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Review

# Microplastic Contamination in Food Processing: Role of Packaging Materials

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**Abstract:** The role of packaging materials in food processing concerning microplastic contamination is a critical concern in today's food industry. Microplastics, deriving from various packaging sources, have raised concerns about their presence in food products and their potential health implications. This review explores the sources, pathways, and entry points of microplastics into the food chain during food processing stages (production, storage, transportation) due to different types of packaging materials. It investigates how microplastics are released from packaging materials into food products. It highlights the current research landscape by emphasizing challenges and limitations in detecting and quantifying these fine particles. The examination of microplastic contamination from packaging materials in food processing reveals the widespread presence of microplastics throughout food production and consumption, posing significant risks to food safety and human health. Additionally, this paper assesses regulatory perspectives, industry initiatives, and future directions for minimizing microplastic contamination by proposing strategies and recommendations for policymakers, industry stakeholders, and consumers to mitigate the risks associated with microplastics in food processing.

***Keywords*:** microplastics, food processing, packaging materials, food safety, risk assessment

## 1. Introduction

Microplastic contamination has become a pressing global issue, infiltrating the food chain and raising significant concerns about environmental integrity and human health. These minuscule plastic particles, typically less than 5 mm in size, originate from various sources or mobilize via the breakdown of larger plastic debris, microbeads found in personal care products, and the fragmentation of synthetic textiles [1]. These particles enter the environment through diverse pathways, including improper waste disposal, runoff from landfills, and the degradation of plastic waste in marine and freshwater ecosystems [2].

Once in the environment, microplastics are ingested by aquatic organisms, ranging from plankton to larger marine species, thereby entering the food chain [3]. These particles accumulate in the tissues of fish, shellfish, and other marine organisms, with studies highlighting their presence in various seafood humans consume [4]. Additionally, agricultural practices using plastic mulching or irrigation systems with water contaminated by microplastics contribute to their introduction into terrestrial food production systems [5].


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Research has detected microplastics in various food items, including seafood, salt, honey, and even beverages, indicating their pervasive presence in the human diet [6-9]. While the potential health impacts of microplastic ingestion on humans are still being studied, emerging evidence suggests possible risks associated with their presence in food products [10]. However, comprehensive understanding and quantification of these risks remain the subject of ongoing investigation and debate within the scientific community. The issue of microplastic contamination in food has unveiled a complex interrelation between packaging materials and the pervasive presence of these minute synthetic particles in consumables. Packaging materials, integral for food preservation and distribution, inadvertently contribute to the release of microplastics into the food chain. These materials encompass a wide array of polymers, including polyethylene terephthalate (PET), polyethylene (PE), polypropylene (PP), and polystyrene (PS), known for their durability and widespread usage in packaging products [11]. During the lifecycle of these materials from production to disposal, the abrasion, degradation, and weathering processes lead to the fragmentation of plastics by generating microplastic particles that can contaminate the packaged food [12].

The universal use of plastic packaging across various sectors, such as food processing, storage, and transportation, significantly contributes to the ingress of microplastics into the food chain [13]. For instance, studies have indicated that contact between food and plastic packaging during processing and storage could lead to the shedding of microplastics into the food products [14]. Furthermore, the lack of stringent regulations regarding the composition and manufacturing processes of packaging materials exacerbates the issue, allowing for the presence of additives and contaminants in plastics that may leach into foods together with microplastics [15]. This link between packaging materials and microplastic contamination in food emphasizes the intricate pathway through which these minute plastic particles infiltrate the human diet. Addressing this issue requires a comprehensive understanding of how microplastics are released from packaging materials, identifying high-risk points in the food processing chain, and developing strategies and sustainable policies to mitigate such contamination.

