Sustainable
Food Technology

ROYAL SOCIETY OF CHEMISTRY

REVIEW

View Article Online
View Journal

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Cite this: DOI: 10.1039/d5fb00847f

Microplastic release from food processing to the environment: contamination pathways, health implications, and sustainability perspectives

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Received 31st October 2025
Accepted 4th March 2026

DOI: 10.1039/d5fb00847f

rsc.li/susfoodtech

Microplastics have rapidly emerged as a key food safety and environmental concern, however their connection with food processing, packaging and human health have not been supported yet with substantial study reported in the literature. Defined as synthetic polymer particles under 5 mm, MPs originate both from intentional manufacturing and from the degradation of larger plastics. This review provides an updated and interdisciplinary perspective by examining the pathways through which MPs migrate from processing equipment, packaging materials, and storage environments into foods, and how these particles subsequently disperse into terrestrial, aquatic, and atmospheric systems. Human exposure to MPs is discussed, primarily through the ingestion of contaminated foods and beverages alongside inhalation and dermal routes. We further summarize available evidence on the toxicological effects of MPs, including oxidative stress, inflammation, and metabolic disruption, and their potential role as the carriers of hazardous chemicals. Advances in detection methods, such as spectroscopic and chromatographic approaches, are critically evaluated, with an emphasis on the current lack of standardized detection protocols. Finally, the review highlights knowledge gaps, regulatory needs, and innovative mitigation strategies, including sustainable alternatives to plastics. By linking food processing, contamination pathways, health implications, and detection strategies, this review offers a comprehensive outlook designed to inform future research, regulatory frameworks, and industrial practices.

Sustainability spotlight

This review highlights the urgent need to integrate sustainability principles into food processing and packaging systems to mitigate microplastic pollution, a critical yet often overlooked sustainability challenge. By tracing the pathways of microplastics from food contact materials and industrial processes to environmental and human exposure routes, the current study highlights the coherence between food safety, ecological integrity, and public health. This review highlights how transitioning toward biodegradable alternatives, circular economy models, and improved waste management strategies can substantially reduce the production of microplastics across the food chain. Moreover, it paves way for research opportunities in green materials, green processing technologies and regulatory harmonization in line with sustainability development goals. Through its holistic synthesis of contamination mechanisms, toxicological insights, and mitigation strategies, this study advances the sustainable transformation of food systems, providing a scientific basis for collaboration among policy, industry, and research toward a plastic-resilient future.

1. Introduction

The numerous benefits of plastics, including their low-cost manufacturing, resistance to degradation, waterproof nature, light weight, and high durability, have resulted in their widespread applications across various industries.[1,2] It is therefore envisaged that the worldwide consumption of plastics would increase considerably, from 464 Mt in 2020 to an estimated 884 Mt in 2050, with an approximate accumulative amount of over 4725 Mt of waste plastics generated from 2000 to 2050.[3] Notwithstanding the advancements in recycling technologies and waste disposal measures, only 21% of global plastic wastes

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are currently being recycled or incinerated, and the majority of them ends up piling up in terrestrial and marine ecosystems.[4,5] Plastics, which were obsolete until the 1950s, acquired immense industrial significance later and are today irreplaceable in different applications such as packaging and building applications, electronics, and medical applications due to their remarkable mechanical strength, thermal resistance, and low costs.[6] The widespread presence of these materials in diverse ecosystems, combined with improper disposal practices, has led to the substantial release of microplastics, synthetic polymer particles smaller than 5 mm in diameter.[7] MPs originate as primary microplastics, which include intentionally manufactured microscale particles and micro-sized fragments formed during the use of consumer and industrial products, and secondary microplastics, which result from the fragmentation of larger plastic debris.[8] From 1950 to 2015, an estimated 6.3 billion tons of plastic materials were produced globally, of which a mere 9% was subjected to recycling processes, 12% was incinerated, and the remaining 79% was disposed of in landfills or directly released into the environment.[9] Currently, over 380 million tons of plastics is being produced worldwide annually, and a substantial amount of these is earmarked for single-use packaging purposes. Upon degradation, the plastics disperse as microplastics and still smaller nanoplastics within the immediate environment. These are found in seawater, rivers, soils, particulate matter within the atmosphere, sea salts, potable waters, seafood, and an array of edibles, including the digestive tracts of marine lifeforms.[8] As a consequence of its minuscule nature and far-reaching distribution, microplastics stand a high chance of being ingested or inhaled by humans during routine eating, drinking, and breathing.[10] Recent analyses indicate the smallest particles have the capacity to cross biological membrane barriers, infiltrate cellular structures, interfere with cellular activities, and evoke inflammatory reactions.[8] However, the extent to which the prevalent microplastics in human tissues will give rise to substantive consequences on health is not clearly known. This continuing ambiguity can be attributed to ethical constraints associated with sampling methodologies, technological impediments in microplastic detection, and the scarcity of suitable long-term experiments on human subjects.[8,9] The health risks associated with microplastics depend mainly on the size of the particles, their chemical nature, the duration of exposure and the biological nature of the tissue that is exposed.[11,12] The fact that microplastics can adversely affect cellular structures, tissues, and whole organ systems *in vitro* under highly controlled laboratory conditions, and thus with a high degree of credibility, raises grave concerns over human health issues. Since there is growing evidence of the occurrence of MP in the food system, the purpose of this review is to.

- Systematically examine the primary and secondary pathways through which microplastics originate, migrate, and accumulate in food processing, packaging, distribution, and storage systems.
- Evaluate human exposure routes and associated toxicological implications, with emphasis on ingestion, inhalation, and dermal contact linked specifically to food-processing and food-contact environments.
- Assess current analytical techniques and emerging sustainable strategies to detect, monitor, and mitigate microplastics across the food industry, while identifying gaps that require future research.

2. Sources of microplastic contamination in food processing

2.1. Primary sources of microplastics in food processing

Microplastics could potentially contaminate food products at various stages in the processing environment, especially when food ingredients come into contact with equipment, surfaces, or process water that is contaminated with microplastics (Fig. 1

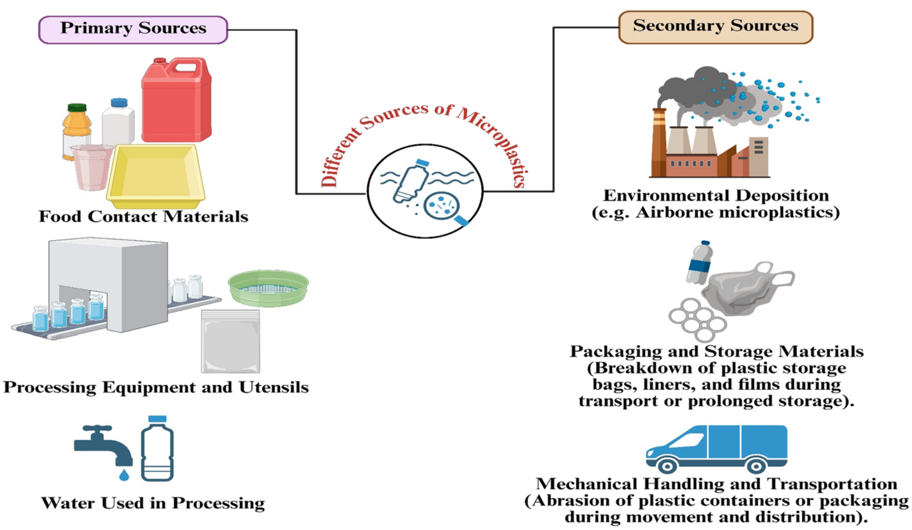

Fig. 1 Primary (within processing lines) and secondary (after packaging and distribution) sources of microplastics in food processing and handling.

