Prepublished copy

Nature Environment & Pollution Technology

This is a peer-reviewed prepublished version of the paper to be published in Vol. 25, No. 2, June 2026 issue

Review Paper

A Review on Microplastics: The Emerging Threat in Food Safety

Sree Sesha Sravanika Bezawada, Amrita Shaw, Bavatharani V. and Jhinuk Gupta†

Department of Food and Nutritional Sciences, Sri Sathya Sai Institute of Higher Learning, Vidyagiri, Prasanthi Nilayam-515 134, Andhra Pradesh, India

†Corresponding author: Jhinuk Gupta; jhinukgupta@sssihl.edu.in

ORCID IDs of Authors - Sree Sesha Sravanika Bezawada - https://orcid.org/0009-0001-5940-278X

Amrita Shaw - https://orcid.org/0009-0009-8439-816X

Bavatharani V - https://orcid.org/0009-0006-2069-2077

Jhinuk Gupta† - https://orcid.org/0000-0002-8759-2648

Key Words	Microplastics, Environmental pollution, Artificial intelligence, Health hazards, Detection technologies
DOI	https://doi.org/10.46488/NEPT.2026.v25i02.B4384 (DOI will be active only after the final publication of the paper)
Citation for the Paper	Bezawada, S.S.S., Shaw, A., Bavatharani, V. and Gupta, J., 2026. A review on microplastics: The emerging threat in food safety. *Nature Environment and Pollution Technology*, 25(2), B4384. https://doi.org/10.46488/NEPT.2026.v25i02.B4384

ABSTRACT

Microplastics (MPs), defined as plastic particles less than 5 millimetres (i.e. 5000 micrometres) in diameter, have emerged as pervasive environmental pollutants due to the massive global production of plastics and their widespread use. Significant research has been carried out all over the world in the last few years to evaluate the severity of MP pollution in the environment, to assess the human health hazards caused by MPs, and to establish novel detection techniques. However, there are very few review articles available that gives a comprehensive overview of this new age pollutant in food matrices. This current review provides an overview of the severity of the MP contamination in foods, emphasizing the type of MPs, their possible routes of transmission, and possible disease mechanisms. The review also focuses on advancements in MP detection techniques in food matrices, with a particular focus on AI-assisted methods, regulatory measures/policies adopted by different countries, and recent research undertaken to mitigate MPs from the environment as well as foods. The data presented here is based on the results of a thorough literature search, which was conducted across multiple research databases for the period from 2013-2025. The search results revealed the presence of high levels of MPs in commercial food products, particularly salt and seafood, with common polymers including polyethylene (PE) and polypropylene (PP). Ingestion led accumulation of MPs in the

human body could be linked to serious health effects, such as neurological dysfunction, liver fibrosis, kidney damage, and impaired reproductive function. AI-assisted computed tomography (CT) imaging using the DeepLabV3+ semantic segmentation model has demonstrated highly promising results, achieving detection accuracies of up to 99–100% in fish tissue samples. Despite these advancements in MP research, critical challenges remain in standardizing detection techniques and establishing effective mitigation strategies.

INTRODUCTION

Microplastics (MPs) are synthetic particles primarily composed of plastic particles less than 5 millimeters in diameter (Kutralam-Muniasamy *et al.*, 2020). In recent years, the global accumulation of plastic waste has intensified, emerging as a significant environmental and public health concern. In 2021 alone, global plastic production surpassed 390.7 million tons (Terrazas-López *et al.*, 2024). Since the 1950s, billions of tons of plastic waste have been released into the environment, accumulating in soil, freshwater, and marine ecosystems, posing long-term ecological and toxicological threats(P. Solanki *et al.* 2024, Ibrahim *et al.*, 2021). Plastic polymers are highly resistant to degradation and can persist in the environment for hundreds to thousands of years, depending on their chemical structure and surrounding conditions(Tympa *et al.*, 2021). Human exposure to MPs occurs primarily through three major routes: ingestion, inhalation, and dermal contact. Among these, ingestion remains the dominant pathway, with studies estimating that humans may consume between 0.1 to 5 grams of MPs weekly through contaminated food and water.

Accumulated MPs have been detected in vital organs such as the brain, heart, kidneys, and reproductive system, raising serious concerns about their long-term health effects. Despite increased recognition of the health risks associated with internal MP accumulation, research into post-exposure interventions remains scarce. While policymakers are being increasingly aware of microplastic contamination in food systems, most countries still lack comprehensive regulatory frameworks or enforceable policies to effectively address the issue. It still remains challenging to formulate evidence-based dietary interventions or therapeutic strategies to mitigate MP bioaccumulation. The major reason for these challenges is the absence of comprehensive reviews that document the extent of MP contamination in diverse food types (both raw and processed), link their chemical characteristics to the type of food matrix, and give an overview of the advanced AI based techniques to quickly detect the MP contaminated foods. Therefore, it is crucial to write such a review to bridge these gaps and evaluate the severity of MPs as an emerging food safety threat.

This review aims to provide a comprehensive overview of the current state of knowledge regarding MP contamination in food, besides covering general overview of types and sources of MPs, its environmental distribution, exposure routes to the human body, health hazards, existing global policies and regulations to control MP pollution, methods for analysing MPs and the potential of artificial intelligence (AI) in MP detection in food. By synthesizing the recent findings, spanning over last 12 years, this review seeks to highlight the key research gaps and outline the future scopes for developing scientifically robust, scalable, and cost-effective solutions to this growing public health challenge.

2. METHODOLOGY

This study is a systematic review aimed at evaluating the emerging threat of microplastics in the context of food safety. A comprehensive and structured literature search was conducted using three major scientific databases: Web of Science (WOS), PubMed, and ScienceDirect. The search strategy was developed based on a set of predefined keywords, including: *"microplastics contamination"*, *"food safety"*, *"human health risk of microplastics"*, *"exposure pathways of microplastics"*, and *"AI-based detection methods for microplastics"*. The review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The review process adhered to the PRISMA guidelines, which involve four main phases: identification, screening, eligibility, and inclusion. In the identification phase, relevant literature was retrieved using the predefined search terms. During the screening phase, duplicate entries and the studies with irrelevant titles / abstracts were excluded. In the eligibility phase, the full texts of the remaining articles were assessed to determine their relevance based on the content. Finally, in the inclusion phase, the following inclusion criteria were chosen. Article type: Scientific reports, review articles and research papers; Language: English; Publication duration: 2013 - 2025. Fig .1, represents a flow diagram of the PRISMA protocol. The flowchart presents the number of records (n = 63,607) identified through database searching, the number of duplicates removed, the records screened, assessed for eligibility, and the final number of studies (n = 133) included in this systematic review. The reasons for exclusion at each stage are documented to ensure transparency of the selection process.

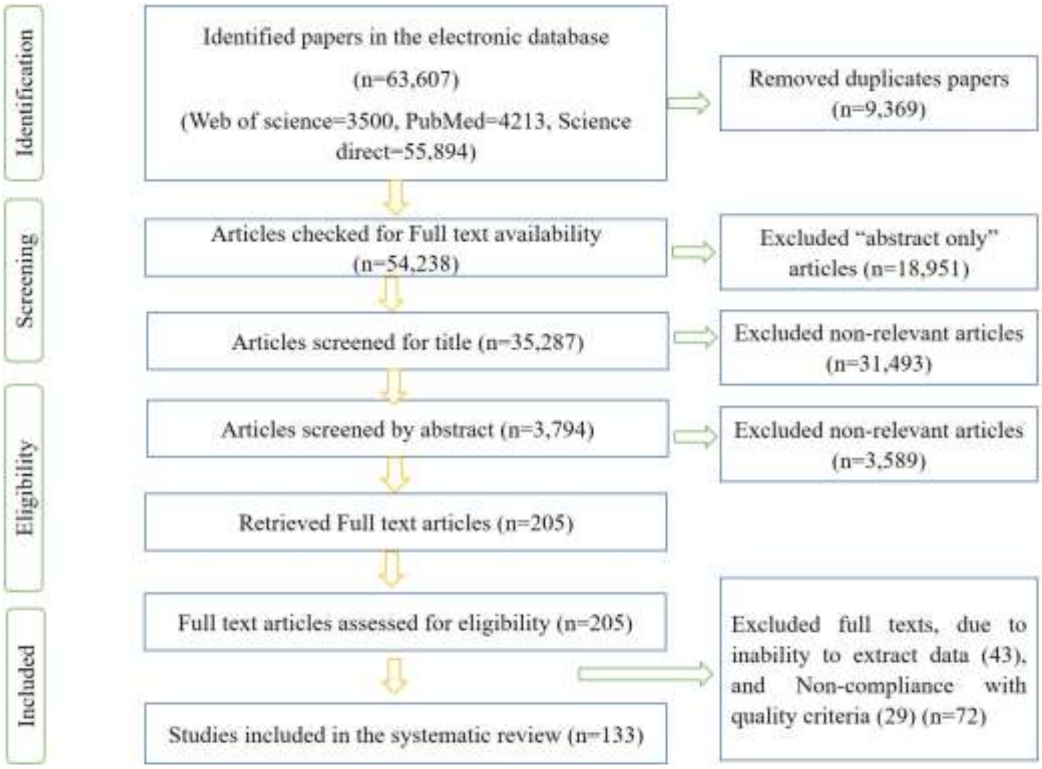

Fig .1: PRISMA flow diagram of this systematic review

3. DISCUSSION

3.1. Microplastics: Types and origins

MPs are typically defined as synthetic polymer particles smaller than 5 μm in length(Sarkar *et al.*, 2022). Even smaller particles (smaller than 1 μm) are usually termed nano plastics (NPs). Micro-nano particle (MNPs) is a collective term often used in scientific literature to refer to both microplastics and nano plastics. The size of plastic particles ranges from 1 nanometre to 5 millimetres(Ramsperger, A.F.R.M. et al., 2023). Common polymer types found in MPs include polyethylene (PE), polypropylene (PP), polystyrene (PS), polyamide (PA or nylon), polyester (PES), and polyacrylic acid (PAA). MPs are present in various morphological forms such as fibers, fragments, spheres, beads, granules, pellets, and flakes. Depending on their polymer density, MPs exhibit distinct behaviors in aquatic environments. Low-density MPs tend to remain buoyant on the water surface, while high-density MPs sink and accumulate in deeper sediment layers. Their ubiquity spans diverse environmental matrices, including oceans, rivers, lakes, terrestrial soils, and even the atmosphere (Amato-Lourenço et al., 2024). Owing to their small size and persistence, MPs pose significant ecological threats and potential health hazards to both wildlife and humans(Guo *et al.*, 2024). Microplastics are generally categorized into two types: **primary microplastics (PMPs)** and **secondary microplastics (SMPs)**. **Primary Microplastics** are intentionally manufactured particles for specific industrial applications, including use in consumer and commercial products. They are commonly incorporated into personal hygiene products, cosmetic formulations, and textiles during the manufacturing process(Yang, Chen & Wang, 2021). **Secondary Microplastics** are not intentionally produced, but instead arise from the breakdown of larger plastic waste materials, such as meso (5 mm–25 mm) or macro (>25 mm) plastics. These particles are generated in the environment through physical, chemical, and biological processes, including fragmentation, photodegradation, and biological degradation, which are often caused by natural environmental factors(Yuan, Nag & Cummins, 2022).