The objective of this paper is to meticulously examine the intricate relationship between microplastic contamination in food processing and the pivotal role played by various packaging materials. By exploring the sources, pathways, and mechanisms of microplastic release from packaging, this study elucidates how different packaging materials contribute to the pervasive microplastic contamination in food. Additionally, it evaluates the associated implications for food safety, human health, and the environment while exploring preventative measures, technological advancements, regulatory frameworks, and consumer awareness initiatives essential for mitigating and addressing the challenges in the food industry.

## 2. Review methodology

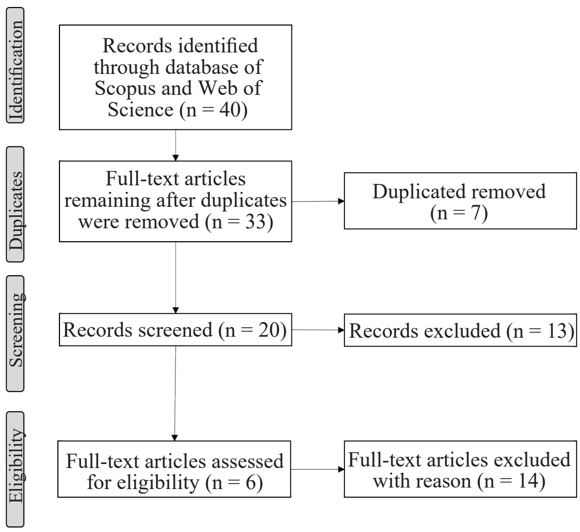


**Figure 1.** Systematic reviews diagram of literature review selection process ("n" = number of publications)

The articles acquired for the study were procured from the international scientific database of Scopus and Web of Sciences from January 2015 to May 2024. The keywords used in the search were "microplastic", "packaging material" and "food" for TITLE-ABS-KEY. The search strings are used to retrieve as many relevant publications as possible but not to extend to unrelated fields [16]. The duplicate publications were excluded for further review. In this study, the review papers, book chapters, conference articles, and non-English papers were omitted, and only full research articles were selected. Thereafter, the title and abstract of the remaining articles were checked, and the articles that met the inclusion criteria were noted. Finally, the remaining full articles were thoroughly assessed for their relevance to the topic covered in this paper. The review results are presented in Figure 1. From the Scopus and Web of Sciences databases, 40 papers were obtained using the selected keywords. However, 7 duplicate papers were removed and 13 papers were omitted based on the chosen exclusion criteria. Out of the remaining 20 papers, only six papers were found relevant based on the topics covered in this review article [17-22]. These papers were analyzed carefully and utilized for discussion in different sections of this review paper.

## 3. Microplastics in the environment

### 3.1 *Definition and classification of microplastics*

Microplastics, defined as plastic particles less than five millimeters in size, encompass a diverse array of polymer-based materials originating from various sources and exhibiting distinct characteristics. These particles are broadly categorized into primary and secondary microplastics based on their production and subsequent breakdown. Primary microplastics are intentionally manufactured at a small size, such as microbeads in personal care products or pellets used in industrial processes [3]. Secondary microplastics result from the degradation and fragmentation of more oversized plastic items, such as bottles, bags, and packaging materials, due to environmental factors like ultraviolet (UV) radiation, mechanical stress, and microbial degradation [23]. In this process, UV radiation initiates photodegradation by breaking down polymer chains via photochemical reactions and producing intermediates like free radicals, hydroperoxides, and carbonyl compounds, resulting in smaller molecules and microplastics. However, accelerated by elevated temperatures, thermal degradation causes thermal oxidation and pyrolysis by generating alkenes, alkanes, and aromatic hydrocarbons. In contrast, mechanical stress induces physical fragmentation without specific chemical intermediates but increases surface area for further degradation. However, microbial degradation involves enzymatic actions, producing by-products like monomers and organic acids. All these processes lead to microplastic release from packaging materials into food products through abrasion, surface erosion, and leaching, with decomposition products including volatile organic compounds. UV and temperature exacerbate these processes by enhancing the fragmentation and release of microplastics and their associated chemical by-products into the environment and food supply.