Table 1 Sources and pathways of microplastic contamination in the food chain

Processing stage	How microplastics enter	Typical polymer types	Source of microplastic release	Examples of food products affected	References
Raw material handling (harvesting, unloading, sorting)	Abrasion from crates, bins, mesh bags; environmental deposition; soil and water adherence	PE, PP, PA, PES	Transport crates, packaging sacks, mesh bags, contaminated soil/water	Fruits, vegetables, grains, nuts, seafood	12–15,18, 20,21,25–27
Washing and cleaning	Release from hoses, tanks, PVC pipes, gaskets, pump seals; contaminated wash water	PVC, PP, PE	Water hoses, cleaning tanks, pipe linings, rubber/plastic seals	Fresh produce, fish, meat, spices	
Cutting, peeling, grinding, slicing	Wear from cutting boards, blades with polymer coatings, HDPE surfaces; conveyor belt friction	HDPE, LDPE, PP	Cutting boards, conveyor belts, polymer-coated blades	Meat cuts, vegetables, cheese, spices, flour	
Mixing, blending, kneading	Shedding from mixers, paddles, polymer-coated shafts, lining materials	PP, PE, PA	Mixer bowls, paddles, internal linings, rotating shafts	Dough, batter, sauces, dairy mixtures	
Thermal processing (boiling, frying, blanching, pasteurizing)	Heat-induced degradation of plastic utensils, non-stick coatings, polymer containers	PTFE, PP, PE	Non-stick cookware, polymer ladles, food-grade plastics exposed to heat	Ready-to-eat meals, soups, bakery fillings	
Filtration, sieving, straining	Release from nylon or polyester mesh filters, cloth filters, sieves	PA (nylon), PES, PP	Strainers, filter cloths, nylon mesh	Tea, coffee, juices, milk products	
Packaging (primary and secondary)	Migration from films, trays, bottles, caps, laminates; tearing and sealing processes	PET, PP, PS, PVC	Plastic films, multilayer laminates, PET bottles, PP caps, PS trays	Bottled water, snacks, meat, bakery items	
Filling and sealing	Friction at sealing jaws, cap torque application, wearing of liners and gaskets	PP, PET, PVC	Sealers, capping machines, gaskets, liners	Beverages, oils, sauces, spreads	
Cold chain and storage	Film cracking, tray deformation, freezer brittleness; abrasion during stacking	PS, PE, PP	Freezer trays, PE wraps, cold storage packaging	Frozen foods, dairy, seafood	
Transport and distribution	Vibration-induced abrasion of packaging materials and pallet films	PE, PP, PET	Pallet stretch wrap, secondary packaging films	All packaged products	
Retail display and handling	Repeated opening, surface rubbing, environmental deposition, film wear	PE, PP, PES	Wrapper films, retail trays, display packaging	Fresh produce, bakery, meat	
Consumer food preparation	Heating in plastic containers; microwave-induced wear; cutting on plastic boards	PP, PE, PS	Microwave containers, plastic bowls, cutting boards	Ready meals, leftovers, reheated foods	

and Table 1).[13,14] The use of plastic in food processing is widespread due to its flexibility, ease of cleaning, chemical resistance, and cost-effectiveness; however, plastics are prone to degradation due to mechanical, thermal, and chemical stress. To ensure that the food production process is clearly understood and the role of microplastics in food products is properly illustrated, the addition of microplastics to food products is described below in five major stages of food processing: raw material processing, washing, mixing and grinding, heat processing, and filling and sealing.

2.1.1. Raw material handling and extraction. The primary potential route for microplastic entry into the system is during handling, processing, and extraction of raw materials. This phase includes activities such as sorting, trimming, cutting, peeling, dehusking, descaling, shelling, and size grading, which are mainly carried out using polymer-based equipment (such as high-density polyethylene HDPE cutting boards, polypropylene PP crates, nylon sorting belts, and plastic composite trays). Frequent contact and friction between food commodities and these materials lead to the abrasion of polymer surfaces and the creation of microplastics that can stick to or be embedded in the food material.[15] In fish processing plants, for example, descaling or filleting is carried out on HDPE boards. The HDPE material is abraded due to repeated use of knives, scraping, and washing, and microplastics can be captured in the grooves formed by the movement of blades and released during subsequent processing cycles.[11,12] More or less the same applies to crustaceans and molluscs that are processed using polypropylene baskets, as the shells and exoskeletons of seafood abrade against polymer surfaces, causing polypropylene to be released in the form of microplastics.[12,16] Sorting conveyor belts and trimming tables used in fruit and vegetable processing are constantly subjected to the abrasive effects of heavy produce such as root vegetables, pumpkins, and melons, resulting in the continuous abrasion of the polymer surfaces.[12,16] Another significant source of microplastic pollution is dry commodity handling, which includes grains, beans, spices, tea leaves, and coffee beans. Other common applications of plastic composites or polyethylene are in equipment such as hoppers, funnels, milling chambers, or storage silos, where they are used to prevent corrosion and caking.[12] Nevertheless, as the grains pass through the processing system, the contact between the moving grains and plastic linings causes micro-abrasions to form microplastics prior to milling or grinding. A combination of these sources of microplastic pollution demonstrates that the processing of raw materials is not a minor contributor but a consistent and primary source of microplastic pollution, arising from the food chain.

2.1.2. Washing and water-based operations. Washing and hydration are among the most serious contamination paths, since direct and extended contact of food with large amounts of water takes place. Municipal water infrastructure, household distribution pipes, recycled industrial water systems, and bottled water may be sources of microplastics in the water network.[17] Untreated tap water may contain fragmented polyethylene, PVC, or polypropylene particles, which may be released from old pipelines or water treatment remnants. Across industrial processing systems, recirculation water in vegetable washing lines, fruit-flumes, and seafood rinsing tanks accumulates larger quantities of microplastics over time, especially in circumstances where filtration mechanisms are unable to remove particles smaller than 2050 μm.[11,18] Small-scale processors and artisanal beverage producers have also been reported to produce bottled water that contains high concentrations of microplastics, with most of them being generated from the bottle tops and inner surfaces of the polyethylene terephthalate (PET) bottles during their transportation and handling. Microplastics in water attach to natural surface discontinuities, porous surfaces, and biofilms of leafy vegetables, tomatoes, berries, and root crops during vegetable and fruit washing. During seafood rinsing processes, the MPs can become lodged in gills, crevices, and soft tissues following successive exposure to washing tanks constructed from PP or fiberglass-reinforced plastic. Furthermore, in cleaning systems, the washing brushes and rollers that are used are covered with polymer bristles that slowly deteriorate when stressed under mechanical forces, which is another source of microplastic release.[11,12,18,19] Therefore, washing serves not only as a source of extrinsic contamination (*via* water), but also as a mechanical one (because of friction caused by plastic-based washing tools). Along with the dual contamination route, this step is one of the most important sources of primary microplastic penetration into fresh and minimally processed food.

2.1.3. Blending, mixing, and grinding. Mechanical interactions between food components and plastic materials can be intensified in mixing and grinding processes, which involve massive mechanical processing sequences such as shearing, crushing, cutting, folding and tumbling of the food components. Polymer-coated paddles, scrapers, bushings or linings are common, with polyethylene, polyurethane, polycarbonate, polypropylene or PVC used in general processing plants employing high-shear mixers, ribbon blenders, dough kneaders, tumbler drums, and spice grinders. These plastics are subjected to constant friction and mechanical forces, which can increase the release of microplastics.[11,15,20] In bakery processing, dough mixers with polyurethane or nylon scrapers show surface wear during kneading cycles, leading to the release of plastic particles into the dough or batter. In the confectionery industry, candy polishing coating drums have polymer-lined interiors, which suffer from abrasions upon contact with sugar crystals and powdered flavorings. Grinding processes are more dangerous, with spice, cereal, and coffee bean grinding involving particle collisions and interactions with container surfaces, thereby increasing surface wear of plastic liners and hoppers. Meat marinating drums and sauce blenders also produce microplastics due to abrasive interactions among ingredients such as salt crystals, spices, and acids. Even in low-shear mixing processes, the presence of water, fat, and mechanical energy leads to the release of microplastics from surfaces.[11,20,21] Taken together, these findings suggest that mixing and grinding are high-risk processing steps for microplastic production because of the high degree of mechanical processing involved.

2.1.4. Thermal processing (heating, boiling, steaming, and pasteurisation). Thermal processing is one of the largest but most neglected sources of microplastic pollution; in this process, high temperatures can accelerate the degradation of polymeric food-processing equipment. Additional factors such as pressure fluctuations, water, and movement may result in high-temperature conditions, which crack, soften, warp, and chemically degrade plastic materials and therefore contribute to higher chances of microplastic leaching. Dairy processing consists of pasteurizers and homogenizers that involve the use of polymeric materials in the form of gaskets, seals, and O-rings, which are subjected to repeated heating and cooling, causing a decrease in material strength.[22] Consequently, minute fragments of elastomeric or polymeric materials drain into the milk or other liquid foods. Polymeric materials (high-temperature silicone seals) in steam processing lines and ready-to-eat food processing of vegetables, noodles, and meat products can degrade under the pressure of steam and thermal expansion. Hot filling (filling foods at temperatures greater than 80–90 °C) produces more friction between hot foods and polymer-coated nozzles or gaskets, thereby subjecting them to microplastic formation. Boiling kettles, retorts, and continuous blanchers of polymers may degrade because of a combination of mechanical and thermal forces. Increased temperatures may also decrease the strength of food-contact surfaces so that they are more likely to be abraded by stirring and agitation. Thus, thermal processing is both a direct and indirect contributor to microplastic pollution, particularly in liquid and semi-liquid food systems where the heat-transfer device has significant contact with foods.[4,12,21]

2.1.5. On-line packaging, sealing and filling. The last stage of primary contamination is associated with filling, sealing and packaging. These are processes that involve high-speed machinery and polymer-packaging materials that are continuously in frictional contact with machine components. During the bottling process, for example, microplastics can be generated by friction between the polyethylene terephthalate (PET) bottle necks and polypropylene or high-density polyethylene (HDPE) bottle caps. Heat-sealing lines made of polyethylene, polystyrene, or laminated materials can also generate microplastics, which are released into the packaged products as the films tend to be softened and become exposed to mechanical forces. Microplastics are also generated by tube fillers, pouch packers and form-fill-seal packaging machines that operate at high speeds, due to abrasion caused by polymer gaskets and nozzles in constant frictional contact with machine components.[11,16,21] Microplastics are also generated by the vibration of conveyor rollers, bar abrasion and high-speed contact with plastic films. It is experimentally proven that expanded polystyrene packaging materials, plastic-lined wrappers, and disposable containers emit more microplastics when exposed to heat or friction.[23,24] In food-processing operations, filling, sealing, and on-line packaging are considered primary sources because they occur in the processing line, and the packaging materials and food have direct contact during production. In comparison, microplastics that are formed as a result of packaging decay during storage, transportation, or distribution can be regarded as secondary sources because they appear after the processing has taken place.