MPs originate in the environment from various sources, including plastic bags, plastic bottles, disposable kitchen/laboratory plasticware, personal care products, paints, sewage, vehicle tyres, etc. **Plastic bags** are commonly used in daily life due to their low cost, lightweight nature, large capacity, and ease of storage. Globally, it is estimated that up to 5 trillion plastic bags are consumed each year, with a maximum recycling rate of only 10%. Despite efforts to reduce plastic bag pollution through various bans and regulations, a substantial number of plastic bags continue to persist in the environment. These discarded bags contribute significantly to microplastic pollution as they degrade over time(Dirk Xanthos & Tony R. Walker, 2017). Similar to plastic bags, **plastic bottles and containers** for carrying liquids and solids such as beverages, pickles, honey, dried fruits, edible oils, and agricultural or veterinary products contribute significantly to MP pollution. (Li-hui An, 2020). **Disposable plastic tableware** includes items such as lunch boxes, plates, saucers, straws, knives, forks, spoons, cups, bowls, and cans, excluding long-term food packaging. Polystyrene, commonly known as foam plastic, is frequently used in the production of disposable food service items such as foam cups, instant noodle containers, and fast-food boxes. When improperly disposed of, plastic tableware can end up in sewers, soil, and aquatic environments. A study by Zhou et al reports that individuals ordering takeaway food 5–10 times per month could ingest between 145 and 5,520 microplastic particles solely from packaging materials(Zhou, Wang & Ren, 2022). Food-grade polypropylene (PP) nonwoven bags, commonly used for filtering food residues and considered safe, have been found to release significant quantities of micro- and nano plastics (M/NPs) when exposed to boiling water. In a controlled study, boiling a single bag for one hour released 0.12–0.33 million microplastics (>1 μm) and 17.6–30.6 billion nano plastics (<1 μm), amounting to 2.25–6.47 mg of plastic particles. The release was independent of bag size but declined with repeated use, and originated from fragile PP fibers. Toxicity assessments using zebrafish (Danio rerio) showed that exposure to these released M/NPs induced oxidative stress in gill and liver tissues, evidenced by altered levels of key biomarkers(Jia

Li, 2023). **Disposable plastic labwares, including plastic syringes**, filter discs, are reported to release MPs, compromising data accuracy and increasing environmental hazards (Cheng & Yu, 2020). Personal care products and cosmetics such as facial cleansers, toothpastes, sunscreens, shower gels, and hair dyes also contain microplastic beads of PE, PP, PS, PTFE, PU, PET, PA and may act as a source of MP pollution. 93% of the total microplastic beads used in personal care products are made of PE (Gouin, T. et al., 2015). Various types of **paints**, used as architectural, automotive, aircraft, and marine coatings, are also reported to be a significant source of environmental microplastics(Dirk Xanthos & Tony R. Walker, 2017). Studies indicate that the application of paint can produce tiny plastic particles, which may be released into the environment through abrasion, aging, and erosion. **Vehicle tyre** wear is recognized as a major source of MPs found in road dust (Kang,H et al., 2022). Rubber particles, with a density of approximately 1.2–1.3 g/cm^3, tend to settle into sediments when entering aquatic environments, though they may remain suspended in water when agitated(RIVM, 2016). These particles can accumulate in various environments, including surface water, sewers, soil, and air. **Washing activities**, including household laundry and industrial washing processes, release significant amounts of plastic microfibers into the environment. These microfibers originate from the shedding of synthetic textiles during washing. It is estimated that a single garment can release over 1,900 microfibers into wastewater during one washing cycle. Wastewater treatment plants, however, are generally ineffective at fully removing microplastics, allowing a significant portion to enter the environment(Pui Kwan Cheung & Lincoln Fok, 2017). According to global research on microplastic pollution, laundry washing in China contributes approximately 10.3% of global microfiber emissions, ranking just behind India and Southeast Asia, which together account for 15.9%. Studies have shown that the release of microfibers is influenced by several factors, including water temperature, washing duration, and the type of detergent used(Francesca De Falco, 2019).

3.2. Presence of microplastics in the Environment

With the virtue of its physical and chemical characteristics, MPs can pollute all three environmental elements: water, air, and soil. In **marine environments**, MPs primarily originate from direct inputs of plastic waste, laundering of synthetic textiles, maritime activities, industrial discharges, and the degradation of floating plastic debris. These sources contribute to the vast accumulation of MPs in oceanic systems, where eventually they pose threats to aquatic life and food safety(Lebreton & Andrady, 2019;Thompson et al., 2015). In **atmospheric environments,** MPs are present both indoors and outdoors. Indoor microplastics largely stem from home furnishings, synthetic textiles, air conditioning systems, and abrasion of household products and electronics(Guanglong Chen, 2020;Chen et al., 2022;Yingxin Chen, 2022). Outdoor sources include vehicular emissions and tyre wear, road marking paints, degraded asphalt surfaces, and urban street dust(Kang et al., 2022;Dehghani, Moore & Akhbarizadeh, 2017). **Soil systems** also serve as major reservoirs for MPs. Key contributors include improperly disposed solid plastic waste, plastic films used for agricultural purposes, and plastic-containing agricultural inputs such as plastic film mulch(Kasirajan & Ngouajio, 2012). Additionally, urban development materials, like synthetic fillers used in landscaping and municipal greening projects, introduce MPs into soil. Industrial wastewater, sewage sludge, and solid waste further contribute to the accumulation of MPs in terrestrial environments through surface runoff and leaching. Due to this widespread environmental presence, human exposure to microplastics is virtually unavoidable (Yang et al., 2023).

3.3. Transmission routes of MPs from the environment to humans

As shown in Fig. 2, there are three vital routes through which MPs can enter the human body, i.e., by ingestion, inhalation, and dermal contact. Evidence showing the presence of microplastics in human placental tissue also suggests fetal/prenatal exposure during gestation. (Ragusa et al., 2021).

3.3.1. Ingestion

Among the three routes, ingestion is the major route through which humans consume MPs (Lehner *et al.*, 2019). MPs ingested through food and water predominantly range in size from 1 to 100 μm. Polyethylene terephthalate (PET) is the most frequently identified polymer, followed by polyamide (nylon), polyurethane, polypropylene (PP), and polyacrylate (Vdovchenko & Resmini, 2024). Studies have found the presence of MPs (primarily PET, PA, and PP) in human stool samples, suggesting consumption of MPs possibly through contaminated food and drinks (Yan et al., 2022). Furthermore, other studies recognized the MPs in blood, breast milk, and human placenta as well (Long Zhu, 2023;Ragusa et al., 2022;Leslie et al., 2022;Kadac-Czapska et al., 2024). However, research on what happens to MPs in humans once they enter the gastrointestinal (GI) tract is still lacking (Salim, Kaplan & Madsen, 2013). Based on the American diet, Cox and colleagues estimated that each person consumes between 39,000 and 52,000 MP particles annually only through ingestion (Cox et al., 2019).Similarly, it is found that Europeans consume 11,000 MPs per individual annually by the intake of commercially available bivalves such as Mytilus edulis and Crassostrea gigas(Van Cauwenberghe & Janssen, 2014; Yang et al., 2015; Karami et al., 2017). Hernandez et al. (2019) highlighted that hot beverages at 95 °C can cause single-use plastic cups to shed approximately 11.6 billion MP particles, including nylon and polyethylene terephthalate (PET) (Hernandez et al., 2019). Ali Yousef et al. conducted a study to assess the presence and characteristics of MPs in tea bags from five popular brands in Iran. The findings revealed MP contamination in all samples, with an average of 518,459 particles per tea bag. Those MPs were mostly made of CA and nylon, of fibrous shape and size ranging from 10 to 50 µm. (Yousefi, Movahedian Attar & Yousefi, 2024).

3.3.2. Inhalation

Another route of human exposure to MPs is by inhalation. Airborne microplastics (MPs) are predominantly fibrous and spherical, typically ranging from 1 to 100 µm in size. Their concentration in the atmosphere varies depending on environmental conditions and geographic location. Commonly detected polymer types in inhaled MPs include polyethylene terephthalate (PET), polyethylene (PE), polypropylene (PP), and polyamide (nylon)(Kannan & Vimalkumar, 2021).

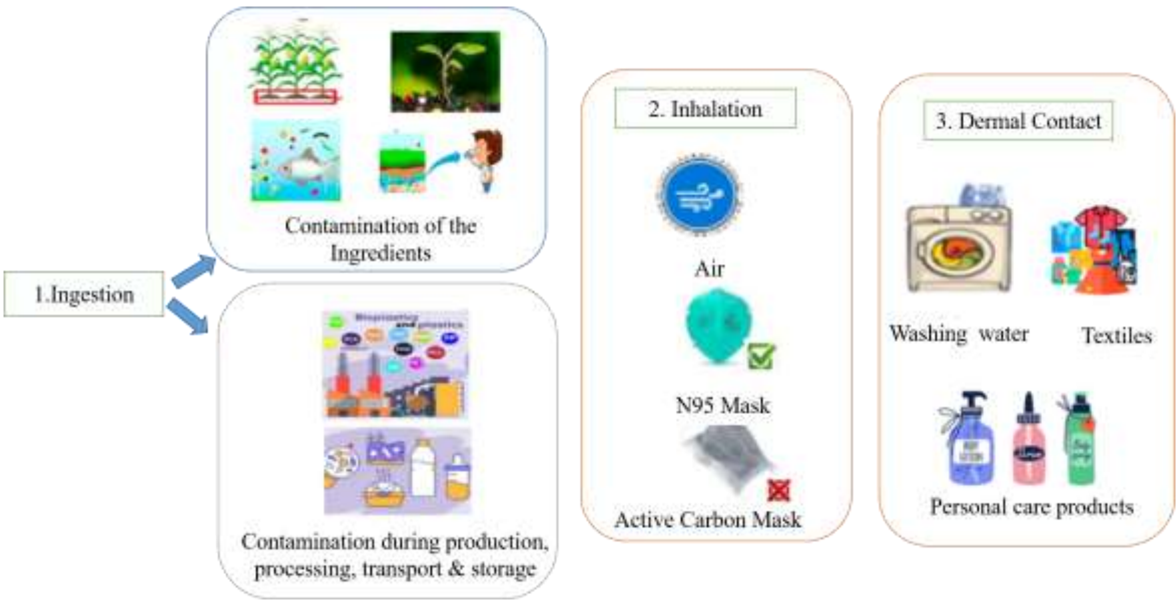

Fig .2: Exposure routes of Microplastics from the Environment to the human body

MPs of diameters between 10 and 8000 µm are widely distributed in both indoor and outdoor settings. Inhaling these particles is newly recognized as a way for human exposure to MP contamination (Liu et al., 2019; Zhang, Wang & Kannan, 2020; Li et al., 2023). The study by Cox et al. on MP exposure in the American population estimated that Americans consume 39,000 to 52,000 microplastic particles annually through diet alone, which increases to 74,000 to 121,000 MPs when inhalation is included. Additionally, individuals relying solely on bottled water may ingest around 90,000 microplastics per year, compared to 4,000 for those drinking only tap water (Cox et al., 2019). During the COVID-19 pandemic, wearing surgical, cotton, fashion, and activated carbon masks posed a higher risk of inhaling fiber-like microplastics from the fabric (Li et al., 2021). Li et al. emphasized that MPs identified in lung tissue were notably smaller than those typically found in ambient air.

3.3.3. Dermal exposure

When compared with ingestion and inhalation, MPs exposure route through skin contact is negligible. Dermal exposure to MPs can occur via two primary pathways. The first involves intentional incorporation of MPs such as microbeads in cosmetic and personal care products to enhance texture, exfoliation, or product stability. The second pathway includes unintentional exposure through contact with contaminated bathing water or products such as facial scrubs, body lotions, and other typically applied formulations. Dermal exposure to microplastics (MPs) remains relatively underexplored; however, existing evidence indicates that nano plastics (<100 nm) may be capable of penetrating the skin, particularly via hair follicles, sweat glands, or compromised skin barriers. The skin's outermost layer, the stratum corneum, serves as a primary barrier against external insults, including chemicals and pathogens. There remains a possibility for dermal penetration under certain conditions (Bouwstra, J. et al., 2001). However, NPs may gain entry into the body through alternative routes such as sweat glands, hair follicles, or damaged skin. Based on typical usage patterns, the study estimated that individuals may be exposed to approximately 40.5 to 215 mg of MPs daily through facial cleansing alone. Beyond personal care products, human skin may also encounter MPs through contact with synthetic fabric fibres, settled dust particles, and other environmental contaminants. However, the extent and dynamics of dermal exposure from these sources remain poorly characterized. Furthermore, current scientific evidence is insufficient to definitively conclude whether MPs can induce allergic reactions or dermatological irritation. (Li et al., 2023).

Based on the above discussion, the ingestion of microplastic-contaminated food and water appears to be the primary route of human exposure to MP-related health hazards.

3.4. Health hazards caused by ingested Microplastics

Ingested MPs smaller than 10 μm possess the ability to traverse cellular membranes and enter systemic circulation. Once in the bloodstream, MPs can accumulate and migrate across various biological compartments through mechanisms such as adsorption, translocation, and chemical transformation. Recent studies have confirmed the presence of microplastics in several vital organs and systems, including the brain, lungs, liver, kidneys, placenta, and reproductive organs, where they are associated with pathological conditions such as fibrosis, organ dysfunction, and impaired reproductive capacity. The health hazards caused by ingested MPs can be broadly categorized into two types: physical and chemical. Physically, MPs can accumulate in vital organs such as the brain, liver, kidneys, and reproductive system, leading to inflammation, tissue damage, and organ dysfunction. Chemically, MPs can degrade into smaller polymeric components or leach hazardous additives such as Bisphenol A (BPA), which may induce systemic toxicity, endocrine disruption, and oxidative stress.

3.4.1. Liver fibrosis

The liver, as the largest gland and the most metabolically active organ in the human body, plays a vital role in maintaining physiological homeostasis. The liver is central to the synthesis, transformation, and degradation of proteins, lipids, carbohydrates, and other biomolecules. When MPs enter the liver via systemic circulation, they can impair hepatic function by inducing nuclear and mitochondrial DNA damage, activating stress-related signaling pathways, and promoting the expression of pro-inflammatory cytokines. Studies in zebrafish have shown disruptions in hepatic glycolipid metabolism at physiological and transcriptomic levels, while research in mice demonstrated that MP accumulation activates pathways leading to liver fibrosis (Yao Zhao, 2020; Rong Shen, 2022). Accumulation of microplastics (MPs) within hepatic tissue has been shown to disrupt normal lipid metabolism by inhibiting the synthesis and storage of fatty acids, fatty acid methyl esters, and fatty acid ethyl esters. This disruption can lead to hepatic steatosis and broader metabolic dysfunction, including disorders of glucose and lipid metabolism. These findings were demonstrated in an *in vitro* study using human liver organoids derived from pluripotent stem cells, providing a human-relevant model to investigate MP-induced hepatotoxicity (Wei Cheng, 2022). Some studies have been reported that microplastic exposure disrupts the amino acid and fatty acid metabolism in the zebrafish liver (Zhao et al., 2020). Furthermore, due to their large surface area and adsorptive capacity, microplastics (MPs) can act as vectors for toxic substances such as heavy metals, including cadmium and iron. Studies based on *in vitro* and animal models have shown that the interaction between MPs and these pollutants can intensify hepatic toxicity and may induce ferroptosis a regulated form of cell death driven by iron accumulation resulting in further liver damage (Xie *et al.*, 2016; Bradney *et al.*, 2019).