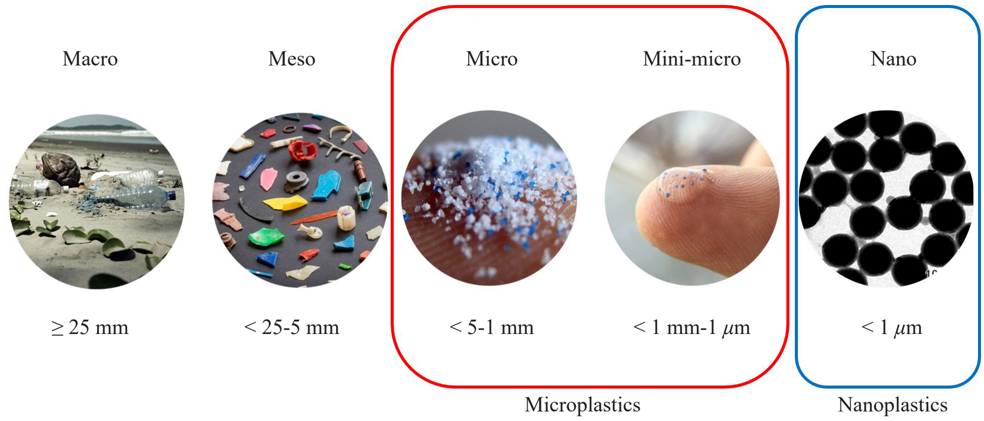


**Figure 2.** Standard classification of microplastics and nanoplastics based on their sizes

Further classification of microplastics is based on their size, including nanoplastics (less than 0.1 µm), microplastics (0.1 µm to 5 mm), and mesoplastics (5 mm to 1 cm) (Figure 2). Within these size classifications, Figure 3 indicates diverse forms of microplastics, such as fragments, fibers, pellets, and microbeads, each exhibiting unique properties and posing varying risks to environmental ecosystems and biota [13]. The identification and classification of microplastics often involve a combination of techniques, including microscopy, spectroscopy (Fourier Transform Infrared Spectroscopy (FTIR), Raman), and chemical analysis, to discern their composition, size, shape, and source. The complex nature of microplastics, arising from their diverse sources, sizes, and forms, necessitates a comprehensive understanding and standardized classification methodologies to assess their distribution, fate, and potential impacts across different environmental compartments.

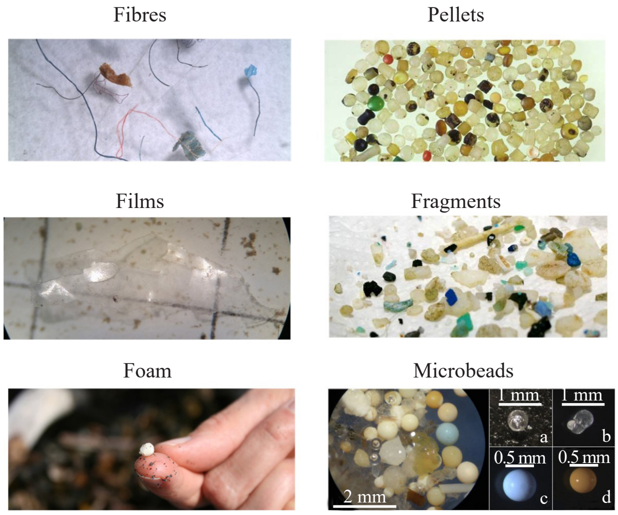


**Figure 3.** Different types of primary/secondary microplastics present in the environment

## 3.2 *Sources and pathways of microplastic contamination in the environment*

Microplastic contamination in the environment stems from diverse sources and follows intricate pathways that contribute to its widespread distribution across terrestrial and aquatic ecosystems (Figure 4). Primary sources include the breakdown of larger plastic items, such as bottles, packaging materials, and fishing gear, due to weathering processes like UV radiation, mechanical abrasion, and chemical degradation [24]. These processes fragment plastics into smaller particles, ultimately forming microplastics. Additionally, microplastics originate from various secondary sources, notably the shedding of microfibers from synthetic textiles during laundry and other activities [25]. Microbeads from personal care products, such as exfoliating scrubs and toothpaste, serve as another source, deliberately manufactured at a small scale for specific applications before entering the environment through wastewater discharge [23].