2.2. Secondary sources of microplastics

Secondary contamination takes place after the food has exited the production line and is primarily linked with the decay of packaging containers during storage, transportation, distribution and retailing processes. Whereas primary sources are the result of direct interaction of food and processing equipment, secondary sources involve the release of microplastics due to physical loads on the packaged food, temperature variation, vibration, or long durations of storage. Here, packaging performs quite differently compared to the on-line packaging steps outlined in Section 2.1.5. On-line packaging occurs in the processing space and it entails direct contact with the equipment, so it is a primary source. Conversely, the degradation of packaging materials that occurs once the processing is finished comes out as a secondary source since it does not occur on the production line. Packaging materials such as expanded polystyrene, plastic-lined packaging, bottle caps, and closure systems have the potential to leach microplastics. The degradation of these plastics is increased when they are subjected to heat, friction, pressure, or storage conditions, and it is easy for microplastic particles to migrate into ready-to-eat and stored foods.[23,24] Indicatively, packaging materials of fast food and plastic-lined paper wrappers and trays have been found to accumulate and liberate microplastics, particularly when subjected to high temperatures or when stored for longer durations.[16] Another source of secondary contamination is through environmental deposition. Microplastics that are present in indoor airways, especially microfibers in clothing, plastic dust and parts of ventilation systems, will tend to deposit on food surfaces. In certain cases, where air filtration is low or storage facilities are not optimal, it is believed that the likelihood of microplastics being present in the surrounding air increases substantially. Further release of microplastics may also occur due to improper handling or through contact of the surfaces. During food transportation and distribution, mechanical stress, temperature fluctuations, and continuous handling of packaging materials can accelerate their degradation, leading to the release and transfer of microplastics from the packaging into the surrounding environment or the food itself. As an example, plastic packages used for rice, dried spices and dehydrated food may fracture during long-distance transportation, releasing even more plastic particles into these foods.[11,16]

2.3. Influence of the food type

The extent of microplastic pollution depends on the type of food, and the marine foods are more susceptible to microplastic contamination. Especially small fish consumed as whole poses serious health risks, due to the accumulation of the microplastics in the gastrointestinal tract of seafoods.[28] Bivalves and filter-feeding organisms are particularly vulnerable owing to the feeding modality of these organisms, which tends to encourage the ingestion of plankton-sized pellets of plastic. Various commercially available food items, such as fish, sea salt, honey, beer, and bottled water, have been reported to contain detectable levels of MPs.[7,29,30] Contamination of foods can arise not only from exposure to the environment but also from contact with processing lines and packaging material surfaces.[31] In addition, inhalation of MPs and dust airborne during food packaging and processing is also a growing exposure pathway.[29] Furthermore, microplastics are made of diverse polymeric materials, produced at microscale level due to the degradation of macroplastics. In seawaters, MPs are similar to plankton and often provide surfaces for the attachment of microbes. This micro-ecosystem is known as the plastisphere and may harbour bacteria of potentially pathogenic species of *Vibrio*, which also introduces another dimension of health risk.[32]

3. Pathways of microplastic contamination from food processing to the environment

3.1. Direct pathway

Some of the most prominent direct sources of microplastic pollution are the processing and packaging of food. During these stages, microplastics may get released into food products through the direct contact at the primary packaging stage, particularly when the package is subjected to thermal treatment or mechanical damage. Important sources are plastic belts, storage containers, covering films, and machine parts.[8] Processes that are highly thermal, *e.g.*, sterilizing or microwaving in plastic containers, are likely to accelerate the movement of microplastic particles and additives, *e.g.*, bisphenol A (BPA) and phthalates, to foods.[10]

3.1.1. Waste disposal. Waste disposal is a significant direct route through which microplastics can find their way into the environment; its contribution is based on the nature of the food processing operation, the waste produced, and the handling mechanisms. The food industry generates a large range of solid, liquid, and sludge-based wastes containing plastic debris due to equipment wear, packaging remnants, and handling materials. The disposal of such waste, when inadequately treated, results in a gradual breaking down of the waste into microplastics that permeate the soil, water masses, and sewage systems. The solid processing of food waste often carries plastic waste due to the high plastic content in the packaging and handling systems, as well as the high use of polymer-based products in food processing.[11,12,33] Bakery and confectionery departments produce scrap polyethylene and multi-layered laminate polypropylene trays in packaging. In landfills, these materials break down to microplastics due to sunlight, moisture or mechanical abrasion. PET bottles, caps, and closures are disposed of by beverage plants, which break down into smaller sizes upon exposure to the environment. Moreover, the solid waste from seafood and meat processing facilities includes the remains of HDPE cutting boards, polypropylene crates, and expanded polystyrene trays used during storage and transportation. When these plastics are exposed to moisture and changes in temperature, they degrade to produce microplastics that are discharged to the soil or, in coastal regions, by run-off and tidal currents.[7,9] Liquid and effluent streams of waste are significant, on aggregate, and frequently show greater concentrations of microplastics than solid waste. One of the main sources of microplastics is the wastewater from fish processing plants due to the regular washing, cleaning, and descaling of the equipment, which leads to the release of high volumes of microplastics from polypropylene (PP) baskets, high-density polyethylene (HDPE) trays, and nylon fishing nets. A critical issue involves wastewater laden with suspended microplastics, which enters drains and ultimately flows into rivers and aquatic systems.[12] Dairy and beverage industries are also sources of microplastics, which are emitted during cleaning-in-place, during which chemicals and high temperatures are used; these processes speed up the degradation of polymer seals, filters, valves, and linings, leading to the release of microplastics into wastewater.[22] The absence of filtration results in wastewater entering water bodies directly, leading to microplastic pollution. Sludge generated by on-site wastewater treatment plants is linked to the third important source of microplastic pollution. Sludge serves as a reservoir of microplastics containing the remnants of cleaning agents made of polymers, fibers of clothing from the workers, and even trash left by processing machines. When such sludge is applied as conditioning soil in the agricultural sector or when deposited in unlined pits, a large portion of the microplastics is transmitted into the soil. Such microplastics may be left in the soil environment, migrate to the root zone, be washed away by groundwater, or carried away by wind and precipitation.[33] Liquid effluent of seafood processing facilities often contains elevated levels of microplastics, probably because of the large amount of water used during cleaning and handling processes. The treatment systems can also serve as a potential reservoir of sludge, and it is likely that microplastics will be released in the event of disposal. Solid waste can also include significant levels of plastic fragments, but its effect on environmental release is usually slower. Taken together, these streams of waste can lead to microplastic dispersion, and the significance of each of the pathways may differ depending on the practices of processing and waste management.[34–37]

3.1.2. Emissions from processing facilities. Another direct route through which microplastics can find their way to the immediate environment is through the emissions of food processing plants. Most food manufacturing processes, such as grinding, mixing, packaging and sanitation, produce airborne microplastics that are spread *via* indoor air and ultimately emitted with the release of air through ventilation systems. The sources are abrasion of polymer conveyor belts, wear caused by friction of HDPE or polypropylene cutting parts, and the shredding of thin plastic films within packaging units.[38–40] Packaging departments are known to generate plastic dust in the air where multilayer films, shrink wraps, and laminated sheets are sliced, sealed, or subjected to thermoprocessing. These tiny scraps are suspended in the atmosphere and deposited on machinery, floors, and food-contact surfaces before being washed off during cleaning.

Flour mills, spice mills, coffee mills and cereal mills are also sources of airborne microplastics. These sectors employ plastic-lined hoppers, storage bins and pneumatic transfer systems, which continuously vibrate as the materials pass through the equipment. This liberates small particles of polymer that are mixed with the dust produced during milling and grinding.[16,40] The fibres of the workers' clothing and the personal protective gear are also synthetic and release fibres into the air when the workers move around the processing plants. Over time, microplastics accumulate in ventilation ducts and are released into the outdoor atmosphere at a minimal rate.[6] Processing plants that do not perform well with respect to air filtration or dust removal become point sources of microplastics that add to the atmospheric load and are deposited on soil and in water bodies.

