish because of litter in their nets. This costs the industry USD 12.9 - 14.3 million each year, cutting about 5% from their total revenue. Plastic pollution causes a 1 - 5% reduction in human benefits leading to annual loss of USD 2,500 billion [46]. According to the 2020 North America plastic recycling market report, the USA spends USD 2.6 billion on recycling and between USD 17 million and 24 million on plastic incineration [47]. The annual damage caused by plastic debris in the Asia-Pacific region is estimated at USD 10.8 billion in 2015, and USD 18.3 billion globally which is increased to USD 21.3 billion in 2020 [48]. This economic damage is estimated to increase to USD 197 billion and 434 billion respectively, by 2030 and 2050 [49].

MNPs in the global food supply chain present serious environmental, economic, and health risks through ingestion, potentially causing inflammation and chronic diseases. They significantly affect economies by putting pressure on industries such as fisheries and tourism, while cleanup efforts result in considerable costs. To address these challenges, stringent regulations are necessary to safeguard health and mitigate the economic impact on the affected sectors.

Knowledge gaps

Research on MNPs has several significant knowledge gaps that inhibit understanding and effective mitigation. Longitudinal studies on the chronic health effects of MNP exposure in humans are lacking, requiring detailed epidemiological research. The mechanisms of MNP absorption, bioavailability, and systemic distribution within the human body are not well understood. Additionally, there is insufficient data on the combined toxicological effects of MNPs and adsorbed pollutants, highlighting the need for focused studies on these interactions.

Non-invasive monitoring techniques for MNPs in the human GI tract are limited, and advancing real-time methods would improve exposure assessment. The broader environmental impacts, economic consequences, and biodegradation processes of MNPs are poorly understood, as are the dynamics of chemical leaching. Health risk assessment frameworks for MNP exposure through food are inadequate, requiring robust models that consider exposure levels, toxicity, and population vulnerability. Data on the global distribution and primary sources of MNPs are also scarce, hindering targeted mitigation efforts. Interdisciplinary research combining toxicology, environmental science, food safety, and public health is essential to address these gaps. Collaborative efforts are crucial to understanding MNP risks and developing strategies to protect both environmental and human health.

The development of biodegradable alternatives to conventional plastic materials holds promise in mitigating MNPs contamination. These alternatives, designed to degrade more readily in natural environments, offer a potential solution to reduce persistent plastic waste that contributes to MNP pollution. However, their widespread adoption requires supportive policy frameworks and effective regulations. Policies can encourage research and development of biodegradable materials, promote their use in consumer products, and encourage industry compliance with sustainable practices. Regulation plays a crucial role in ensuring the safety and efficacy of biodegradable alternatives, setting standards for their biodegradability, toxicity profiles, and environmental impacts. By integrating robust policies and regulations, stakeholders can foster innovation in sustainable materials and effectively mitigate the environmental and health risks posed by MNPs.

Conclusion and Suggestions for Future Study

In conclusion, this comprehensive review highlights the critical challenges posed by the ubiquitous presence of MNPs in the global food chain. The intricate journey of MNPs from macro plastic fragmentation to their absorption within the human GI tract highlights the multifaceted risks to both environmental sustainability and human health. The release of chemicals during digestion increases these concerns, necessitating a balanced approach to regulatory measures that safeguard public health without unduly burdening industries. As we navigate this complex landscape, future research directions should prioritize longitudinal health studies to unravel the chronic effects of prolonged MNP exposure, particularly in vulnerable populations. Investigating the combined effects of chemicals leached from plastics during digestion is crucial for a nuanced risk assessment, and the development of standardized analytical protocols for MNPs in diverse food matrices is imperative for accurate and comparable research findings. Additionally, exploring non-invasive monitoring techniques for *in-situ* analysis of MNPs in the GI tract and assessing the broader environmental impact of MNPs contamination will contribute to a more comprehensive understanding of the challenges and potential solutions in mitigating the impact of MNPs in our food supply chain.

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Conflict of Interest

None.

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