**Figure 4.** Multiple sources of microplastics leach into the environment

Pathways of microplastic contamination encompass complex routes that facilitate their dispersion throughout the ecosystems. Atmospheric transport plays a role, with microplastics transported through the air and subsequently deposited onto terrestrial and aquatic environments, leading to contamination in remote regions far from their sources [26-27]. Aquatic systems, including rivers, lakes, and oceans, are major microplastic transport conduits [28]. Runoff from urban areas and improper waste disposal contributes to the transfer of microplastics from land to water bodies [29]. Once in aquatic environments, microplastics may sink, float, or be suspended in water columns [30], being ingested by organisms across various trophic levels and further propagating through the food web [3]. The complexity of microplastic sources and pathways underscores the need for comprehensive strategies to mitigate their contamination across diverse ecosystems and emphasizes the urgency of addressing this global environmental challenge.

### 3.3 *Entry points of microplastics into the food chain and food processing system*

Microplastics enter the food chain through multiple pathways, including direct ingestion by organisms or indirect contamination during food processing stages, thereby permeating various segments of the human diet (Figure 5). Aquatic organisms, such as plankton, fish, mollusks, and crustaceans, serve as primary entry points for microplastics into the food chain [3]. These organisms actively or passively ingest microplastics in water bodies, often mistaking them for food due to their small size and resemblance to natural prey. As these organisms are consumed by larger predators, the accumulated microplastics are transferred up the food chain, potentially reaching humans through seafood consumption [4].

Furthermore, microplastic contamination occurs during food processing stages, exacerbating their presence in consumables (Figure 4). The use of plastic packaging materials and equipment during various food processing activities lead to the shedding or leaching of microplastics into the processed food [13]. For instance, contact between food and plastic packaging or machinery during manufacturing, storage, and transportation results in microplastic transfer. The abrasion or degradation of plastic-based equipment used in food processing facilities may also contribute to the release of microplastics into food products [13-14, 31]. The entry of microplastics into the food chain through both direct ingestion by organisms and indirect contamination during food processing underscores the need for comprehensive measures to mitigate their presence at various stages of the food production and processing continuum. The existing studies often need a thorough understanding of all potential contamination pathways, so future research should focus on identifying and quantifying less obvious entry points, such as during food handling and packaging, to create a complete contamination profile.

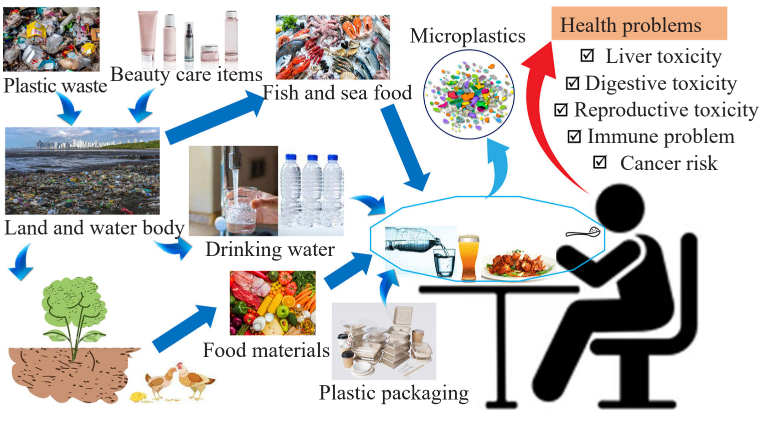


**Figure 5.** Microplastics in the food chain and potential health impacts (adopted from Mamun et al. [32], License Number: 5704121397369)