3.2. Indirect pathways

Another major possible source of microplastic contamination is the transportation of food commodities packaged in plastic wrappings or containers. Long-distance delivery of goods causes changes in temperature and mechanical strains that lead to tearing of the wrapping material, ultimately causing microplastic dust to be deposited on the surfaces of edible goods or in the immediate surrounding environment.[4] Furthermore, emissions of transport fuel and tire wear from transport vehicles contribute to microplastic buildup on the roadway and soil ecosystems.

3.2.1. Consumer behaviour. One of the most significant indirect causes of microplastic contamination is packaging degradation. Food packaging plastics, such as polyethylene terephthalate, polypropylene, polystyrene, and multilayer laminates, are subjected to constant physical, thermal, and environmental pressures. In storage and transportation, the packaging materials are subjected to temperature differences, pressure differences, vibration, and mechanical force.[21,38,40] The impact of mechanical forces on polymeric materials challenges the integrity of the material and leads to the development of micro-fragments that are scattered around the environment. EPS trays, which are food packaging trays, used in packing meat, fish and vegetables, tend to get cracks upon changes in thermal conditions, resulting in the release of tiny fragments of polystyrene. Fast-food restaurant wrappers are commonly made of plastic-coated paper, which has high emission rates of microplastics, particularly when stored over long periods or when the wrappers contain warm or oily food.[23] Drinks packaged in bottles made of polyethylene terephthalate (PET) are also among the most densely emitting sources of microplastics; microplastics are released during opening and closing operations (cap and neck sections) and during their transportation and storage. The disposal of packaging materials in the open environment leads to faster degradation of the materials since solar radiation, mechanical forces, and other environmental factors break down the materials to eventually form microplastics and nanoplastics.[4] Microplastics generated from the breakdown of packaging containers tend to accumulate in soil, freshwater, and drainage systems, and this process is believed to be a major global source of microplastic pollution due to the high use of food packaging containers.

3.2.2. Environmental pathways. Environmental deposition is the atmospheric transfer of microplastics onto food surfaces, packaging, processing equipment or storage containers. Sources that produce airborne microplastics include urban dust, vehicles, textile fibers, construction debris, and industrial processes. Airborne deposition in food processing plants refers to the deposition of microplastics from the environment on food or food-processing equipment. Furthermore, inadequate ventilation, open processing lines, and inadequate air filtration increase the deposition of particles on surfaces, floors, and conveyors.[6]

Deposition is a complex process that takes place in open markets, cold storage units, and distribution centers where foods are packed without sealed protective packaging. Airborne fibers of polyethylene, polypropylene, and polyester are found in the atmospheres of urban areas and are deposited on both packaged and unpackaged foods during unloading, sorting, and marketing. The deposited materials are then removed through waste streams during cleaning or become attached to packaging materials, which degrade into microplastics upon disposal.[11,12,14,15] Environmental deposition of microplastics is a complex transport process, and the atmosphere is the major vector through which microplastics are transported from food-processing environments to the natural environment.

3.2.3. Airborne microplastics. The generation of microplastics is also closely associated with supply chain activities and manufacturing processes. The microplastics are generated as a result of the natural dynamics of vibration, friction, compression, and temperature fluctuations experienced by packaging materials.[25] Flexible plastic packaging of rice, cereals, lentils, spices, and dried foods undergoes internal friction generated by interactions between the product and the inner surfaces of the packaging, which can result in the generation of microplastic particles embedded in the packaged product.[41,42] The cold chain logistics associated with frozen foods further aggravate this problem by generating temperature variations over a wide range: from very low to relatively higher temperatures. Temperature variations also affect packaging materials such as trays, films, and laminates. At the consumer level, microplastics can be generated through microwave reheating, adding hot liquids to plastic cups, or storing oily and/or acidic foods in plastic containers, which can accelerate plastic degradation.[10] As a result, these microplastics are discharged into the domestic waste stream, sewage systems, composting plants, or landfills, ultimately accumulating in the environmental reservoir of microplastics.

4. Environmental impacts of microplastics from food processing

4.1. Aquatic ecosystems

Being the byproduct of food packaging materials and processing, microplastics are a recent pollutant that has been detected in oceans and freshwater systems. Microplastics are produced by abrasion, degradation, and photolysis, and are released into sewage systems and distributed by rivers, ponds, coastal areas, and aquaculture systems, where they are suspended or deposited in the bottom sediments. Due to their small size and ability to persist, the microplastics are absorbed by plankton, fish, and bottom-living organisms, thereby affecting their feeding, nutrient, and physiological processes.[19] In addition, microplastics serve as channels for the transportation of pesticides, heavy metals and pathogens, which are subsequently released as contaminants *via* predator–prey relationships in the aquatic food web.

4.1.1. Marine contamination. Marine ecosystems ultimately act as the terminal destination of microplastics emitted during various phases of food processing, handling, management, and packaging. The major routes that allow these particles to gain entry into terrestrial and freshwater ecosystems include the discharge of untreated or partially treated wastewater, stormwater-driven runoff, and the illicit dumping of plastic waste. In marine ecosystems, microplastics show a high degree of resistance to decomposition and can remain suspended within sediments for long periods, thereby imposing considerable ecological demands. The process raises considerable concern because the seas and oceans of the world host massive biodiversity, comprising plankton, hard and soft corals, molluscs, crustaceans, fish, seabirds, and marine mammals.[43,44] Many organisms found within these ecosystems ingest microplastics directly, thus suffering mechanical damage, loss of feeding efficiency, and suppression of growth.[44] In molluscs during the planktonic larval phase of their life, microplastics can cause damage to loosely attached structures and important internal organs. Beyond the immediate effect of causing mechanical damage, microplastics interfere with major ecological processes such as nutrient cycling and habitat integrity and thus destabilize trophic webs of the seas.[45] In addition, microplastics act as transporters of harmful chemicals and pathogens. Their hydrophobic surfaces have adsorption sites for persistent organic pollutants, petroleum hydrocarbons, and heavy metals. These contaminant-laden microplastics can then transfer through trophic levels *via* biomagnification, ultimately accumulating in apex predators, including commercially important fish species. Besides undermining the stability of marine ecosystems, the process has critical implications for seafood safety and the health of the population.[46] The issue involves sensitive ecosystems, including valuable and sensitive reef systems around the world, where the accumulation of microplastics at a particular location inhibits transmission of light and subsequently interferes with the photosynthetic activities of the symbiotic algae, eventually reducing the structural integrity of the reef. Floating microplastics also decrease light reception by phytoplankton and, thus, inhibit primary productivity and microbial processes required to fix carbon. This impairment of various processes does not allow the marine bodies to effectively fight against climate change and it exposes them to exposure to extreme temperatures and acidity. Control of this international issue requires enhanced garbage-disposal systems, stricter control over human activity in the industrial spheres, and unification of sustainable manufacturing operations.[45,47]

4.1.2. Freshwater contamination. Rivers, lakes and reservoirs are the major pathway for the release of microplastics. Since freshwater systems are closer to human populations and industries compared to the marine ecosystems, they tend to be major sources of localized pollution. The effluents released by food preparation industries, run off from garbage dumps that have not been properly controlled, and the fragmentation of littered plastics are the primary vectors of this contamination.[48,49] Microplastics may be spread over the whole column of water or embedded within sediments, with their persistence and subsequent release contributing to significant ecological risks. Ingestion of microplastics by zooplankton, benthic invertebrates and amphibians may affect their ability to consume food, give spurious hunger signals, and take up energy stores. At high trophic levels, the predation of these species results in gastrointestinal tract injury and induces taxa-specific reproductive dysfunction and growth-related shifts, thus propagating cascade effects within the food webs in respective ecosystems. It is revealed that some of the freshwater species provide the insight about the entire ecosystem in the energy flux driven food webs. Besides their environmental value, microplastics influence the workings of ecosystems and water quality.[48] Microplastics are known to participate in microbial facilitation webs and could lead to cascades in nutrient cycling, decomposition rates and dissolved gas movement. In addition, microplastics can adsorb heavy metals, pesticides, and drugs, thereby increasing their toxicity on biodiversity. Moreover, microplastics may accumulate in sediments, with consequences for the sediment properties and benthic organisms that engage with sediment substrates, particularly when a substrate is patterned in a particular way. The freshwater ecosystems serve as vectors, which transport microplastics between terrestrial, estuarine and open-ocean ecosystems. The control of contamination may be considered by the ecological condition of the water bodies, the regulations related to the production of effluents, and food systems to validate the biodiversity, water quality and marine ecosystems.[48,49]

4.2. Terrestrial ecosystems

The terrestrial ecosystem encompasses much lesser area than the aquatic ecosystem, that may serve as sources and sinks of food packaging and degradation of plastics resulting in the leaching out of microplastics. The most common pathways by which microplastics enter terrestrial ecosystems are littering, landfill leachates, land application of sewage sludge and manure, and atmospheric deposition.[33] Microplastics can persist in soil for up to several decades. The movement of microplastics into deeper layers of soil is determined by the size of the particles and other physicochemical characteristics. It has been suggested that the presence of microplastics in soil can impact the soil structure, water-holding capacity, and soil fertility, thereby affecting the growth and productivity of plants. Earthworms and nematodes absorb microplastics as soil organisms, which can affect their reproduction, burrowing behaviour, and nutrient cycling in the soil.[33,50,51] Moreover, microplastics can also affect microbial communities, reduce the rate of decomposition, and potentially contribute to the spread of pollutants, thereby threatening the health of the soil and its sustainability in agriculture.