3.4.2. Kidney dysfunction

The kidney is recognized as a critical target organ for MP accumulation, with experimental studies indicating that MP exposure can lead to significant renal dysfunction, particularly in laboratory mice(Deng *et al.*, 2017; Joana Correia Prata, 2022). The primary mechanism underlying this damage involves the induction of oxidative stress, which subsequently triggers inflammatory responses and tissue injury. In a study conducted in mice, microplastics were shown to be internalized by renal cells, stimulating the production of mitochondrial reactive oxygen species (ROS) and upregulating the expression of related stress-response proteins (Wang *et al.*, 2021). In parallel, the study by Dongdong Zhang (2020) investigated the effects of PS-MPs on kidney tissue using an *in vivo* animal model with juvenile rats. The findings revealed that PS-MP exposure led to their accumulation in the kidneys, triggering increased oxidative stress and inflammation. This disruption affected multiple cellular signaling pathways, including endoplasmic reticulum (ER) stress, activation of inflammatory cascades, and altered autophagy processes, collectively contributing to renal cell injury and impaired kidney function (Dongdong Zhang, 2020).

3.4.3. Reproductive Capacity Impairment

The accumulation of microplastics (MPs) in reproductive organs has been associated with reproductive toxicity and impaired fertility. Multiple studies have documented the detrimental effects of MPs on the reproductive system in both female and male models(Hou, B., Wang, F., Liu, T. and Wang, Z., 2021; Ru An, 2021; Cui-Lan Bai, 2022; Zhaolan Wei, 2022). **In males**, MPs can induce testicular inflammation, disrupt the integrity of the testicular blood barrier, and activate pro-inflammatory signalling pathways such as NF-KB and p38 MAPK. These molecular disruptions contribute to abnormal spermatogenesis, characterized by reduced sperm count and motility, along with an increased incidence of sperm morphological defects was observed in mice.(Hou et al., 2021; Hou, B., Wang, F., Liu, T. and Wang, Z., 2021). In males, exposure to polystyrene microplastics (PS-MPs) of approximately 5 μm size has been shown to adversely affect spermatogenesis by reducing sperm viability and inducing testicular inflammation, atrophy, and apoptosis. These deleterious effects are primarily mediated through the Nrf2/HO-1/NF-κB signalling pathway, as demonstrated in *in vivo* studies using mouse models (Hou, B., Wang, F., Liu, T. and Wang, Z., 2021). *In vivo* studies further demonstrated disrupted testicular architecture, lowered sperm quality, and reduced serum levels of testosterone, FSH, and LH. Complementary *in vitro* research revealed that PS-MPs were internalized by Leydig cells, where they suppressed the expression of luteinizing hormone receptors, key steroidogenic enzymes, and steroidogenic acute regulatory (StAR) protein. This suppression occurred through inhibition of the adenylyl cyclase (AC)/cyclic AMP (cAMP)/protein kinase A (PKA) signalling pathway(Jin *et al.*, 2022). On the other hand, **in female** rodents, polystyrene microplastics (PS-MPs) have been shown to infiltrate ovarian granulosa cells, leading to fibrosis and apoptosis via activation of the Wnt/β-catenin signalling pathway, which is driven by oxidative stress (Ru An, 2021). Additional findings by Liu et al. (2022), based on an *in vivo* animal study using juvenile rats, demonstrated that exposure to PS-MPs leads to their accumulation in ovarian tissue, impairs follicular development, and induces inflammation, contributing to reproductive toxicity.(Cui-Lan Bai, 2022). Similarly, Xie et al. observed significant reductions in ovarian follicle numbers and overall ovary size, accompanied by decreased serum levels of follicle-stimulating hormone (FSH) and luteinizing hormone (LH) in female mice exposed to PS-MPs. These disruptions were associated with reduced pregnancy rates and a lower number of viable embryos(Zhaolan Wei, 2022).

3.4.4. Adverse Cardiac Effects

Recent studies indicate that MP accumulation in the heart may cause oxidative stress and inflammation, potentially leading to cardiac dysfunction, arrhythmias, or even heart failure in severe cases. A study conducted by Yun Zhang et al. explored the relationship between micro-nano particles (MNPs) in coronary arteries and major adverse cardiac events (MACE) in patients with myocardial infarction (MI). This prospective observational study included 142 patients undergoing coronary angiography, with 110 completing a 31.5-month follow-up. The analysis of coronary blood samples revealed the presence of various MNPs, including polystyrene (43.6%), polyamide 66 (61.8%), polyethylene (71.8%), and polyvinyl chloride (PVC) (95.4%). Especially, PVC levels were significantly higher in patients who experienced MACE, and these levels were positively correlated with proinflammatory markers such as IL-1β, IL-6, IL-18, and TNF-α. For each 10-unit increase in PVC, the risk of MACE increased by 1.374-fold (OR: 1.090, 95% CI: 1.032–1.1523, P = 0.002). Furthermore, blood and thrombus samples from 21 MI patients showed that PVC concentrations in coronary thrombi were associated with inflammation and monocyte/macrophage infiltration(Zhang et al., 2025).

3.4.5. Neurological dysfunction – Brain

Small-sized MPs can cross the blood–brain barrier (BBB), resulting in elevated levels of reactive oxygen species (ROS) and malondialdehyde (MDA), along with a significant reduction in glutathione (GSH) concentrations. This oxidative imbalance induces neurotoxicity in mouse brain tissue, decreases acetylcholine levels, and impairs cognitive functions such as learning and memory(Mohammadi *et al.*, 2025). Additionally, MP exposure has been shown to downregulate the expression of connexins associated with the blood-brain barrier (BBB), stimulate reactive oxygen species (ROS) production leading to neuronal apoptosis, and promote micro thrombosis in juvenile crucian carp (Carassius auratus). These effects contribute to a reduction in Purkinje cell numbers, ultimately resulting in neurological dysfunction. (Huang *et al.*, 2024). In April 2024, a cross-sectional case-series study investigated the presence and characteristics of microplastics (MPs) in the human olfactory bulb, analyzing their size, morphology, color, and polymeric composition. The study involved post-mortem tissue samples from 15 adult individuals who had lived in São Paulo for over 5 years, with a median age of

69.5 years. MPs were detected in 8 out of 15 samples, with particles (75%) and fibers (25%) identified. 16 types of polymers were detected, where the predominant polymer was polypropylene (43.8%). Particle sizes ranged from 5.5 µm to 26.4 µm, and the average length of the fibers was 21.4 µm (Amato-Lourenço et al., 2024).

The above findings underscore the urgent need for raising global awareness about the hidden dangers associated with MP-contaminated food and the immediate implementation of effective mitigation strategies to reduce microplastic contamination in food.

3.5. Foods Most Vulnerable to Microplastic Contamination

Microplastics present in the environment get multiple scopes to enter the food chain at various stages of production, such as during cultivation, harvesting, post-harvest processing, packaging, transportation, distribution, and even during consumption(Yates *et al.*, 2021). A food item may become contaminated with MPs either through the use of MP-infested ingredients or via contact with the processing equipment, packaging materials, and plastic cutlery used during cooking and consumption. As listed in Table 1, let us discuss the major food groups and food items that are highly contaminated with MPs.

3.5.1. Microplastics in Drinking Water and Beverages

The primary sources of drinking water are surface freshwater bodies, such as rivers and lakes, as well as groundwater. The large extent of microplastics in surface water is derived from the direct degradation of plastic wastes in the environment as well as from domestic and industrial wastewater. Microplastic contamination in drinking water poses a greater risk to human health compared to other exposure pathways, such as the consumption of fish and seafood, due to the significantly higher volume of water ingested daily (Chang, 2015; Hartline *et al.*, 2016). Since the first detection of microplastics in tap water by Kosuth et al. in 2018, numerous studies have subsequently confirmed the presence of microplastics in bottled water, beverages, beer, tea, and functional drinks. The higher levels of microplastics found in bottled water and beverages, compared to tap water, are largely attributed to the extensive use of plastic materials throughout their production, processing, and packaging (Kosuth, Mason & Wattenberg, 2018; Shruti, V.C., et al., 2020, 2021; Li et al., 2022). Furthermore, mechanical abrasion from production equipment contributes to the release of microplastic particles, making contamination sources in bottled products more diverse and widespread. Among the different forms of microplastics identified in bottled water, fragments are the most prevalent, accounting for approximately 65% of particles. Polypropylene

(PP) and polyethylene terephthalate (PET) are the dominant polymer types detected, likely originating from common plastic components used in bottle caps and containers. In a comparative study conducted by Schymanski et al., micro-Raman spectroscopy was employed to analyse drinking water stored in plastic bottles, glass bottles, and beverage cartons. The results showed that microplastic concentrations were lowest in glass bottles. Interestingly, disposable plastic bottles and beverage cartons contained fewer microplastics than reusable plastic bottles, suggesting that repeated use and cleaning of plastic containers may contribute to elevated microplastic release (Darena Schymanski, 2018). The volume of water consumed daily by an adult varies depending on various factors such as climate change, gender, diet, and levels of physical activity. The World Health Organization (WHO) recommends a guideline intake of 2 liters per day for an average adult weighing 60 kg. Based on data compiled from eight representative studies, it is estimated that an adult may drink approximately $(0.22–1.20) \times 10^6$ microplastic particles in a single year only through drinking water.

3.5.2. Microplastics in marine foods

Seafoods, which contribute to over 17% of global protein intake(Fao, 2017) and serve as a vital source of human nutrition due to their high-quality protein, PUFA multiple micronutrient content (Jin *et al.*, 2021), are highly prone to MP contamination. Land-based MP sources such as municipal waste, industrial discharges, wastewater effluents, and plastic debris transported by wind or tidal movements account for more than 80% of the plastic pollution found in marine environments. Marine organisms may ingest plastic particles due to their visual similarity to natural prey or through accidental adherence to their external appendages(Meng *et al.*, 2015). Therefore, there is a potential risk of human exposure to microplastics (MPs) through the consumption of contaminated seafood. This risk is particularly significant for small fish species that are ingested whole, such as sardines and anchovies. In contrast, the risk is comparatively lower for larger fish species, as they are typically gutted prior to consumption (Fao, 2017). A study conducted in the central Adriatic Sea detected microplastics (MPs) in 26% of red mullet (*Mullus barbatus*) and 20% of European hake (*Merluccius merluccius*) samples(Damaris Benny Daniel, 2020). Research from Sardinia further highlighted differences in MP ingestion among fish occupying various zones of the water column. Surface-dwelling species exhibited the highest incidence of MP ingestion (41%), followed by mid-water species (22%) and bottom-dwelling species(Palazzo et al., 2021). Mollusks and crustaceans also play a significant vectors for human exposure to MPs. Mussels, particularly *Mytilus edulis* and *Mytilus galloprovincialis,* have been found to contain MPs in multiple European countries. For instance, a study on Belgian mussels reported concentrations of up to 0.51 MP particles per gram(Dambrosio *et al.*, 2023). Similarly, research from the Apulia region of Italy, MPs were detected and characterized in mussel sample consisted of 60 individuals divided into three aliquots of 20, while each oyster sample included 6 individuals split into three aliquots of 2. A total of 789 microplastic particles were found in mussels and 270 in oysters, ranging from 10 to 7350 µm. Most fragments were between 5-500 µm, with blue particles predominant in mussels and transparent ones in oysters. (Quaglia *et al.*, 2023) . The polymer composition of these MPs varied, with mussels primarily containing nylon and polyamide, while oysters predominantly contained polypropylene. In another study analyzing canned fish samples from the Turkish market, MPs were detected in all tested products, with polyolefins being the most prevalent polymer type. These findings highlight the role of food processing and packaging as potential sources of MP contamination in canned seafood(Gündoğdu & Köşker, 2023).