## 4. Role of packaging materials in microplastic contamination

### 4.1 *Types and composition of packaging materials*

Packaging materials in the food industry encompass diverse compositions, each with distinct properties suited for specific applications. Plastics constitute a significant portion of packaging materials owing to their versatility, durability, and cost-effectiveness. Polyethylene, including high-density polyethylene (HDPE) and low-density polyethylene (LDPE), is widely used due to its flexibility and moisture resistance [33]. Polypropylene is another common plastic employed in packaging, valued for its high melting point and excellent barrier properties against moisture and gases [34]. Polystyrene, often used for foam packaging and rigid containers, offers insulation and cushioning for food products. However, it has drawn concerns due to its non-biodegradability and potential environmental impact [35]. Polyethylene terephthalate, recognized for its transparency and strength, is extensively utilized for beverage containers and food packaging [36].

Metallic packaging materials, such as aluminum and tinplate, provide practical barriers against light, oxygen, and moisture. Aluminum foil, prized for its impermeability and heat resistance, is commonly used for wrapping and sealing food items [37]. Tinplate, consisting of steel coated with a thin layer of tin, offers corrosion resistance and is frequently employed for cans used in food preservation and packaging. Additionally, paper and paperboard-based materials from wood pulp find applications in various packaging formats, including cartons, boxes, and bags. These materials are renewable, biodegradable, and often favored for their eco-friendly characteristics [38]. The diverse array of packaging materials, ranging from plastics to metals and paper-based products, provides various options catering to specific needs in terms of durability, shelf-life extension, barrier properties, and environmental considerations. While numerous studies feature the types and compositions of packaging materials, more research is needed to compare the microplastic release potential across different material types under various conditions. This comparative approach would help identify the most and least harmful materials.

## 4.2 *Packaging materials contribution to microplastic contamination*

Different packaging materials significantly contribute to microplastic contamination during various food processing stages, encompassing production, storage, and transportation. Interactions between food and packaging materials throughout these stages lead to microplastics' shedding, degradation, or leaching into food products. During production, using plastic-based packaging materials involves machinery and processes that may inadvertently introduce microplastics into food. Contact between food and plastic packaging during filling, sealing, and labeling procedures can result in the shedding of microplastics [13]. Moreover, the abrasion or wear of plastic-based equipment used in food processing facilities, such as conveyor belts or mixing tools, contributes to the release of microplastics.

Storage conditions, especially when food is stored in plastic packaging, exacerbate microplastic contamination. Factors like temperature variations, exposure to light, and extended storage times likely accelerate the degradation of plastic materials, which leads to the generation of microplastic particles [13]. Additionally, repeated handling or mechanical stress on plastic packaging during storage may cause the shedding of microplastics into food products [13-14]. The transportation of food products in plastic-based packaging further contributes to the potential microplastic contamination. Vibrations, friction, and physical movements during transportation induce mechanical stress on the packaging materials, releasing microplastics [13]. Additionally, exposure to environmental conditions, such as sunlight and temperature fluctuations during transportation, may accelerate the degradation of plastic packaging by contributing to microplastic generation [13-14]. The multifaceted ways in which different packaging materials interact with food during production, storage, and transportation stages emphasize the need for comprehensive strategies to minimize microplastic contamination in the food processing continuum. Packaging materials contribute significantly to microplastic contamination, yet more data on the specific contribution of different materials and manufacturing processes needs to be collected. Further studies should quantify these contributions more accurately and explore alternative materials with lower contamination risks.