4.2.1. Soil contamination. Soil contamination by microplastics due to various agricultural practices and packaging is global concern compromising ecological integrity and food safety.[52] Contrary to the seas and sea surfaces, whereby the process of dilution and dispersion dilutes the deposits of plastics, soils act as century-long storage facilities and hence provide the plastics with persistence due to the long-lasting property of degradation. Plastics enter soils by different routes, including dumping of packaging material on soil surfaces and contamination from leachates, sewage, manure, irrigation and wastewater.[51] Once incorporated into soil matrices, particulate plastics alter the physical and chemical characteristics of the soil. These changes modify soil structure by promoting bulk densification and altering the texture, which, in turn, affects aeration, water infiltration, and root penetration. These kinds of changes lead to infertility of the soil and inhibition of crop production. Also, plastic fragments offer delivery systems for pesticides, heavy metals, and persistent organic poisons, thereby increasing the toxic load within the soil and facilitating the transfer of these chemicals into crops.[50–52] The presence of soil microflora with different species like nematodes, springtails and earthworms consume microplastics due to the availability of organic matter. Its consumption leads to reproductive capacity suppression, loss of biomass, and disturbance of ecological aerations and nutrient cycles. Moreover, plastic surfaces also offer colonization foci for opportunist and pathogenic fungi and bacteria that outcompete the native populations of fungi and bacteria and disrupt the processes of organic matter decomposition and carbon sequestration.

A second cause of concern centers on the absorption of micro- and nano-plastic particles by crop root hairs, resulting in the introduction of such particles into the food system and human diet.[33] The long term exposure to the microplastic contamination may pave way for depletion of soil fertility, affecting sustainable agriculture as well as human health. Efficient management requires strict adherence to regulations controlling the correct disposal of plastics in landfills, new studies into effective technologies for product encapsulation, and enhanced attention to the study of soil-microplastic interactions.

4.2.2. Wildlife impact. Food production and packaging processes result in microplastics that have impactful effects on wildlife in terrestrial, fresh-water, and marine ecosystems.[33,43,49,50,53] Due to their small size and resemblance to natural particulate foods, microplastics are easily taken up by different organisms, including zooplankton, benthic invertebrates, fish, birds and terrestrial mammals. Consumption normally causes blockages of the gastrointestinal tube, false fullness, and the inability to absorb nutrients, and eventually causes retarded growth, reproduction, and survival.[46] Filter-feeding bivalves such as mussels and clams are highly vulnerable as they continuously release microplastics when they filter suspended particles, thereby compromising their feeding and physiological performances. When contaminated prey is consumed through direct ingestion, predatory animals subsequently accumulate additional loads of plastics and associated toxicants, leading to further bioaccumulation and biomagnification within the food web.[43] Such an endpoint is represented by seabirds that are dependent on fish and plankton, and there are records of plastic gruel in the stomachs of birds, leading to internal injuries, reduced fitness and reduced success in breeding.[45] On land, ruminants swallow plastics attached to grasses and soils, whereas insects, including pollinators, experience diminished foraging efficiency and survival. Besides ingestion, microplastics also physically interact with gills, wings, or fur, hence affecting locomotion, foraging, and predator evasion.[51] Besides biological impacts, microplastics also affect species richness, keystone species, and reduce overall biodiversity. The created ecosystem inequalities are also projected to enhance the effects of climate change, pollution, and habitat destruction, which together form a significant threat to biodiversity.[51] To mitigate this problem, there is a need to employ preventive measures to reduce plastic pollution from the food industry.

4.3. Ecosystem disruption

Microplastics originating from food preparation and packaging have been found to have substantial ecological significance because of their interaction with various species and assemblages of the ecosystem.[11,15,53] The ability of microplastics to migrate, persist, and accumulate in high amounts leads to their extensive distribution in the ecosystem. Microplastics are non-biodegradable, unlike other pollutants, which makes their continuous accumulation and impact on the ecosystem more severe. The impact of microplastics on the ecosystem is caused by the disruption of microbial communities. Microplastics provide habitats for opportunistic and pathogenic microbes, which develop and thrive in these new environments, while simultaneously reducing the amount of beneficial microbes.[51,53] This can lead to the disruption of critical ecological processes, such as the decomposition of organic matter, dinitrogen fixation, and carbon sequestration. In aquatic ecosystems, this can significantly affect water quality and the concentration of dissolved oxygen, while in terrestrial ecosystems, it can affect soil quality, agricultural productivity, and vegetation.[49,50] A second mechanism is the ingestion of microplastics by a wide variety of species, such as zooplankton, birds, mammals, and invertebrates. The ingestion of microplastic particles causes physiological harm and decreases reproductive rates and population numbers, with the population-level impact being considerably more adverse in keystone populations.[45,47–49] Decreased population numbers have a negative impact on trophic cascades and cause top-down effects due to decreased plankton in major water layers or decreased plant pollination in terrestrial ecosystems. In addition, microplastics have direct habitat-related effects. The presence of microplastics in terrestrial and aquatic sediments changes chemical and physical properties, which have negative effects on benthic organisms, while the accumulation of microplastics in coral reef habitats, whether hard or soft, reduces light transmission and negatively affects reef structure.[47,48] In terrestrial ecosystems, microplastics change soil properties and decrease water infiltration, with secondary effects on plant survival and organism activity, thereby affecting soil function.[50] These large-scale effects represent significant threats to ecosystem services that are critical to human health, including water filtration, nutrient cycling, and climate regulation.[33] To counteract these effects, it is necessary to decrease plastic inputs simultaneously with habitat restoration in disturbed regions.

5. Health Implications of microplastic release from food processing

Food contact materials that give rise to microplastics differ depending on the polymer type and the specific use of the polymer in the processing and packaging systems. Polyethylene terephthalate is widely used in bottles, trays, and beverage containers, while polypropylene is used in caps, closures, and hot-fill products. Polyethylene, in both high-density and low-density forms, is extensively utilized in films, liners, and flexible packaging, whereas polyvinyl chloride is employed in tubing, gaskets, and certain conveyor components. These uses are directly related to the category of materials listed in Table 1, which are most closely related to food-related exposure to microplastics. Exposure of humans to microplastics (MPs) is primarily *via* three major routes: ingestion, inhalation, and dermal exposure.[54] Ingestion is considered the dominant pathway and involves the consumption of MPs *via* foods and beverages. Microplastics (MPs) have been found to abound within a very large spectrum of edible products, including seafood, mussels, fruits and vegetables, meat, cereals and legumes, sea salts, sugars, and drinks.[55] The major polymers that represent the MPs within food and beverages include polypropylene (PP), polyethylene terepthalate (PET), PVC, polyethlyene including LDPE and HDPE respectively.[55] Additionally, another pathway through which MPs can be breathed in is significantly narrowed down to indoor and urban areas. Microplastics can enter the air through various emission processes, including textile and rubber tyre breakdown, building exterior emissions, and resuspension of aerosols after their initial deposition.[56] Airborne microplastics primarily comprise man-made fibers and particulate matter emitted from PP, acrylics, polyester, polyamide (PA), and PE.[25,57] Although attracting less attention, dermal exposure is another significant pathway; this can arise through contact with MPs contained within personal care and cosmetic products, and within households through a portion of the ambient dust, and upon contact with manmade textile fibers. Cosmetics that contain fibers and microbeads, along with particles that shed from clothes, represent a significant pathway of exposure to PE, PP, PET, and nylon through the dermis.[54]

In summary, there are three major routes through which MPs can enter the human body: ingestion, inhalation, and dermal contact. As discussed above, ingestion of MPs can occur from foods and drinks contaminated by MPs. Inhalation of MPs can happen through airborne particles originating from synthetic textiles, urban dust, and rubber tyres.[58] Dermal exposure to MPs that can be present in cosmetic products, textiles, or dust may occur through wounds, sweat glands, or hair follicles.[59,60] These routes will be further explained in the following sections.