3.5.3. Microplastics in Salt

Salt, particularly sea salt, often contains elevated levels of microplastics (MPs) due to its origin from marine environments, which are known to be major sinks for plastic and eventually microplastic pollution. These MPs become dispersed throughout the water column and can readily contaminate seawater used in salt production. During the salt crystallization process, while water evaporates, MPs are not eliminated and instead become concentrated within the salt matrix. As a result, salt has been identified as a significant and unavoidable pathway for human microplastic exposure, with potential health risks linked to daily consumption(Kim et al., 2018). Numerous studies have confirmed the presence of MPs in table salts derived from marine, lake, well, and rock sources across various countries(Yang et al., 2015; Renzi & Blašković, 2018; Zhu et al., 2019). Sea salt, in particular, has been shown to contain the highest levels of microplastic contamination, primarily due to polluted seawater used in its production. Common polymers identified include polyethylene terephthalate (PET), polyethylene (PE), and polystyrene (PS), with particles smaller than 200 µm, particularly fibrous forms, accounting for about 55% of the total MPs(Renzi & Blašković, 2018). In lake and well salts, polystyrene is the most frequently detected polymer. Salt samples from Asia, especially Indonesia, have been reported to contain the highest concentrations of MPs, reflecting elevated coastal plastic pollution levels in the region(Seth & Shriwastav, 2018). In another cross-country study, salt samples were collected from several countries, such as Italy, Croatia, China, India, Senegal, and Thailand. Three distinct sample types: sea salt, lake salt, and rock salt, were collected and analysed. Among these, sea salt exhibited the highest level of microplastic contamination, with concentrations ranging from 56 to 39,800 MPs/kg. The predominant polymer types identified were polyethylene (PE), polypropylene (PP), polyamide (PA), polystyrene (PS), polyester (PES), and chlorinated polyethylene (CP). Lake salt showed moderate levels of contamination, with concentrations varying between 28 and 462 MPs/kg. The detected polymer types included PP, PE, PS, polyethylene terephthalate (PET), polyvinyl chloride (PVC), PA, and polyurethane (PU). Rock salt demonstrated the lowest MP contamination, with a concentration of 12.5 MPs/kg; the polymer types found were PP, PE, PES, polyoxymethylene (POM), and PET (Kim et al., 2018).

3.5.4. Microplastics in Plants

Accumulation of MPs has been reported in a wide variety of crops such as green leafy vegetables (*Arabidopsis thaliana*, lettuce), staple cereals (wheat, and rice) (Qi *et al.*, 2018; Liu *et al.*, 2022). MPs are absorbed by plant roots through various mechanisms, such as surface adhesion and root uptake, and move upwards. Finally, those get accumulated in the different edible parts of the plants, such as, stem, leaves, fruits, etc. Comparative studies examining MP concentrations in fruits and vegetables, including carrots, lettuce, broccoli, potatoes, apples, and pears, identified apples as the most contaminated fruit and carrots as the most contaminated vegetable(Oliveri Conti et al., 2020). Despite growing concern, standardized methodologies for the collection, separation, characterization, and quantification of MPs in agricultural produce remain underdeveloped. Current analytical techniques are often inadequate, limiting the accuracy and comparability of results. Moreover, research on MP contamination in fruits and vegetables is still limited. One of the few available studies estimated the daily intake of MPs from fruits to be approximately 4.48–4.62 × 10^5 particles per adult, and from vegetables to be around 2.96–9.55 × 10^4 particles per adult, highlighting the potential for significant dietary exposure(Oliveri Conti et al., 2020). In plant-based commodities, the food samples include fruits, root vegetables, and green leafy vegetables such as apples, pears, carrots, cabbage, and lettuce collected from Catania and Italy. After analysis, apple fruit was found to contain the highest concentration of MPs, ranging from 195500±128687 particles/g, and the least was found in green leafy vegetable - lettuce with a range of 50550±25011 particle/g.

3.5.5. Microplastics in Honey and Sugar

In honey, the most commonly detected MP shapes are fibers, consecutively a smaller proportion of fragments. Some studies suggest that foraging bees may play a role in transporting airborne microplastics to the hive, where they may become incorporated into the honey(Liebezeit & Liebezeit, 2013). In contrast, contamination from harvesting, processing, and packaging appears to contribute minimally to the overall MP content of honey. Reported microplastic concentrations in honey samples range from 2–82 fragments/kg and 10–336 fibers/kg(Liebezeit,G. & Liebezeit,E., 2015). Research on microplastic contamination in sugar is limited. However, one study by Liebezeit, G., and Liebezeit, E., identified synthetic plastic particles in both refined and unrefined cane sugar. Higher concentrations were observed in unrefined samples, with

560 fibers/kg and 540 fragments/kg, compared to 388 fibers/kg and 270 fragments/kg in refined sugar. These findings suggest that the level of processing may influence microplastic content in sugar products.(Liebezeit & Liebezeit, 2013).

Table 1: Major food groups which are at high risk of MP contamination. The chemical composition and concentration of MPs across different food groups demonstrate significant diversity and elevated levels of contamination.

Classification	Region	Sample type	Concentration of microplastics	Unit	Chemical component*	References
Salt	Italy, Croatia	Sea salt	1570–39800	Particles/kg	PET, PP	(Renzi & Blašković, 2018b)
	China	Sea salt	550–681	Particles/kg	PET, PE, PES, PB, PP, CP	(Yang *et al.*, 2015)
	India	Sea salt	56–103	Particles/kg	PET, PA, PE, PS	(Seth & Shriwastav, 2018b)
	China and Senegal	Lake salt	28–462	Particles/kg	PP, PE, PS, PET, PVC, PA, EVA, PC, PR, PU, PW	(Kim et al., 2018)
	Thailand	Rock salt	12.5	Particles/kg	PP, PE, PES, PEI, PET, POM	(Lee *et al.*, 2019)
Plants	Catania, Italy	Apple	195500 ± 128687	Particles/g	-	(Oliveri Conti *et al.*, 2020b)
		Pear	189550 ± 105558	Particles/g	-	
		Cabbage	126150 ± 80715	Particles/g	-	
		Lettuce	50550 ± 25011	Particles/g	-	
		Carrot	101950 ± 44368	Particles/g	-	
Drink	Europe	Running water	628	Particles/L	PET, PP	(Danopoulos, Twiddy & Rotchell, 2020)
	USA	Beer	14.3	Particles/L	-	(Kosuth, Mason & Wattenberg, 2018b)
	Czech Republic	Drinking water	340-630	Particles/L	PET, PP, PE	(Pivokonsky *et al.*, 2018)
Aquatic products	French Atlantic coast	Mussel	0.23 ± 0.20	Particles/g	PP, PE	(Phuong *et al.*, 2018)

Philippines	Rabbitfish	0.6	Particles/g	PE, PP, PA, PVC, PET, PVA	(Bucol *et al.*, 2020)
Mawei Sea, China	Blue mussel	3.69–9.16	Particles/g	PP, PE	(Zhu *et al.*, 2019)

*PP: polypropylene, PET: polyethylene terephthalate, PS polystyrene, PE polyethylene, PA polyamide, PC polycarbonate, PVC polyvinyl chloride, PU polyurethane, POM polyoxymethylene, PES polyethersulfone, EVA ethylene vinyl acetate, PB polybutadiene, PVA polyvinyl alcohol, PR propyl, PW paraffin wax, CP cyclophosphamide, PEI polyetherimide.

3.6. Methods for analyzing Microplastics

All discussions above, related to the shape, size, type of MPs, their exposure routes, and health effects, are based upon how well the MPs could be detected, quantified, and monitored. Now, let us have a broad overview of the various methods available for analyzing microplastics. The MP analytical techniques developed so far can be broadly divided into two categories: physical and chemical methods. Physical analysis typically involves the visual identification of microplastics using the naked eye, stereo-microscopes, optical microscopes, and electron microscopes (SEM and TEM). These methods are often used for preliminary screening to classify particles based on size, shape, and color. However, visual inspection alone can be subjective and may lead to misidentification, especially when distinguishing microplastics from natural particles. Chemical analysis of MPs can be done in two ways (Fig. 3, such as destructive and non-destructive testing. (Du *et al.*, 2020).

3.6.1. Destructive analytical methods:

These methods involve altering or destroying the sample to analyze it. These include *Thermogravimetric analysis coupled with differential scanning calorimetry (TGA_DSC)* (Mansa, R. &Zou, S., 2021), *Thermal desorption gas chromatography mass spectrometry* (TD_GC_MS) (Zytowski, Eric & Baldermann, Susanne, 2025), *Pyrolysis gas chromatography mass spectrometer* (Cho *et al.*, 2023), and *Liquid chromatography* (Jiménez-Skrzypek *et al.,* 2021).

3.6.2. Non – destructive analytical methods:

These are done without causing any harm to the sample, which include *Fourier transform infrared spectroscopy (FT-IR):* This method identifies the type of polymer present in the MP by identifying the functional groups. This is a highly efficient analytical technique, widely used for studying molecular vibrational spectra. It offers several advantages, including high signal throughput, rapid data acquisition, and precise digital data processing. However, one limitation of the technique is its high cost, which can be a barrier to broader accessibility. (Amato-Lourenço et al., 2024). *Raman spectroscopy: this* uses laser light to measure molecular vibrations, helping to identify the chemical structure of material and, in turn, helps to identify the polymer present in the MP. Raman spectroscopy provides several advantages, including no sample preparation, minimal sample size, and contactless molecular information, which make it highly valuable. However, it faces challenges such as high equipment costs and low signal intensity (Chakraborty, I. *et al.,* 2022). *Energy dispersion X-ray spectroscopy (EDX):* This method analyses the elemental composition of material by measuring the characteristics of X-rays emitted by it. Energy-dispersive X-ray spectroscopy (EDX) is a valuable technique for elemental analysis, offering rapid, non-destructive insights into a wide range of materials. Its advantages include the ability to quickly identify and quantify elements, compatibility with other imaging techniques like SEM and TEM, and versatility across different sample types. However, EDX also has limitations, such as challenges in detecting low concentrations of light elements, potential interferences from overlapping spectral peaks, and sensitivity to beam damage in certain materials. (Long Zhu, 2023). *Micro–Raman spectroscopy* is the most sensitive and wise technique for the detection of microplastics in all samples because of its high sensitivity in detecting particles smaller than 1ng in weight and 1µm in size (Darena Schymanski, 2018).

Unfortunately, all the analytical techniques discussed above work well when MPs are either present in a relatively simplebmatrix like water. MPs present in complex matrices like soil and food require to undergo a multi-step extraction process to be detected and identified correctly.

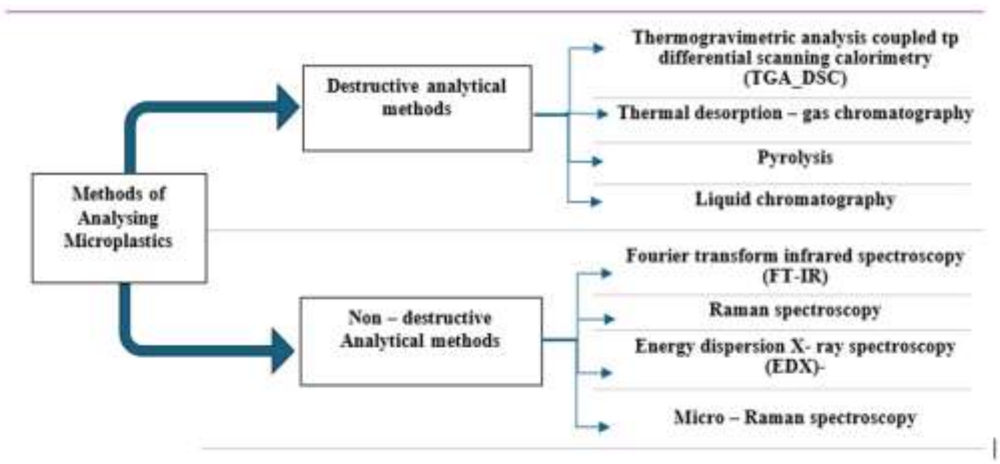

Fig. 3: Methods of analyzing microplastics

3.6.3. Role of Artificial intelligence in Microplastic detection

With the advancement of AI, MP analysis is also being attempted by the direct intervention of AI. Currently, AI-based microplastic detection technologies are being developed that utilize cutting-edge ML/DL algorithms to detect MPs, identify their polymer type, and quantify with enhanced precision and accuracy at a much quicker analysis time. These advanced models have revolutionized traditional microplastic detection methods. The process of AI-based microplastic detection typically involves several key steps: sampling of microplastics, processing, characterization, identification, classification, and quantification (Guo *et al.*, 2024). Table 2, enlists the recent advancements in microplastic (MP) detection where AI-powered technologies have been successfully employed. High-resolution digital cameras, Scanning Electron Microscopy (SEM), Fourier-transform infrared (FTIR) spectroscopy, Raman spectroscopy, hyperspectral imaging, surface-enhanced Raman spectroscopy (SERS), and computed tomography (CT) imaging are coupled with machine learning models such as Principal Component Analysis (PCA), Support Vector Machine (SVM), K-Nearest Neighbours (KNN), and Linear Discriminant Analysis (LDA) for building the majority of such AI-assisted tools. In addition, deep learning algorithms like YOLACT, YOLOv6, R-CNN, YOLOv5, sparse autoencoders, U-Net Counting, MultiResUNet, U-Net Segmentation, and DeepLabV3+ have been widely employed for microplastic detection. Most studies have focused on detecting microplastics from environmental sources such as oceans, lakes, seas, and soil biota. And showed remarkable detection accuracies exceeding 95%, which is highly commendable. Interestingly, one study successfully detected microplastics in fish using computed tomography images combined with the DeepLabV3+ model, achieving a 100% accuracy rate (Guo *et al.*, 2024).

Based on the above insights, it can be anticipated that future research in MP detection in food will evolve around ML and DL technologies to enhance the detection accuracy, which will in turn effectively mitigate microplastic contamination in food sources.