## 4.3 *Mechanisms of microplastic release from packaging materials into food products*

Microplastics are released from packaging materials into food products through various mechanisms, primarily involving physical and chemical processes during handling, storage, and transportation (Figure 6). Physical degradation is a prominent mechanism through which microplastics are released from packaging materials. Abrasion and friction during the handling of plastic packaging, such as flexing, stacking, or agitation during transportation, cause the shedding of particles [13]. These physical stresses result in microplastics detachment from the packaging materials' surface, leading to their incorporation into the food products. Furthermore, environmental factors such as temperature variations and exposure to UV radiation accelerate the physical degradation of plastic packaging [14]. UV radiation generally weakens the structural integrity of plastics by promoting their fragmentation into smaller particles, i.e., microplastics or nanoplastics [13]. The elevated temperature, as commonly encountered during transportation or storage, also contributes to the degradation of plastics and the subsequent release of microplastics into food products.

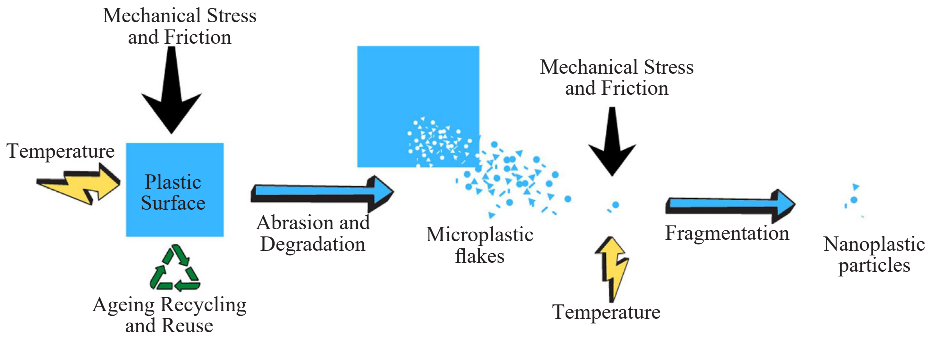


**Figure 6.** Abrasion, flaking, and degradation mechanism of plastic packaging materials, adopted from Jadhav et al. [14]

Chemical leaching is another mechanism by which microplastics are released from packaging materials into food. The plastic additives, including plasticizers, antioxidants, and stabilizers, leach out of the packaging and contaminate food products [13]. These additives may facilitate the release of microplastics and other chemicals into the food matrix. Moreover, the composition of the packaging material itself may contain inherent microplastics or nanoplastics that leach into the food due to interactions between packaging materials and their food content [13]. They outlined several mechanisms through which microplastics are released from packaging materials, including abrasion, degradation, and leaching. However, these mechanisms must be fully understood under different environmental and storage conditions. Detailed mechanistic studies are needed to fill these gaps. The combination of physical degradation, ecological stressors, and chemical leaching processes emphasizes the complexity of microplastic release from packaging materials into food products. This indicates the need for thorough understanding and mitigation strategies in the food processing industry.

## 5. Impact on food safety and human health

### 5.1 *Potential health risks associated with the consumption of microplastic-contaminated food*

The potential health risks associated with consuming food contaminated by microplastics are an area of growing concern and ongoing scientific investigation. While the exact health implications remain complex and not fully understood, several potential risks have been highlighted in the scientific literature (Figure 5). One primary concern is the physical presence of microplastics in food products. Due to their small size and varied shapes, microplastics may pose an extra risk of physical damage to tissues in the gastrointestinal tract upon ingestion [39]. There are concerns that larger microplastics may cause abrasions or mechanical damage in the digestive system, potentially leading to inflammation or other gastrointestinal issues [13].