5.1. Ingestion

Major human exposure to microplastics is through ingestion.[57] This exposure pathway is confirmed by the fact that microplastics are found in human feces; the most common polymeric substances are polyethylene terephthalate, polyamide, and polypropylene.[61,62] Collectively, these studies indicate the probability that microplastics penetrate the human body through polluted food and beverages. Besides the gastrointestinal tract, microplastics have also been detected in the human placenta,[63] human breast milk,[64] human blood,[65] infant formula,[66] and some oral products.[67] The prevalence of microplastics in different biological samples indicates that there might be systemic exposure following the translocation of microplastics through the gastrointestinal barrier. However, the ultimate fate of microplastics within the human gastrointestinal system remains largely unresolved in existing research, highlighting the need for further studies on how these particles are processed in the GI tract. Exposure occurs through the ingestion of food and beverages containing microplastics, as well as through mucociliary uptake following inhalation.[68] As indicated, microplastics have been detected in some food and drink items, including seafood, table salt, sugar, honey, bottled water, and beer. Table salt is typically contaminated during seawater evaporation, crystallization, and milling, with polyethylene, polypropylene, and polystyrene fragments and fibers being the most prevalent. In bivalves, microplastics are derived from uptake and depuration tank water, with polyethylene, polypropylene, and nylon fibers being the most abundant. Contamination of sugar may occur during refining, crystallization, milling, and packaging in polypropylene- or polyethylene-lined bags, and bottled water contamination may mostly be associated with scratching of the PET and polypropylene bottle surfaces and caps. Polyethylene and polypropylene pieces can also be present in cereals and flour, with silo linings, conveyor belts, and milling equipment being the source of contamination. Cox *et al.* (2019)[69] estimated that an average American diet might expose an individual to approximately 39 000 to 52 000 microplastic particles annually. Eighteen thousand particles were estimated to be consumed by Europeans every year through the consumption of bivalves alone.[28] Table salt research points out that there are different amounts of microplastic consumption across geographical areas, including Europe and China.[7,55] Such estimates highlight the nutritional relevance of dietary intake and demonstrate that even simple food groups and condiments can significantly influence overall microplastic exposure.

The behaviour of microplastics in the gastrointestinal tract after ingestion is dependent on the size, surface chemistry, and shape, as well as their ability to interact with mucus and epithelial tissues. The paracellular route of transit of microplastics may seem to be unlikely due to the tight junctions between intestinal epithelial cells which have pore sizes of approximately 1.5 nm and cannot allow normal microplastic particles to pass through them.[70] Rather, the absorption of microplastics tends to occur *via* specialised immune apparatus in the gut. The microplastics may enter the digestive tract *via* a cellular process called endocytosis by the microfold cells of Peyer's patche.[71] Experimental murine model studies also strengthen the idea of the involvement of immune cells in microplastic processing. Peritoneal macrophages have been shown to phagocytose polymethyl methacrylate and polystyrene particles of 1 µm, 5 µm, and 12 µm, with uptake varying according to particle size. This demonstrates that phagocytic cells recognize and internalize particles in a size-dependent manner.[72] In the physiological environment, dissolvable particles may circumvent the intestinal mucus layer. Their mobility in mucus is increased as they develop a protein corona; this happens when proteins on the intestinal surface stick to the particle surface and change their hydrophobicity, charge, and biological interactions.[73] This study demonstrates that oral exposure may influence the potential of particles to be taken up by epithelial or immune cells, and may influence the retention or clearance of particles in the gastrointestinal tract. There are also other interaction modes of microplastics with the gastrointestinal components (digestive enzymes, bile salts, lipids, and food components) within the gastrointestinal environment. Such interactions impact on the characteristics of microplastics, aggregation, or bioavailability. Excretion of larger particles, which are not absorbed, is normally through feces, as shown in the analysis of human fecal samples.[61] However, smaller particles in the micro- and submicron-size ranges are more likely to interact with immune tissues or translocate into the systemic circulation, as shown in the recent studies on microplastics in human blood, placenta, and breast milk.[63–65] All these observations suggest that ingestion is the most common and important route of human exposure to microplastics. The types of polymers found in the gastrointestinal tract are similar to the polymers found in food packaging materials, food processing equipment, cooking utensils, and storage containers, thus highlighting the role of the food chain in microplastic uptake. Further studies are required to understand the implications of microplastic ingestion in humans.

5.2. Inhalation

High-friction food processing activities, including spice and grain grinding, dough and sauce processing, and packaging processes, including film cutting, sealing, and high-speed form-fill-seal processing (also explained in Section 2.1.3 and 2.1.5), are sources of high inhalation exposures of airborne microplastics (MPs) in food processing plants (Fig. 2). Moreover, micro-exposure to synthetic fibers from personal protective equipment (PPE) and textiles takes place during handling.[57] The respiratory tract provides a substantial alveolar surface of roughly 150 m^2, having a thin epithelial barrier (less than 1 mm), enabling deep penetration of small MPs (less than 5 mm in diameter). These particles may result in macrophage phagocytosis and inflammation through the ROS (Reactive oxygen Species) and may result in systemic translocation. The daily exposure of the microplastics varied significantly during different industrial activities.[74,75]

5.3. Dermal exposure

Direct interaction with wet, semi-liquid, or contaminated food-processing materials that contain microplastics (MPs) is the major cause of dermal exposure in food-processing settings. Another source of exposure is through abrasion and shedding of polymer-based personal protective gear, including disposable gloves, aprons, sleeve covers, hairnets, and protective clothes worn in food-processing areas (Fig. 2). The another route through microplastics may get embedded into skin includes equipment cleaning. Cutting, sealing and high-speed packaging

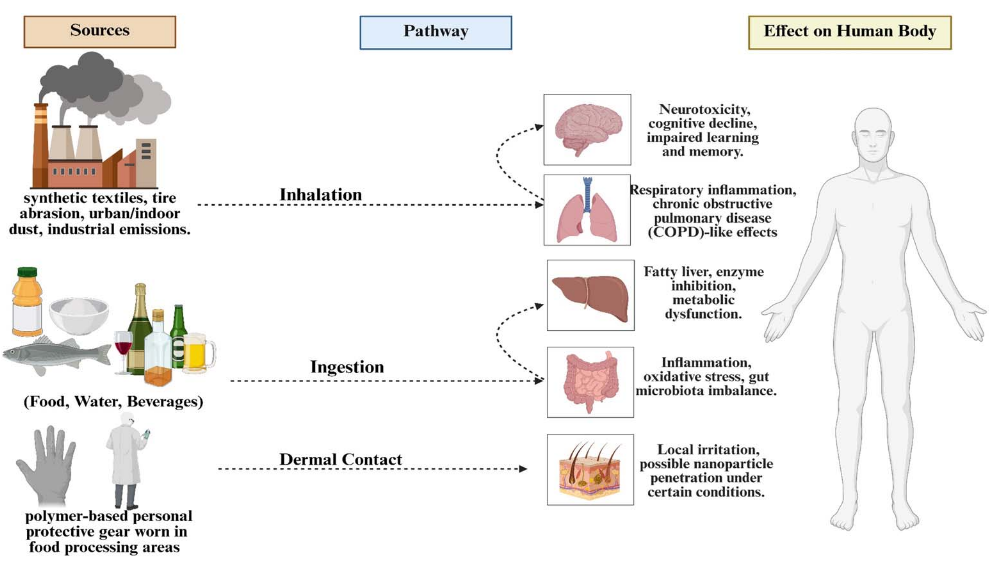

Fig. 2 Human exposure pathways to microplastics and their associated health risks.

processes generate fine plastic dust that gets on the hands and forearms of the operatives. Wet processes such as rinsing seafood, washing meat, and processing vegetables promote the adhesion of MP to moist surfaces of the body through microabrasions, hair follicles or sweat ducts. The microplastics incorporation through dermal route is not so substantial than through ingestion and inhalation routes, there is a reason to believe that nanoscale particles (less than 100 nm) may penetrate the *Stratum corneum* barrier under the influence of moisture, repeated contact and chemical cleaners, which would either result in localized inflammation or serve as an additive carrier.[59,60,76]

5.4. Biomonitoring of microplastics in humans

Biomonitoring is used to determine exposure to environmental contaminants by measuring the chemical constituents themselves, their transformation products or their metabolites within biological media such as blood, stool, urine or tissue materials.[77] The biomonitoring encompasses the various routes of exposure (foods, cosmetics and personal care products, water and air) to the various routes of exposure (dermal adsorption, ingestion and inhalation).[78] Biomonitoring provides the direct evidence about the presence of specific chemicals within the human body.[79] One of the key limitations regarding the information about the quantum of uptake of MPs by human population is the availability of limited data to validate the exposure of human population to the microplastics and study their effect on the human cellular mass.[80] One of the significant shortcomings within the measurement of human uptake of MPs is sparse data to answer exposure of inhabitants, including workers, dispersion, and dynamics of MPs into the tissue of the organic mass of the living being, and the potential cocktail effect MPs can cause with other co-present contaminants.[81] Regardless of human beings incessantly faced by humongous amounts of contaminants, including MPs, various biological barricades are installed to protect human beings against the entry of foreign and potentially harmful entities.[82]