Table 2: Recent advancements in Artificial Intelligence for the detection of MPs in environmental and food samples.

S. No	Detection Technique	AI Model Employed	Source (Environment/ Food)	Performance	Reference
1	Digital camera	YOLOv6	Environment	95.6% (Accuracy)	(Ibrahim, 2023)
2	Digital camera	YOLOv5	Marine and freshwater environment	100% (Recall)	(Sarker, 2023)

3	Digital camera	RCNN	Marine environments	94% (F1 Score)	(Han, 2023)
4	FTIR	PCA + SVM, KNN, LDA	Environment	99% (Accuracy)	(Michel, 2020)
5	Raman Spectroscopy	Sparse autoencoder (Deep Neural Network)	Water Environments	99.1% (Accuracy)	(Luo, 2022)
6	Hyperspectral Imaging	PCA + 2-D CNN	Soil biota	92.6% (Accuracy)	(Ai, 2022)
7	Digital images	U-Net Counting	Marine environments	98.8% (Accuracy)	(Lorenzo-Navarro, 2021)
8	SEM images	MultiResUNet	Marine environments	93.6% (Accuracy)	(Lorenzo-Navarro, 2021)
9	Digital images	U-Net Segmentation	Urban waters	98.5% (MIoU)	(Xu, J. & Wang, Z., 2024)
10	Computed Tomography images	DeepLabV3+Semantic segmentation Model	Fish	100% (IoU)	(Strafella *et al.*, 2024)

3.7. Existing global policies to handle MPs contamination

Despite the global scale of plastic pollution, only a limited number of countries, such as the United States, Malaysia, China, Australia, and India, have taken concrete steps toward establishing legal frameworks and policies aimed at mitigating the impact of MP pollution. Table 3 provides a summary of selected laws, policies, and strategic initiatives implemented by a few countries in their efforts to combat plastic pollution in the environment.

Table 3: Country-specific policies and legislative measures to control plastic pollution (Usman *et al.*, 2020).

S. No	Country	Policy	Function	References
1	USA	Microbead-Free Waters Act (2015)	Prohibition of sales of personal care products containing microbeads.	(Wu, Yang and Criddle, 2017)
2	Malaysia	Road map for zero single-use plastic (2018)	Taxation on single-use plastic bags and plastic manufacturers, communication, education, and public awareness.	(MESTECC, 2018)

3	China	Law on the Prevention and Control of Environmental Pollution by Solid Wastes (2020)	Regulates waste dumping in rivers, lakes, and reservoirs.	(Zhang *et al.*, 2018)
4	Australia	Recycling and waste reduction (2020)	Banning of plastic export, provides flow chart of waste management and recycling	(DAWE, 2020)
5	India	Plastic Waste Management Amendment Rules (2021)	Compulsory ban on polythene bags	(UNEP, 2021)

In the United States, the Microbead-Free Waters Act of 2015 prohibits the manufacture and sale of rinse-off cosmetics containing plastic microbeads, marking one of the earliest legislative efforts to restrict microplastic contamination. Malaysia has introduced a comprehensive Roadmap Towards Zero Single-Use Plastics, which includes strategies such as taxing plastic bags, regulating plastic manufacturers, and promoting communication, education, and public awareness. China has enacted the Law on the Prevention and Control of Environmental Pollution by Solid Waste (LPCEPSW), aimed at regulating the disposal of plastic waste, including strict controls on dumping in rivers, lakes, and reservoirs. In Australia, the Recycling and Waste Reduction Act 2020 focuses on banning plastic waste exports and provides a structured framework for domestic waste management and recycling processes. India has implemented the Plastic Waste Management (Amendment) Rules, 2021, which enforce a compulsory ban on single-use plastic items such as polythene bags and promote extended producer responsibility (EPR) for plastic waste management.

The above-mentioned policies may help controling environmental microplastic pollution and reducing contamination of food during cultivation and pre-harvest stages; however, to date no regulations have been enacted in any country specifically aimed at preventing MP contamination in food during post-harvest handling and processing. In the Indian context, as of August 2025, the Food Safety and Standards Authority of India (FSSAI) has officially recognized MPs and nanoplastics as emerging food contaminants and launched a flagship initiative to address them. Under the project titled *"Micro-and Nano-Plastics as Emerging Food Contaminants: Establishing Validated Methodologies and Understanding the Prevalence in Different Food Matrices"*, FSSAI began collaborating with top research institutions—such as CSIR-IITR (Lucknow), ICAR-CIFT (Kochi), and BITS Pilani to develop standardized analytical methods, validate detection protocols, and generate exposure data specific to Indian food systems (Yow, 2024).

3.8. Attempts to remove microplastics from the environment and food

After finding out about the harmful health hazards of MPs, a worldwide drive has been started to mitigate MPs from water, soil, air, and food. A range of removal techniques has been explored, especially for water and wastewater treatment plants. Methods such as membrane bioreactors, activated sludge processes, rapid sand filtration, electrocoagulation, dissolved air flotation, and constructed wetlands have shown varied effectiveness in eliminating microplastics, with membrane bioreactors achieving over 99% removal efficiency (Romphophak *et al.*, 2024). A recent study conducted by Glenn Johansson et al. aimed at eliminating MPs from urban water sources. A pilot-scale rain garden system with 13 bioretention filters was operated for approximately 12 weeks, treating stormwater runoff from a highway and nearby impervious surfaces. Ten filters were planted with species such as *Armeria maritima*, *Hippophae rhamnoides*, *Juncus effusus*, and *Festuca rubra*. Filter media included sandy loam mixed with either incineration bottom ash (IBA), biochar, or Sphagnum peat. Influent and effluent samples were analyzed to evaluate the removal efficiency of microplastics (>10 µm), organic pollutants, metals, and nutrients. All filter types demonstrated effective removal of MPs, organic contaminants, and most metals during the start-up period(Johansson *et al.*, 2024). A study conducted by Savita Kalshan et al. demonstrates the effectiveness of membrane bioreactor (MBR) technology in removing microplastics from wastewater in the paper recycling industry. The effluent, initially containing 148 pieces/L of microplastics, underwent conventional treatment prior to further processing by the MBR system, achieving 64.9% reduction in microplastic concentration (Savita Kalshan *et al.* 2024). The latest study conducted by Gonçalo A.O. Tiago et al. investigated the effects of solar and gamma irradiation on the biodegradability of Low-Density Polyethylene (LDPE) microplastics (MP), which are non-biodegradable and contribute to micropollutants in urban treated wastewater. LDPE samples were pretreated with simulated solar irradiation both with and without TiO_2 nanoparticles (photocatalysis), followed by gamma irradiation, resulting in surface cracks, roughness, decreased thermal stability, and increased carbonyl index and crystallinity, indicative of oxidation and chain scission. Aerobic biodegradability was assessed using a static respirometer at 58°C, with green compost as the inoculum. The combination of photocatalysis and gamma irradiation exhibited a synergistic effect, significantly enhancing photodegradation and promoting biodegradation, as shown by a high specific oxygen uptake rate (SOUR) and the greatest biodegradation kinetics constant (k_{O2} = 0.0178 h^{-1})(Tiago *et al.*, 2025). Another study explores a sustainable, green photocatalytic approach for removing microplastics from water, activated by visible light. The proposed method utilizes glass fiber substrates to capture low-density microplastics, such as polypropylene (PP), while simultaneously supporting a photocatalytic material. Zinc oxide nanorods (ZnO NRs) were immobilized onto the glass fibers in a flow-through system to degrade PP microplastics suspended in water under visible light irradiation. Over two weeks, the average particle volume of PP microplastics was reduced by 65%(Uheida *et al.*, 2021). A study by Gulizia et al. investigated the biodegradation of PS and PVC microplastics (<200 µm) with and without plasticizers (DEHP and BPA) under simulated tropical seawater conditions over 21 days. It was observed that degradation was strongly influenced by polymer type, plasticizer, and exposure time, with PS-BPA microplastics showing the most significant breakdown. This degradation was linked to shifts in bacterial community composition and an increased abundance of biodegradative bacteria, highlighting that the chemical properties of microplastics play a critical role in shaping marine biofilm activity and biodegradation potential (Gulizia et al., 2025).

While current research has predominantly focused on the removal of microplastics (MPs) from contaminated water sources, unfortunately, there are very few attempts to remove MPs from food. The complex, opaque food matrix makes both the detection and removal of MPs highly challenging.

4. CONCLUSION

In conclusion, this review critically assessed the food safety risks posed by microplastic (MP) contamination. Continuous ingestion of MPs through food and water contributes to bioaccumulation, oxidative stress, and endocrine disruption, underscoring a growing public health concern. Current global mitigation efforts largely prioritize reducing plastic usage rather than removing existing MPs. Available removal and detection techniques are mainly suited for water systems and are inadequate for solid or semi-solid food matrices. The review therefore stresses the urgent need for efficient, scalable, and cost-effective technologies for MP detection and elimination. It also highlights the emerging potential of AI in this domain.

While compiling the review, challenges limited availability of relevant full-text articles, redundancy in search results, and lack of standardization in experimental designs across studies. Additionally, comparison of AI-based detection methods was hindered by differences in performance metrics. Nonetheless, by summarizing the research over the past 12 years, this work provides a comprehensive perspective on MP contamination in foods and outlines future research directions.

Author Contributions:

Conceptualization - Sree Sesha Sravanika, Amrita Shaw and Jhinuk Gupta; Methodology- Sree Sesha Sravanika, Amrita Shaw and Jhinuk Gupta; Draft preparartion - Sree Sesha Sravanika, Amrita Shaw, Jhinuk Gupta and Bavatharani V; Writing review and editing - Jhinuk Gupta and Sree Sesha Sravanika; Supervision- Jhinuk Gupta. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors are grateful to Sri Sathya Sai Institute of Higher learning for facilitating the writing of the review.

Conflicts of Interest: The authors declare no conflicts of interest.

REFERENCES

1. Ai, W., Liu, S., Liao, H. and Du, J.,2022. Application of hyperspectral imaging technology in the rapid identification of microplastics in farmland soil. *Science of the Total Environment*, 807, 151030.https://doi.org/10.1016/j.scitotenv.2021.151030

2. Amato-Lourenço, L.F., Fernandes, C.P., da Silva, A.A., Moura, F.G., Santos, M.L., Oliveira, R.S., Almeida, D.R., Costa, E.M., and Pereira, J.T., 2024. Microplastics in the Olfactory Bulb of the Human Brain, *JAMA Network Open*, 7(9), p. e2440018. https://doi.org/10.1001/jamanetworkopen.2024.40018.

3. Anagnosti, L., Varvaresou, A., Pavlou, P., Protopapa, E. and Carayanni, V., 2021. Worldwide actions against plastic pollution from microbeads and microplastics in cosmetics focusing on European policies: Has the issue been handled effectively? *Marine Pollution Bulletin*, 162, p.111883. https://doi.org/10.1016/j.marpolbul.2020.111883

4. An, L.-h., Yu, Q.L., Ding, Y. and Wang, W., 2020. Sources of microplastic in the environment. In: D. He and Y. Luo, eds. *Microplastics in Terrestrial Environments*. Cham: Springer Nature, April 2020. https://doi.org/10.1007/698_2020_449

5. An, R., Wang, X., Yang, L., Zhang, J., Wang, N., Xu, F., Hou, Y., Zhang, H. and Zhang, L., 2021. Polystyrene microplastics cause granulosa cells apoptosis and fibrosis in ovary through oxidative stress in rats. *Toxicology*, 449, p.152665. https://doi.org/10.1016/j.tox.2020.152665

6. Bai, C.-L., Liu, L.-Y., Guo, J.-L., Zeng, L.-X. and Guo, Y., 2022. Microplastics in take-out food: are we over taking it? *Environmental Research*, 215, p.114390. https://doi.org/10.1016/j.envres.2022.114390.

7. Bradney, L., Wijesekara, H., Palansooriya, K.N., Obadamudalige, N., Bolan, N.S., Ok, Y.S., Rinklebe, J., Kim, K.H., Kirkham, M.B., 2019. Particulate plastics as a vector for toxic trace-element uptake by aquatic and terrestrial organisms and human health risk. *Environment International*, 131, p.104937. https://doi.org/10.1016/j.envint.2019.104937

8. Bouwstra, J., Pilgram, G., Gooris, G., Koerten, H., Ponec, M., 2001. New aspects of the skin barrier organization. *Skin Pharmacology and Applied Skin Physiology*, 14, pp.52-62. https://doi.org/10.1159/000056391

9. Bucol, L.A., Romano, E.F., Cabcaban, S.M., Siplon, L.M.D., Madrid, G.C., Bucol, A.A., Polidoro, B., 2020. Microplastics in marine sediments and rabbitfish (Siganus fuscescens) from selected coastal areas of Negros Oriental, Philippines', *Marine Pollution Bulletin*, 150., pp.110685. https://doi.org/10.1016/j.marpolbul.2019.110685.

10. Chang, M., 2015. Reducing microplastics from facial exfoliating cleansers in wastewater through treatment versus consumer product decisions, *Marine Pollution Bulletin*, 101(1), pp. 330–333. https://doi.org/10.1016/j.marpolbul.2015.10.074.