Clearance mechanisms such as sneezing, coughing, mucociliary escalator, macrophage-mediated phagocytosis, as well as clearance through the lymphatic transport system, are induced to prevent particles from penetrating biological barriers, reaching target cells or organs, or leading to bioaccumulation.[83,84] To date, no study has reported categorical findings for the biokinetics of human microplastics. As such, their uptake, distribution, retention, and excretion are not accurately known, unlike the highly studied nanoparticles. Polymer nanoparticles have been extensively studied for use in both diagnostic applications and drug delivery applications because of their high stability.[85,86] Polymeric nanoparticles not only cross biological barriers but are also transported by certain organs into the bloodstream for systemic distribution. Consequently, nanoparticles access secondary organs as well as the central nervous and immune systems.[87] The diameter of nanoparticles significantly determines their deposition within the extrathoracic and intrathoracic parts of the respiratory tract.[82] Apart from particle size, additional factors such as material characteristics, shape, surface functionalization, and structural characteristics together affect nanoparticle biodistribution.[81] Similarly, the size of the microplastics dictates the uptake by the digestive tract,[88] the respiratory system,[89] as well as the integumentary system itself.[90] Larger particulates tend to be eliminated from the organism by faecal excretion,[29] but the smaller particulates could go into systemic circulation and cause physiologic effects such as endocrine disruption or elevated obesity.[81] Microplastics have been found in numerous biological matrices, such as blood, urine, feces, placenta, and breast milk.

5.5. Toxicological effects of microplastics

Microplastics (MPs) induce toxicological responses by multiple mechanisms that are governed by their physical and chemical properties, such as size, morphology, surface charge, additives, and environmental interactions.[91,92] They not only exhibit inherent toxicity but also act as vectors for other contaminants, such as heavy metals and hydrophobic organic compounds (HOCs), and thus allow their entry into biological compartments.[93,94] The toxicity of MPs is typically evaluated across multiple biological levels, ranging from whole organisms to subcellular structures, using diverse experimental models comprising both *in vitro* and *in vivo* testing.[91] Multiple physicochemical parameters define the toxicity profile of MPs. Small particles exhibit an enhanced capability for cell internalization and induce robust oxidative stress responses.[95] Irregularly structured particles induce larger volumes of mechanical injuries relative to their sphere-structured counterparts.[96] Cellular uptake depends greatly on the surface-charge zeta potential of the particle, leading to the efficient internalization of positive-charge MPs.[97] Weathering processes as well as environmental aging modify the shape of the surface, the crystalline nature, and the chemical reactivity, thereby enhancing their biological reactivity potential.[93] Moreover, microplastics often contain additives that can leach under the physicochemical conditions of the human body, potentially contributing to their increased toxicity.[91,93] High surface areas of MPs enable the adsorption of co-contaminants such as HOCs (Hydrophobic Organic Compounds) as well as heavy metals, potentially as a consequence of an increase in their cumulative toxicity.[19,94] When broken down into nanoplastics, these materials can create a biomolecular corona that can modify their bioavailability, persistence, and toxicity, which is then modulated by environmental aging.[92] At the cellular scale, MPs have been found to cause cytotoxic effects through oxidative stress, membrane disruption, and DNA damage. Such processes heavily rely on particle size, concentration, charge, exposure duration, and additive types.[88,98] Human cell lines, including gastrointestinal, airway, and immune cells, respond to MPs with varying levels of sensitivity, with some demonstrating immune dysregulation depending on the surface modifications of the MPs.[88,99] MPs have been found to suppress growth and impair the antioxidant system of microalgae.[100,101] Advanced developments using organoid technology provide better physiologically relevant systems to determine MP toxicity. The self organized 3D tissue cultured stem cells derived from forebrain, intestinal and liver have shown substantial organ impairement when exposed to MPs.[102,103] MPs have been found to infiltrate through cellular layers, cause apoptosis, trigger inflammatory processes, and impair lipid metabolism through these models. Importantly, co-exposure of MPs with other chemicals, including bisphenol A (BPA), results in combined hepatotoxic effects, affirming the role of MPs as chemical transport agents.[102] Animal models also confirm the potential toxicity of MPs, with many of their organ systems impaired. MPs contribute to metabolic impairment, including disrupted lipid digestion, liver injury with oxidative damage, enzyme inhibition, and gut microbiota dysbiosis in both fish and rodent models.[104,105] Immune-mediated toxicity consists of inflammatory cytokine expression augmentation (*e.g.*, IL-1β and TNF-α) and disruption of mucosal immunity after exposure to MPs.[106,107] Neurotoxicity is attributed to as MPs block acetylcholinesterase (AchE) activity, disruption in blood–brain barrier integrity, impaired learning and memory in animal models.[108,109] MPs have adverse effects on reproductive health in terms of lowered oocyte and sperm quality, disruption of the sexual ratio, and impaired embryo growth.[86,110] It was proposed that these adverse effects could be monitored using immunoglobulin A (IgA) as a biomarker.[110] Epidemiologic findings of human contact with MPs are infrequent but disturbing. Professionals working in the plastic industry have been susceptible to exposure to MPs, resulting in the chronic respiratory ailments.[111,112] Patients with inflammatory bowel disease exhibit increased fecal concentration of MPs as compared to the healthy controls, and this was correlated with disease progression.[62] Cirrhotic liver tissue and arterial thrombi in human liver were found to contain MPs, which can be indicative of a relationship with liver and cardiovascular pathology.[113,114] It can be concluded from the studies reported, that there is growing concern about the public health problems attributed to exposure to MPs as well as about the future research in this area, whereas authentic cause can be validated only after the substantial reasearch is conducted in this field.

6. Detection and monitoring of microplastics in food processing and the environment

Different analytical methods are used to analyze microplastics in food samples and are optimized to achieve this goal (Table 2). The main techniques used are visual analysis, microscopy, and spectroscopic analysis.[16] In visual analysis, the first step, which is very important for larger microplastics (larger than 1 mm), is done manually based on criteria such as particle size, shape, and colour. Microscopic analysis, which includes optical microscopy, stereomicroscopy, and scanning electron microscopy (SEM), allows microplastics to be visualized and provides information on morphology and surface characteristics.[16] Besides morphological analysis, chemical and molecular analyses are needed. Fourier transform infrared (FTIR) spectroscopy and Raman spectroscopy are mainly used for this purpose, making it possible to specifically analyze polymeric materials rather than non-polymeric materials in food samples. By combining visual, microscopic, and spectroscopic analyses, a more detailed analysis of microplastics can be made, including both morphological and chemical characteristics.[115] Pyrolysis gas chromatography-mass spectrometry (Py-GC/MS) is one of the most widely used analytical techniques for polymeric materials. This technique involves the thermal decomposition of microplastics into smaller pieces, which are then separated

Table 2 Analytical approaches for microplastic detection and their suitability for different food matrices

Analytical method	Information obtained	Strengths	Limitations/challenges	Best suited food matrices
Visual inspection/light microscopy	Size, color, shape	Fast; inexpensive; preliminary sorting	Not reliable for confirmation; cannot identify polymers	Large visible plastics; low-fat solids; coarse foods
Stereo zoom microscopy/SEM	Detailed morphology, surface characteristics	High resolution; suitable for morphology	Requires clean, debris-free samples; SEM costly	Powders (spices, tea), cereals, seafood tissues
FTIR spectroscopy (ATR-FTIR, μFTIR)	Polymer identification	Widely used; reliable chemical fingerprinting	Particles must be > 20 μm; organic residues interfere	Bottled water, salt, sugar, dried foods
Raman spectroscopy	High-resolution polymer identification	Detects submicron particles; strong chemical specificity	Fluorescence interference; sensitive to pigments	Seafood, beverages, ready-to-eat meals, spices
Pyrolysis–GC–MS	Polymer composition (mass-based)	Works well for complex matrices; no visual sorting needed	No particle counts; destructive method	High-fat foods, oils, meat emulsions, dairy
Thermal extraction and desorption GC-MS	Polymer mass, additives	Suitable for contaminated samples; high sensitivity	Cannot size/count particles	Packaged foods, processed foods, bakery items
Enzymatic digestion (pretreatment)	Removes proteins/fats	Gentle; preserves particle integrity	Time-consuming; expensive	Meat, seafood, dairy, infant formula
Oxidative digestion (H_2O_2)	Removes organic matter	Useful for plant-based foods	May damage sensitive polymers	Fruits, vegetables, cereals, spices

and analyzed by GC-MS. Py-GC/MS provides information on the chemical composition of microplastics, making it possible to identify and measure microplastics in food samples.[16] These methods have been widely used in various studies to assess microplastic contamination in food samples, with a focus on packaging-based sources. For example, Xu *et al.* (2019)[116] employed FTIR microscopy to analyze microplastic contamination in bottled water, finding physical abrasion and leaching to be the main contamination sources. Identical research employed Raman spectroscopy and pyrolysis-gas chromatography-mass spectrometry (Py-GC-MS) to determine microplastics in seafood, and the study revealed that the level of contamination is higher as the packaging materials degrade. In another study, thermal extraction and desorption GC-MS were used by Singh and Kumar (2024)[117] as a method of analyzing microplastics in different foodstuffs; this study also clarified the significance of thermal degradation during food processing and storage. The multi-analytical method of visual analysis, FTIR spectroscopy and scanning electron microscopy (SEM) analysis of microplastics in canned foods is gaining support due to the evidence of contamination associated with the mechanical force of the canning process.[116,118] According to Sewwandi *et al.* (2023),[14] based on FTIR and Raman spectroscopy studies, the migration of microplastics from bottle caps and closures into beverages is significant, underscoring the need for improved packaging designs. Despite the significant advances in the study of microplastics in the food chain, certain issues remain regarding inconsistencies in the concentration, type, and size of the microplastics.[13] Future research must aim to enhance the sensitivity and rate of analysis and establish cost-efficient solutions that can be easily practiced in the food sector. The analytical methods to be adopted in applied studies may be determined by the food matrix being studied, but particular attention should focus on fatty and protein-rich foods. Oils, meat, dairy products, nuts, seeds, emulsified foods, and other foods that consist of complex samples might demand complex sample preparation procedures to minimize interference by the lipid and protein food matrix components. This interference is most severe in oils, meat, dairy products, nuts, seeds, and emulsified foods, as these foods require complex preprocessing steps to counter lipid and protein interference. Digestion by protease or lipase enzymes can allow more effective removal of proteins and lipids while maintaining the integrity of polymers that may otherwise be broken down by severe chemical oxidants. Digestion with hydrogen peroxide is more suitable for carbohydrate-containing samples, which have to be carefully processed to prevent the destruction of polymers. For lipid-rich samples, solvent extraction with ethanol or hexane can simplify the sample matrix prior to filtration, making the preparation process easier. During microscopic and spectroscopic analysis of particulate substances, especially spices, tea, coffee, flour, and cereals, density separation is required to eliminate interference of organic matter or mineral particulates. It is possible to isolate buoyant microplastics using buoyancy solutions that include sodium chloride, zinc chloride, or sodium iodide to allow the separation of particles. By applying these sample preparation methods, complex matrices may not provide desirable results in optical clarity and spectroscopy analysis, thus pyrolysis GC/MS and thermal extraction methods could be used as alternative methods in samples, where particle counting and visualization are not viable. All these factors underscore the paramount role of sample preparation for the successful analysis of microplastics in food. It is also crucial to select analytical tools that are compatible with the food matrix under consideration and its characteristics.

7. Emerging sustainable strategies for reducing plastic use in the food industry

The concept of sustainability has gained significant importance in contemporary food technology, particularly in connection with microplastic contamination, environmental destruction, and inefficient resource usage. The present research emphasis is to reduce the utilization of conventional fossil-derived plastics and promote the utilization of the more environmentally friendly materials, processes, and packaging technologies in the food industry. The synergistic push of scientific advancement and government policy, and the growing demand for environmentally safe and sustainable food packaging technologies, drives the agenda of innovation. The innovation agenda focuses on the development and evaluation of bio-based and biodegradable polymers for food packaging applications.[119–122] Bio-based and biodegradable polymers such as polylactic acid, polyhydroxyalkanoates, starch-based films, cellulose-based composites, and chitosan-based coatings have become popular due to their biodegradability and bio-based nature. There is empirical evidence to show that these materials can be designed to possess mechanical, barrier, and thermal properties similar to those of some fossil fuel-based plastics.[120–125] Despite these improvements, there remain issues with regard to the rate of processing, water resistance, and the ability to withstand high temperatures in the food processing industry. Current research aims to enhance functional properties through compounding, nanocomposite reinforcement, and surface modification. In addition to these developments, current research and development in sustainable food processing technologies aim to decrease plastic usage in food processing plants.[119,120,122] This involves redesigning components traditionally manufactured from polymeric materials by replacing them with reusable high-grade stainless-steel surfaces and enhancing wear-resistant coatings, thereby reducing particle flaking. Food processing companies are also pursuing developments in cleaning-in-place technology and closed-loop water management systems to reduce the discharge of plastic particles into wastewater. Contemporaneous research and development in modular packaging systems, refillable packaging designs, and bulk-dispensing packaging configurations aim to decrease single-use plastics in foodservice and retail packaging.[126] Recycling and the circular economy are major goals of sustainability projects. Technological developments in recycling, such as chemical recycling and depolymerization, are expected to make it possible to recycle mixed or contaminated plastics back into reusable monomers or feedstocks. These results are not possible with traditional mechanical recycling, which is limited in its ability to recycle multilayer packaging materials, colored polymers, and food-contaminated packaging. The Easily Recyclable Mono-Material Packaging and Smart Labeling project is a strategic measure to enhance food packaging material sustainability (advancing the sorting efficiency). Estimation of microplastic emissions of alternative materials is one of the main research fields. Although biodegradable and compostable plastics are suggested as environmentally friendly alternatives to plastics, there are emerging indications that these plastics may degrade into nanoparticles under some degradation conditions.[120–122,126] More studies are needed to better predict the environmental destiny of these plastics, with emphasis on the processes of degradation and fragmentation and how this affects soil and water. This is an area that needs immediate research focus to ensure the transition to sustainable packaging does not lead to new sources of particulate pollution. Sustainability laws in the food industry have been on the rise, including the outlawing of single-use plastics, recycling, compostability, and biodegradability guidelines, which are already in place in most nations. All these sustainability requirements demand that the food industry and the research fraternity collaborate to develop safe, functional, and sustainable materials.

Generally, strategies employed to enhance the sustainability of plastics in food processing and packaging adopt a holistic strategy entailing the search for alternatives and innovations, a circular economy strategy, and creating an enabling environment. More research is required to refine these methods and ensure that the developed sustainable food systems contribute to a reduction in microplastic pollution.

8. Conclusion

Microplastic pollution in food webs is a critical issue for food safety, health, and the sustainability of ecosystems in the long term. The present review shows that microplastics can contaminate food throughout the food chain, which includes the primary processing stage, processing equipment abrasion, packaging material degradation, storage, transportation and handling. Primary and secondary sources are analyzed, and it is revealed that the extent of microplastic transfer depends on the nature of the polymer, the nature of the food-contact material, and the amount of mechanical, thermal, and chemical forces applied during food processing. Ingestion is found to be the main route to exposure, and seafood, bottled water, salt, sugar, breakfast cereals, and ready-to-eat foods are found to be important sources. Although inhalation and dermal exposure are significant routes to exposure, their relative contribution is lower but still important. Biomonitoring studies have confirmed the presence of microplastics in the human biological system, and current research on gastrointestinal interactions, immune cell uptake, and cellular responses suggests a need for further toxicological studies. Current analytical difficulties remain, especially in complex food samples in which lipids, proteins, and particulates cause interference in microplastic separation and analysis. The use of modern pretreatment methods together with sophisticated spectroscopic and thermogravimetric/thermal analytical instruments is necessary to ensure the accuracy and comparability of the results for a wide range of food samples. The growing emphasis on sustainability is becoming increasingly evident in strategies developed to mitigate microplastic pollution across the agri-food chain. Bio-based and biodegradable polymers, single-material recyclable packaging systems, process technologies, and circular economy solutions are promising approaches to reduce plastic use and, consequently, limit microplastic transfer to food. However, it is crucial to assess the environmental fate of new materials to prevent pollution in other industries. In conclusion, a holistic approach to interventions that are developed to counteract microplastic exposure and food quality issues is necessary. With the development of the food industry, technologies that can reduce microplastics in food processing and packaging systems are expected to play a crucial role in ensuring food safety.

Author contributions

Md Sabir Ahmad Mondol; wrote the whole manuscript, Mehvish Ayoub; revised the manuscript, Ubaida Akbar; formal analysis, Kshirod Kumar Dash; project administration, Aamir Hussain Dar; conceptualization, Urba Shafiq Sidiqi; software.

Conflicts of interest

The authors declare no competing interests.

Data availability

No new data were generated or analysed as part of this review.

Acknowledgements

No funding was received for this study.

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