11. Chakraborty, I., Banik, S., Biswas, R. and Yamamoto, T., 2022. Raman spectroscopy for microplastic detection in water sources: a systematic review. *International Journal of Environmental Science and Technology*, 20(9), pp.10435–10448.https://doi.org/10.1007/s13762-022-04505-0

12. Cheng, W., Li, X., Zhou, Y., Yu, H., Xie, Y., Guo, H., Wang, H., Li, Y., Feng, Y., Wang, Y., 2022. Polystyrene

microplastics induce hepatotoxicity and disrupt lipid metabolism in the liver organoids. *Science of The Total Environment*, 806(Pt 1), p.150328. https://doi.org/10.1016/j.scitotenv.2021.150328

13. Cheng, Y.Y. and Yu, J.Z., 2020. Minimizing contamination from plastic labware in the quantification of C16 and C18 fatty acids in filter samples of atmospheric particulate matter and their utility in apportioning cooking source contribution to urban PM2.5. *Atmosphere*, 11(10), p.1120. https://doi.org/10.3390/atmos11101120

14. Chen, Q., Gao, J., Yu, H., Su, H., Yang, Y., Cao, Y., Zhang, Q., Ren, Y., Hollert, H., Shi, H., Chen, C., Liu, H., 2022. An emerging role of microplastics in the etiology of lung ground glass nodules, *Environmental Sciences Europe*, 34(1), p.25.https://doi.org/10.1186/s12302-022-00605-3.

15. Chen, Y., Liu, X., Xu, Z., Yang, Z., Wang, G., Rao, W., and Ding, H., 2022. Air conditioner filters become sinks and sources of indoor microplastic fibers. *Environmental Pollution*, 292, p.118260. https://doi.org/10.1016/j.envpol.2021.118260.

16. Chen, G., Feng, Q., Wang, J**.**, 2020. Mini-review of microplastics in the atmosphere and their risks to humans. *Science of The Total Environment*, 703, p.135504. https://doi.org/10.1016/j.scitotenv.2019.135504.

17. Cheung, P.K. and Fok, L., 2017**.** Characterisation of plastic microbeads in facial scrubs and their estimated emissions in Mainland China. *Water Research*, 122, pp.53–61. https://doi.org/10.1016/j.watres.2017.05.053

18. Cho, M.-H., Song, Y.-J., Rhu, C.-J. and Go, B.-R., 2023. Pyrolysis process of mixed microplastics using TG-FTIR and TED-GC-MS. *Polymers*, 15(1), p.241. https://doi.org/10.3390/polym15010241

19. Cox, K.D., Covernton, G.A., Davies, H.L., Dower, J.F., Juanes, F. and Dudas, S.E., 2019. Human consumption of microplastics. *Environmental Science & Technology*, 53(12), pp. 7068–7074. https://doi.org/10.1021/acs.est.9b01517

20. Daniel, D.B., Ashraf, P.M. and Thomas, S.N., 2020. Abundance, characteristics and seasonal variation of microplastics in Indian white shrimps (Fenneropenaeus indicus) from coastal waters off Cochin, Kerala, India. *Science of The Total Environment*, 737, p.139839. https://doi.org/10.1016/j.scitotenv.2020.139839

21. Dambrosio, A., Cometa, S., Capuozzo, F., Ceci, E., Derosa, M., Quaglia, N.C., 2023. Occurrence and Characterization of Microplastics in Commercial Mussels (Mytilus galloprovincialis) from Apulia Region (Italy)', *Foods*, 12(7), p.1495. https://doi.org/10.3390/foods12071495.

22. Danopoulos, E., Twiddy, M. and Rotchell, J.M., 2020. Microplastic contamination of drinking water: a systematic review. *PLoS One*, 15(7), p.e0236838. https://doi.org/10.1371/journal.pone.0236838

23. DAWE (Department of Agriculture, Water and the Environment), 2020. *Australia Recycling and Waste Reduction Bill*. http://www.environment.gov.au/protection/waste-resource-recovery/recycling-waste-reduction-bill-2020.

24. Dehghani, S., Moore, F. and Akhbarizadeh, R., 2017. Microplastic pollution in deposited urban dust, Tehran metropolis, Iran, *Environmental Science and Pollution Research*, 24(25), pp. 20360–20371. https://doi.org/10.1007/s11356-017-9674-1.

25. Deng, Y., Zhang, Y., Lemos, B. and Ren, H., 2017. Tissue accumulation of microplastics in mice and biomarker responses suggest widespread health risks of exposure. *Scientific Reports*, **7**, p.46687. https://doi.org/10.1038/srep46687

26. Dirk Xanthos and Tony R. Walker., 2017. International policies to reduce plastic marine pollution from single-use plastics (plastic bags and microbeads): A review, *Marine Pollution Bulletin*, 118, pp. 17–26. https://doi.org/10.1016/j.marpolbul.2017.02.048

27. De Falco, F., Gullo, M.P., Gentile, G., Di Pace, E., Cocca, M., Gelabert, L., Brouta Agnèsa, M., Rovira, A., Escudero, R., Villalba, R., Mossotti, R., Montarsolo, A., Gavignano, S., Tonin, C., Avella, M., 2018. Evaluation

of microplastic release caused by textile washing processes of synthetic fabrics. *Environmental Pollution*, 236**,** pp.916–925. https://doi.org/10.1016/j.envpol.2017.10.057

28. Du, F., Cai, H., Zhang, Q., Chen, Q., Shi, H., 2020. Microplastics in take-out food containers, *Journal of Hazardous Materials*, 399, p.122969. https://doi.org/10.1016/j.jhazmat.2020.122969.

29. Enyoh, C.E., Shafea, L., Verla, A.W., Verla, E.N., Qingyue, W., Chowdhury, T. and Paredes, M., 2020. Microplastics exposure routes and toxicity studies to ecosystems: an overview. *Environmental Analysis Health and Toxicology*, 35(1), p.e2020004. https://doi.org/10.5620/eaht.e2020004

30. FAO, 2017. Microplastics in fisheries and aquaculture: status of knowledge on their occurrence and implications for aquatic organisms and food safety. *FAO Fisheries and Aquaculture Technical Paper* No. 615. Food and Agriculture Organization of the United Nations, Rome. https://openknowledge.fao.org/handle/20.500.14283/i7677en

31. Gouin, T., Avalos, J., Brunning, I., Brzuska, K., de Graaf, J., Kaumanns, J., Koning, T., Meyberg, M., Rettinger, K., Schlatter, H., Thomas, J., van Welie, R. and Wolf, T., 2015. Use of micro-plastic beads in cosmetic products in Europe and their estimated emissions to the North Sea environment. *SOFW-Journal*, 141(3), pp.40–46. https://www.researchgate.net/publication/291326701
32. Gulizia, A.M., Bell, S.C., Kuek, F., Santana, M.F.M., Edmunds, R.C., Yeoh, Y.K., Sato, Y., Haikola, P., van Herwerden, L., Motti, C.A., Bourne, D.G., Vamvounis, G., 2025. Biofilm development as a factor driving the degradation of plasticised marine microplastics', *Journal of Hazardous Materials*, 487, p.136975. https://doi.org/10.1016/j.jhazmat.2024.136975.

33. Gündoğdu, S. and Köşker, A.R., 2023. Microplastic contamination in canned fish sold in Türkiye, *PeerJ*, 11, p.e14627. https://doi.org/10.7717/peerj.14627.

34. Guo, P., Wang, Y., Moghaddamfard, P., Meng, W., Wu, S. and Bao, Y., 2024. Artificial intelligence-empowered collection and characterization of microplastics: A review. *Journal of Hazardous Materials***,** 471, p.134405.

https://doi.org/10.1016/j.jhazmat.2024.134405

35. Han, X.-L., Jiang, N.-J., Hata, T., Choi, J., Du, Y.-J. and Wang, Y.-J., 2023. Deep learning based approach for automated characterization of large marine microplastic particles. *Marine Environmental Research*, 183**,** p.105829. https://doi.org/10.1016/j.marenvres.2022.105829

36. Hartline, N.L., Bruce, N.J., Karba, S.N., Ruff, E.O., Sonar, S.U. and Holden, P.A., 2016. Microfiber Masses Recovered from Conventional Machine Washing of New or Aged Garments, *Environmental Science and Technology*, 50(21), pp. 11532–11538. https://doi.org/10.1021/acs.est.6b03045.

37. Hernandez, L.M., Xu, E.G., Larsson, H.C.E., Tahara, R., Maisuria, V.B. and Tufenkji, N., 2019. Plastic teabags release billions of microparticles and nanoparticles into tea. *Environmental Science & Technology*, 53(21), pp.12300–12310. https://doi.org/10.1021/acs.est.9b02540

38. Hou, B., Wang, F., Liu, T. and Wang, Z., 2021. Reproductive toxicity of polystyrene microplastics: in vivo experimental study on testicular toxicity in mice. *Journal of Hazardous Materials*, 405**,** p.124028. https://doi.org/10.1016/j.jhazmat.2020.124028

39. Hou, J., Lei, Z., Cui, L., Hou, Y., Yang, L., An, R., Wang, Q., Li, S., Zhang, H. and Zhang, L., 2021 Polystyrene microplastics lead to pyroptosis and apoptosis of ovarian granulosa cells via NLRP3/Caspase-1 signaling pathway in rats, *Ecotoxicology and Environmental Safety*, 212, p.112012. https://doi.org/10.1016/j.ecoenv.2021.112012.

40. Huang, Y., Li, W., Dong, K., Li, X., Li, W. and Wang, D., 2024.Effect of Polystyrene Microplastic Exposure on Individual, Tissue, and Gene Expression in Juvenile Crucian Carp (Carassius auratus), *Fishes*, 9(10), p.385. https://doi.org/10.3390/fishes9100385.

41. Ibrahim, A.E., Shoitan, R., Moussa, M.M., Elnemr, H.A., Cho, Y.I. and Abdallah, M.S., 2023. Object detection-based automatic waste segregation using robotic arm. *International Journal of Advanced Computer Science and*

Applications (IJACSA), 14(6), pp.912–926. https://doi.org/10.14569/IJACSA.2023.0140697

42. Ibrahim, Y.S., Tuan Anuar, S., Azmi, A.A., Wan Mohd Khalik, W.M.A., Lehata, S., Hamzah, S.R., Ismail, D., Ma, Z.F., Dzulkarnaen, A., Zakaria, Z., Mustaffa, N., Tuan Sharif, S.E. and Lee, Y.Y., 2021. Detection of microplastics in human colectomy specimens, *JGH Open*, 5(1), pp. 116–121. https://doi.org/10.1002/jgh3.12457.

43. Jiménez-Skrzypek, G., Ortega-Zamora, C., González-Sálamo, J., Hernández-Sánchez, C. and Hernández-Borges, J., 2021. The current role of chromatography in microplastic research: Plastics chemical characterization and sorption of contaminants. *Journal of Chromatography Open*, 1, p.100001. https://doi.org/10.1016/j.jcoa.2021.100001

44. Jin, H., Yan, M., Pan, C., Liu, Z., Sha, X., Jiang, C., Li, L., Pan, M., Li, D., Han, X. and Ding, J., 2022. Chronic exposure to polystyrene microplastics induced male reproductive toxicity and decreased testosterone levels via the LH-mediated LHR/cAMP/PKA/StAR pathway, *Particle and Fibre Toxicology*, 19(1), p.13. https://doi.org/10.1186/s12989-022-00453-2.

45. Jin, M., Wang, X., Qian, Y., Liu, H., Wang, L., and Xu, S., 2021. Microplastics contamination in food and beverages: Direct exposure to humans, *Journal of Food Science*, 86(9), pp. 2816–2837. https://doi.org/10.1111/1750-3841.15802

46. Johansson, G., Fedje, K.K., Modin, O., Haeger-Eugensson, M., Uhl, W., Andersson-Sköld, Y. and Strömvall, A.M., 2024. Removal and release of microplastics and other environmental pollutants during the start-up of bioretention filters treating stormwater, *Journal of Hazardous Materials*, 468, p.133532. https://doi.org/10.1016/j.jhazmat.2024.133532.

47. Kadac-Czapska, K., Trzebiatowska, P.J., Knez, E., Zaleska-Medynska, A. and Grembecka, M., 2024. Isolation and identification of microplastics in infant formulas – A potential health risk for children, *Food Chemistry*, 440, p.138246. https://doi.org/10.1016/j.foodchem.2023.138246.

48. Kadac-Czapska, K., Knez, E. and Grembecka, M., 2024. Food and human safety: the impact of microplastics, *Critical Reviews in Food Science and Nutrition*, 64(12), pp. 3502–3521. https://doi.org/10.1080/10408398.2022.2132212.

49. Kalshan, S., Dhankhar, R., Narwal, S., Chhillar, A., Desondia, M., Yadav, P. and Yadav, S., 2025. Enhanced Microplastics Removal from Paper Recycling Industry Wastewater Using Membrane Bioreactor Technology. *Nature Environment and Pollution Technology*, *24*(2), pp.1-9. 10.46488/NEPT.2025.v24i02.B4240

50. Kang, H., Park, S., Lee, B., Kim, I. and Kim, S., 2022.Concentration of Microplastics in Road Dust as a Function of the Drying Period—A Case Study in G City, Korea, *Sustainability (Switzerland)*, 14(5), p.3006. https://doi.org/10.3390/su14053006.

51. Kannan, K. and Vimalkumar, K., 2021. A review of human exposure to microplastics and insights into microplastics as obesogens. *Frontiers in Endocrinology*, Frontiers Media S.A., 12, p.724989. https://doi.org/10.3389/fendo.2021.724989

52. Karami, A., Golieskardi, A., Keong, C.H., Larat, V., Galloway, T.S. and Salamatinia, B., 2017. The presence of microplastics in commercial salts from different countries. *Scientific Reports*, 7, p.46173. https://doi.org/10.1038/srep46173

53. Kasirajan, S. and Ngouajio, M. 2012. Polyethylene and biodegradable mulches for agricultural applications: A review, *Agronomy for Sustainable Development*. Springer-Verlag France, 32(2), pp.501–529. https://doi.org/10.1007/s13593-011-0068-3.

54. Kim, J.-S., Lee, H.-J., Kim, S.-K. and Kim, H.-J., 2018. Global pattern of microplastics (MPs) in commercial food-grade salts: Sea salt as an indicator of seawater MP pollution. *Environmental Science & Technology*, 52(21), pp.12819–12828. https://doi.org/10.1021/acs.est.8b04180

55. Kosuth, M., Mason, S.A. and Wattenberg, E.V., 2018. Anthropogenic contamination of tap water, beer, and sea salt. *PLoS ONE*, 13(4), p.e0194970. https://doi.org/10.1371/journal.pone.0194970

56. Kutralam-Muniasamy, G., Pérez-Guevara, F., Elizalde-Martínez, I. and Shruti, V.C., 2020. Branded milks – Are they immune from microplastics contamination?', *Science of the Total Environment*, 714, p.136823.https://doi.org/10.1016/j.scitotenv.2020.136823.

57. Lebreton, L. and Andrady, A., 2019. Future scenarios of global plastic waste generation and disposal. *Palgrave Communications*, 5(1), p.6. https://doi.org/10.1057/s41599-018-0212-7

58. Lee, H., Kunz, A., Shim, W.J. and Walther, B.A., 2019. Microplastic contamination of table salts from Taiwan, including a global review. *Scientific Reports*, 9(1), p.6649. https://doi.org/10.1038/s41598-019-46417-z

59. Lehner, R., Weder, C., Petri-Fink, A. and Rothen-Rutishauser, B., 2019. Emergence of Nanoplastic in the Environment and Possible Impact on Human Health, *Environmental Science and Technology*, 53(4), pp. 1748–1765. https://doi.org/10.1021/acs.est.8b05512.

60. Leslie, H.A., Dehaut, A., Romans, B., Sussarellu, R., Koelmans, A.A., Huvet, A., Rinnert, E., Wilson, S., Jenkinson, I., Carvalho, G., Galloway, T.S., Tassin, B. and Gigault, J., 2022. Discovery and quantification of plastic particle pollution in human blood. *Environment International*, 163, p.107199. https://doi.org/10.1016/j.envint.2022.107199

61. Li, C., Busquets, R. and Campos, L.C., 2020. Assessment of microplastics in freshwater systems: a review. *Science of the Total Environment*, 707**,** p.135578. https://doi.org/10.1016/j.scitotenv.2019.135578

62. Li, J., Wang, Q., Cui, M., Yu, S., Chen, X. and Wang, J., 2023. Release characteristics and toxicity assessment of micro/nanoplastics from food-grade nonwoven bags. *Science of The Total Environment*, 883, p.163642. https://doi.org/10.1016/j.scitotenv.2023.163642

63. Liebezeit, G. and Liebezeit, E., 2013. Non-pollen particulates in honey and sugars, *Food Additives and Contaminants - Part A*, 30(12), pp. 2136–2140. https://doi.org/10.1080/19440049.2013.843025.

64. Liebezeit, G. and Liebezeit, E., 2015. Origin of synthetic particles in honeys, *Polish Journal of Food and Nutrition Sciences*, 65(2), pp. 143–147. https://doi.org/10.1515/pjfns-2015-0025.

65. Li, L., Zhao, X., Li, Z. and Song, K., 2021. COVID-19: Performance study of microplastic inhalation risk posed by wearing masksss, *Journal of Hazardous Materials*, 411, p.124955. https://doi.org/10.1016/j.jhazmat.2020.124955.

66. Liu, C., Li, J., Zhang, Y., Wang, L., Deng, J., Gao, Y., Yu, L., Zhang, J. and Sun, H., 2019. Widespread distribution of PET and PC microplastics in dust in urban China and their estimated human exposure, *Environment International*, 128, pp. 116–124. https://doi.org/10.1016/j.envint.2019.04.024.

67. Liu, Z., Zhuan, Q., Zhang, L., Meng, L., Fu, X. and Hou, Y., 2022. Polystyrene microplastics induced female reproductive toxicity in mice, *Journal of Hazardous Materials*, 424, p.127629. https://doi.org/10.1016/j.jhazmat.2021.127629.

68. Li, Y., Peng, L., Fu, J., Dai, X. and Wang, G., 2022. A microscopic survey on microplastics in beverages: the case of beer, mineral water and tea, *Analyst*, 147(6), pp. 1099–1105. https://doi.org/10.1039/d2an00083k.

69. Li, Y., Tao, L., Wang, Q., Wang, F., Li, G. and Song, M., 2023. Potential health impact of microplastics: A review of environmental distribution, human exposure, and toxic effects. *Environmental Health (Washington)*, 1(4), pp.249–257. https://doi.org/10.1021/envhealth.3c00052

70. Lorenzo-Navarro, J., Castrillón-Santana, M., Sánchez-Nielsen, E., Zarco, B., Herrera, A., Martínez, I. and Gómez, M., 2021. Deep learning approach for automatic microplastics counting and classification. *Science of*

the Total Environment, 765, p.142728. https://doi.org/10.1016/j.scitotenv.2020.142728

71. Luo, Y., Su, W., Xu, X. and Dewen, X., 2022. Raman spectroscopy and machine learning for microplastics identification and classification in water environments. *IEEE Journal of Selected Topics in Quantum Electronics*, 28(3), pp.1–8.https://doi.org/10.1109/JSTQE.2022.3222065

72. Mansa, R. and Zou, S., 2021. Thermogravimetric analysis of microplastics: A mini review. *Environmental Advances*, 5, p.100117. https://doi.org/10.1016/j.envadv.2021.100117

73. Meng, Q.-J., Ji, Q., Zhang, Y.-G., Liu, D., Grossnickle, D.M. and Luo, Z.-X., 2015. An arboreal docodont from the jurassic and mammaliaform ecological diversification, *Science*, 347(6223), pp. 764–768. https://doi.org/10.1126/science.1260879.

74. MESTECC, 2018. *Malaysia's Roadmap Towards Zero Disposable Plastic Use 2018–2030*. https://www.pmo.gov.my/ms/2019/07/pelan-hala-tuju-malaysia-ke-arah-sifar-penggunaan-plastiksekali-guna-2018-2030/

75. Michel, A.P.M., Morrison, A.E., Preston, V.L., Marx, C.T., Colson, B.C. and White, H.K., 2020. Rapid identification of marine plastic debris via spectroscopic techniques and machine learning classifiers. *Environmental Science & Technology*, 54(17), pp.10630–10637. https://doi.org/10.1021/acs.est.0c02099

76. Mohammadi, L., Baluchnejadmojarad, T., Goudarzi, M., Khodashenas, V., Khoshravesh, R. and Roghani, M., 2025. Promising protective potential of MiR-103a-3p against polystyrene microplastic neurotoxicity in rats, *Frontiers in Toxicology*, **7**, p.1560980. https://doi.org/10.3389/ftox.2025.1560980.

77. Oliveri Conti, G., Ferrante, M., Banni, M., Favara, C., Nicolosi, I., Cristaldi, A., Fiore, M. and Zuccarello, P., 2020. Micro- and nano-plastics in edible fruit and vegetables: The first diet risks assessment for the general population. *Environmental Research*, 187, p.109677. https://doi.org/10.1016/j.envres.2020.109677

78. Palazzo, L., Coppa, S., Camedda, A., Cocca, M., De Falco, F., Vianello, A., Massaro, G. and de Lucia, G.A.,

2021. A novel approach based on multiple fish species and water column compartments in assessing vertical microlitter distribution and composition. *Environmental Pollution*, 272, p.116419. https://doi.org/10.1016/j.envpol.2020.116419

79. Phuong, N.N., Poirier, L., Pham, Q.T., Lagarde, F. and Zalouk-Vergnoux, A., 2018. Factors influencing the microplastic contamination of bivalves from the French Atlantic coast: Location, season and/or mode of life?, *Marine Pollution Bulletin*, 129(2), pp. 664–674. https://doi.org/10.1016/j.marpolbul.2017.10.054.

80. Pivokonský, M., Čermáková, L., Novotná, K., Peer, P., Cajthaml, T. and Janda, V., 2018. Occurrence of microplastics in raw and treated drinking water, *Science of the Total Environment*, 643, pp. 1644–1651. https://doi.org/10.1016/j.scitotenv.2018.08.102.

81. Prata, J.C. 2018. Airborne microplastics: Consequences to human health? *Environmental Pollution*, 234, pp. 115–126. https://doi.org/10.1016/j.envpol.2017.11.043

82. Prata, J.C., da Costa, J.P., Lopes, I., Duarte, A.C. and Rocha-Santos, T., 2020. Environmental exposure to microplastics: An overview on possible human health effects, *Science of The Total Environment*, 702, p. 134455. https://doi.org/10.1016/j.scitotenv.2019.134455

83. Qi, Y., Yang, X., Mejia Pelaez, A., Huerta Lwanga, E., Beriot, N., Gertsen, H., Garbeva, P. and Geissen, V., 2018. Macro- and micro- plastics in soil-plant system: Effects of plastic mulch film residues on wheat (Triticum aestivum) growth', *Science of the Total Environment*, 645, pp. 1048–1056. https://doi.org/10.1016/j.scitotenv.2018.07.229.

84. Quaglia, N.C., Capuozzo, F., Ceci, E., Cometa, S., Di Pinto, A., Mottola, A., Piredda, R. and Dambrosio, A., 2023. Preliminary survey on the occurrence of microplastics in bivalve mollusks marketed in Apulian fish markets, *Italian Journal of Food Safety*, 12(2). https://doi.org/10.4081/ijfs.2023.10906.

85. Ragusa, A., Svelato, A., Santacroce, C., Catalano, P., Notarstefano, V., Carnevali, O., Papa, F., Rongioletti, M.C.A., Baiocco, F., Draghi, S., D'Amore, E., Rinaldo, D., Matta, M. and Giorgini, E., 2021. Plasticenta: First evidence of microplastics in human placenta. *Environment International*, 146, p.106274. https://doi.org/10.1016/j.envint.2020.106274

86. Ragusa, A., Notarstefano, V., Svelato, A., Belloni, A., Gioacchini, G., Blondeel, C., Zucchelli, E., De Luca, C., D'Avino, S., Gulotta, A., Carnevali, O. and Giorgini, E., 2022. Raman Microspectroscopy Detection and Characterisation of Microplastics in Human Breastmilk, *Polymers*, 14(13), p.2700. https://doi.org/10.3390/polym14132700.

87. Ramsperger, A.F.R.M. *et al*.**,** 2023. Nano- and microplastics: a comprehensive review on their exposure routes, translocation, and fate in humans. *NanoImpact*, 29, 100441. https://doi.org/10.1016/j.impact.2022.100441
88. Renzi, M. and Blašković, A., 2018. Litter and microplastics features in table salts from marine origin: Italian versus Croatian brands, *Marine Pollution Bulletin*, 135, pp. 62–68. https://doi.org/10.1016/j.marpolbul.2018.06.065.
89. RIVM, 2016. Emission of microplastics and potential mitigation measures: abrasive cleaning agents, paints and tyre wear. *RIVM Report* 2016-0026. National Institute for Public Health and the Environment, Bilthoven, The Netherlands. https://www.rivm.nl/publicaties/emission-of-microplastics-and-potential-mitigation-measures
90. Romphophak, P., Faikhaw, O., Sairiam, S., Thuptimdang, P. and Coufort-Saudejaud, C., 2024. Removal of microplastics and nanoplastics in water treatment processes: A systematic literature review. *Journal of Water Process Engineering*, 64**,** p.105669.https://doi.org/10.1016/j.jwpe.2024.105669.

91. Salim, S.Y., Kaplan, G.G. and Madsen, K.L., 2013. Air pollution effects on the gut microbiota: A link between exposure and inflammatory disease, *Gut Microbes*, 5(2), pp. 215–219. https://doi.org/10.4161/gmic.27251.

92. Sarkar, B., Dissanayake, P.D., Bolan, N.S., Dar, J.Y., Kumar, M., Haque, M.N., Mukhopadhyay, R., Ramanayaka, S., Biswas, J.K., Tsang, D.C.W., Rinklebe, J. and Ok, Y.S., 2022. Challenges and opportunities in sustainable management of microplastics and nanoplastics in the environment. *Environmental Research*, 207, p.112179. https://doi.org/10.1016/j.envres.2021.112179

93. Sarker, M.A.B., Butt, U., Imtiaz, M.H. and Baki, A.B.M., 2023. Automatic detection of microplastics in the aqueous environment. In: *Proceedings of the IEEE 13th Annual Computing and Communication Workshop and Conference (CCWC 2023)*. IEEE, March 2023. https://doi.org/10.1109/CCWC57344.2023.10099253

94. Schymanski, D., Goldbeck, C., Humpf, H.-U. & Fürst, P., 2018. Analysis of microplastics in water by micro-Raman spectroscopy: release of plastic particles from different packaging into mineral water. *Water Research*, 129, pp.154–162. https://doi.org/10.1016/j.watres.2017.11.011

95. Seth, C.K. and Shriwastav, A., 2018. Contamination of Indian sea salts with microplastics and a potential prevention strategy. *Environmental Science and Pollution Research*, 25(30), pp.30122–30131. https://doi.org/10.1007/s11356-018-3028-5

96. Shen, R., Yang, K., Cheng, X., Guo, C., Xing, X., Sun, H., Liu, D., Liu, X. and Wang, D., 2022. Accumulation of polystyrene microplastics induces liver fibrosis by activating cGAS/STING pathway. *Environmental Pollution*, 300, p.118986. https://doi.org/10.1016/j.envpol.2022.118986

97. Shruti, V.C., Pérez-Guevara, F., Elizalde-Martínez, I. and Kutralam-Muniasamy, G., 2020. First study of its kind on the microplastic contamination of soft drinks, cold tea and energy drinks - Future research and environmental considerations. *Science of The Total Environment*, 726, p.138580. https://doi.org/10.1016/j.scitotenv.2020.138580

98. Shruti, V.C., Pérez-Guevara, F., Menon, M.G.K., 2021. Toward a unified framework for investigating micro(nano)plastics in packaged beverages intended for human consumption. *Environmental Pollution*, 268, p.115797. https://doi.org/10.1016/j.envpol.2020.115797

99. Solanki, P., Jain, S., Mehrotra, R., Mago, P. and Dagar, S., 2024. Microplastics in Agricultural Soil and Their Impact: A Review. *Nature Environment and Pollution Technology*, *23*(4), pp.2143-2155. 10.46488/NEPT.2024.v23i04.019

100. Strafella, P., Giulietti, N., Caputo, A., Pandarese, G. and Castellini, P., 2024. Detection of microplastics in fish using computed tomography and deep learning. *Heliyon*, 10(21), p.e39875. https://doi.org/10.1016/j.heliyon.2024.e39875

101. Terrazas-López, R., López, D., Alvarado-Zambrano, B., Santillán, L., Díaz, A. and Rodríguez-Espinosa, P., 2024. The occurrence of microplastics in the marine food web in Latin America: Insights on the current state of knowledge and future perspectives. *Sustainability (Switzerland)*, 16(14), p.5905. https://doi.org/10.3390/su16145905

102. Thompson, R.C., Moore, C.J., vom Saal, F.S. and Swan, S.H., 2015**.** Lost at sea: Where is all the plastic? *Science*, 304(5672), pp.838–838. http://www.sciencemag.org/cgi/content/full/304/5672/838/

103. Tiago, G.A.O., Martins-Dias, S.M., Marcelino, L.P.P.G. and Marques, A.C.L., **2025.** Promoting LDPE microplastic biodegradability: The combined effects of solar and gamma irradiation on photodegradation. *Journal of Hazardous Materials*, 492, p.138227. https://doi.org/10.1016/j.jhazmat.2025.138227

104. Tympa, L.E., Katsara, K., Karapati, S., Tzavara, E., Psarrou, E., Rousis, N.I. and Thomaidis, N.S., 2021. Do microplastics enter our food chain via root vegetables? A Raman-based spectroscopic study on *Raphanus sativus*. *Materials*, 14(9), p.2329. https://doi.org/10.3390/ma14092329

105. Uheida, A., Eriksson, M., Nguyen, T., Pugliese, D., Arcos Martínez, M.J. and Nadhir, A., 2021. Visible light photocatalytic degradation of polypropylene microplastics in a continuous water flow system. *Journal of Hazardous Materials*, 406, p.124299. https://doi.org/10.1016/j.jhazmat.2020.124299.

106. UNEP (United Nations Environment Programme), 2021. *Plastic Waste Management Amendment Rules, 2021 (India)*. LEAP – Law and Environment Assistance Platform. https://leap.unep.org/en/countries/in/national-legislation/plastic-waste-management-amendment-rules-2021.

107. Usman, S., Ahmad, A., Khan, M., Hussain, I., Islam, S., Sarfraz, M., Iqbal, M., Ali, M., Yang, X., Zhang, L. and Zhu, J., 2020. Microplastics pollution as an invisible potential threat to food safety and security, policy challenges and the way forward. *International Journal of Environmental Research and Public Health*, 17(24), pp.1–24. https://doi.org/10.3390/ijerph17249591

108. Van Cauwenberghe, L. and Janssen, C.R. 2014. Microplastics in bivalves cultured for human consumption, *Environmental Pollution*, 193, pp. 65–70. https://doi.org/10.1016/j.envpol.2014.06.010.

109. Vdovchenko, A. and Resmini, M., 2024. Mapping microplastics in humans: Analysis of polymer types, and shapes in food and drinking water—A systematic review. *International Journal of Molecular Sciences*, 25(13), p.7074. https://doi.org/10.3390/ijms25137074

110. Wang, Y.-L., Lee, Y.-H., Hsu, Y.-H., Chiu, I.-J., Huang, C.-C., Chih-Chia Huang, Z.-C., Lee, C.-P., Lin, Y.-F. and Chiu, H.-W., 2021. The kidney-related effects of polystyrene microplastics on human kidney proximal tubular epithelial cells HK-2 and male C57BL/6 mice. *Environmental Health Perspectives*, 129(5), p.057010. https://doi.org/10.1289/EHP7612

111. Wei, Z., Wang, Y., Wang, S., Xie, J., Han, Q. and Chen, M., 2022. Comparing the effects of polystyrene microplastics exposure on reproduction and fertility in male and female mice. *Toxicology*, 465, p.153013. https://doi.org/10.1016/j.tox.2021.153013.

112. Wu, W.M., Yang, J. and Criddle, C.S., 2017. Microplastics pollution and reduction strategies. *Frontiers of Environmental Science & Engineering*, 11, pp.1–4. https://doi.org/10.1007/s11783-017-0890-1.

113. Xie, Y., Hou, W., Song, X., Yu, Y., Huang, J., Sun, X., Kang, R. and Tang, D., 2016. Ferroptosis: Process and function. *Cell Death and Differentiation*, 23(3), pp.369–379. https://doi.org/10.1038/cdd.2015.158.

114. Xu, M., Halimu, G., Zhang, Q., Song, Y., Fu, X., Li, Y., Li, Y. and Zhang, H., 2019. Internalization and toxicity: A preliminary study of effects of nanoplastic particles on human lung epithelial cell. *Science of the*

Total Environment, 694, p.133794. https://doi.org/10.1016/j.scitotenv.2019.133794

115. Xu, J. and Wang, Z., 2024. Efficient and accurate microplastics identification and segmentation in urban waters using convolutional neural networks. *Science of the Total Environment*, 911, 168696. https://doi.org/10.1016/j.scitotenv.2023.168696

116. Yang, D., Shi, H., Li, L., Li, J., Jabeen, K. and Kolandhasamy, P., 2015. Microplastic Pollution in Table Salts from China, *Environmental Science and Technology*, 49(22), pp. 13622–13627. https://doi.org/10.1021/acs.est.5b03163.

117. Yang, H., Chen, G. and Wang, J., 2021. Microplastics in the marine environment: Sources, fates, impacts and microbial degradation. *Toxics*, 9(2), pp.1–19. https://doi.org/10.3390/toxics9020041.

118. Yang, Z., Wang, M., Feng, Z., Wang, Z., Lv, M., Chang, J., Chen, L. and Wang, C., 2023. Human micro-plastics exposure and potential health risks to target organs by different routes: A review. *Current Pollution Reports*, 9(4), pp.468–485. https://doi.org/10.1007/s40726-023-00273-8.

119. Yan, Z., Liu, Y., Zhang, T., Zhang, F., Ren, H. and Zhang, Y., 2022. Analysis of microplastics in human feces reveals a correlation between fecal microplastics and inflammatory bowel disease status. *Environmental Science & Technology*, 56(1), pp.414–421. https://doi.org/10.1021/acs.est.1c03924.

120. Yates, J., Borthwick, F., Parlee, S., Vrancken, C. and Godwin, H., 2021. A systematic scoping review of environmental, food security and health impacts of food system plastics', *Nature Food*, 2(2), pp. 80–87. https://doi.org/10.1038/s43016-021-00221-z.

121. Yousefi, A., Movahedian Attar, H. and Yousefi, Z., 2024. Investigating the release of microplastics from tea bags into tea drinks and human exposure assessment, *Environmental Health Engineering and Management*, 11(3), pp. 337–347. https://doi.org/10.34172/EHEM.2024.33.

122. Yow, A., 2024. *Microplastic contamination: India assessing exposure among consumers, plans new regulations*. FoodNavigator-Asia.https://www.foodnavigator-asia.com/Article/2024/09/30/microplastic-contamination-india-assessing-exposure-among-consumers-plans-new-regulations

123. Yuan, Z., Nag, R. and Cummins, E., 2022. Human health concerns regarding microplastics in the aquatic environment - From marine to food systems, *Science of the Total Environment*, 823**,** p.153730. https://doi.org/10.1016/j.scitotenv.2022.153730.

124. Zhang, J., Wang, L. and Kannan, K., 2020. Microplastics in house dust from 12 countries and associated human exposure. *Environment International*, 134, p.105314. https://doi.org/10.1016/j.envint.2019.105314.

125. Zhang, K., Shi, H., Peng, J., Wang, Y., Xiong, X., Wu, C. and Lam, P.K.S., 2018. Microplastic pollution in China's inland water systems: A review of findings, methods, characteristics, effects, and management. *Science of the Total Environment*, 630, pp.1641–1653. https://doi.org/10.1016/j.scitotenv.2018.02.300.

126. Zhang, Y., Gao, Q., Xu, M., Fang, N., Mu, L., Han, X., Yu, H., Zhang, S., Li, Y. and Gong, Y., 2025. Microplastics and nanoplastics increase major adverse cardiac events in patients with myocardial infarction. *Journal of Hazardous Materials*, 489, p.137624. https://doi.org/10.1016/j.jhazmat.2025.137624.

127. Zhang, D., Cui, Y., Zhou, H., Jin, C., Yu, X., Xu, Y., Li, Y. and Zhang, C., 2020. Microplastic pollution in water, sediment, and fish from artificial reefs around the Ma'an Archipelago, Shengsi, China. *Science of The Total Environment*, 703, p.134768. https://doi.org/10.1016/j.scitotenv.2019.134768

128. Zhao, Y., Bai, Z., Zhang, W., Zhang, F., Yu, F. and Jiang, Y., 2020. Polystyrene microplastic exposure disturbs hepatic glycolipid metabolism at the physiological, biochemical, and transcriptomic levels in adult zebrafish. *Science of the Total Environment*, 710, p.136341. https://doi.org/10.1016/j.scitotenv.2019.136341.

129. Zhao, Y., Bao, Z., Wan, Z., Fu, Z. and Jin, Y., 2020. *Polystyrene microplastic exposure disturbs hepatic glycolipid metabolism at the physiological, biochemical, and transcriptomic levels in adult zebrafish*. Science of The Total Environment**,** 710, p.136279. https://doi.org/10.1016/j.scitotenv.2019.136279

130. Zhou, X., Wang, J. and Ren, J., 2022. Analysis of Microplastics in Takeaway Food Containers in China

Using FPA-FTIR Whole Filter Analysis. *Molecules*, 27(9), p.2646. https://doi.org/10.3390/molecules27092646.

131. Zhu, L., Zhang, J., Rong, Z., Zhang, Q., Xu, Y., Qin, Y. and Liu, Q., 2023. Identification of microplastics in human placenta using laser direct infrared spectroscopy. *Science of the Total Environment*, 856, p.159069. https://doi.org/10.1016/j.scitotenv.2022.159069

132. Zhu, J., Fan, W., Qiu, Q., Zhang, D., Li, Z. and Zheng, S., 2019. Microplastic pollution in the Maowei Sea, a typical mariculture bay of China. *Science of the Total Environment*, 658, pp.62–68. https://doi.org/10.1016/j.scitotenv.2018.12.192.

133. Zytowski, Eric and Baldermann, Susanne, 2025. Thermal desorption and extraction coupled with gas chromatography and mass spectrometry for the quantification of polystyrene nanoplastic in pak choi. *Rapid Communications in Mass Spectrometry*, 39(14), p.e10046. https://doi.org/10.1002/rcm.10046