Moreover, microplastics can act as carriers for other contaminants. These contaminants might include persistent organic pollutants (POPs), heavy metals, or other harmful chemicals that are adsorbed onto the surface of microplastics in the environment [2]. When ingested with microplastics in food, these associated pollutants could be released in the gastrointestinal tract, leading to bioaccumulation or tissue transfer, possibly causing toxicological effects over time [13, 39]. Furthermore, there are concerns regarding the potential for chemical additives used in manufacturing plastics to be leached into food by posing health risks upon ingestion. These additives, such as plasticizers and stabilizers, could adversely affect human health and cause concern if transferred into the body through microplastic-contaminated food [39]. It may be noted that the current understanding of the health risks associated with the consumption of food contaminated by microplastics is still evolving. Although past studies have highlighted these potential risks, there is a need for further research to comprehend better the extent of these risks, including long-term effects on human health, the accumulation of microplastics in tissues, and the potential bioavailability of associated chemicals. More extensive and long-term research is essential to understand the chronic effects of microplastic ingestion on human health.

## 5.2 *Effects of microplastic ingestion on human health*

Numerous studies have investigated the potential health effects of microplastic exposure, primarily through contaminated food and beverages. Much of this research has focused on understanding microplastics' uptake, distribution, and toxicological effects in animal models rather than humans due to ethical constraints and methodological challenges in directly studying human exposure. However, animal studies have suggested potential adverse effects of microplastics on various organ systems, including the liver, kidneys, and immune system [40-41]. Additionally, experimental research has shown that nanoplastics (plastics smaller than 100 nm) could potentially cross biological barriers and cellular membranes and raise concern about their ability to accumulate in tissues [13].

Some epidemiological studies have attempted to indirectly link microplastic exposure with human health outcomes. For instance, a study published in the journal Annals of Internal Medicine in 2019 reported the detection of microplastics in human stool samples, indicating potential ingestion and subsequent excretion in the human body [42]. However, the health implications of these findings are still being debated, and a direct causative link between microplastic ingestion and adverse health effects in humans is yet to be firmly established. Overall, the existing research suggests the potential for microplastics to enter the human body through ingestion and inhalation (Figure 7). Still, comprehensive and conclusive evidence regarding their direct impacts on human health, especially in chronic exposure scenarios, remains a subject of ongoing investigation and debate within the scientific community. There is also a critical need for real-world data and clinical studies to assess the actual impact on human health.

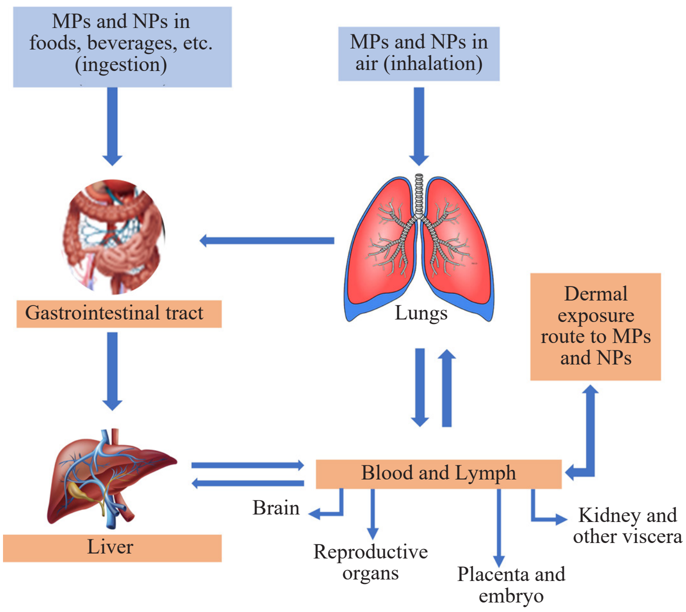


**Figure 7.** Ingestion and inhalation hazard of microplastics (MPs) and nanoplastics (NPs) to humans, modified from Kumar et al. [43]

## 5.3 *Regulatory perspectives and guidelines regarding microplastic's presence in food*

Several regulatory agencies, such as the European Food Safety Authority (EFSA) and the United States Food and Drug Administration (US-FDA), have initiated assessments and research programs to evaluate the potential risk of microplastics in food and drinking water. These agencies have set guidelines and maximum limits for specific contaminants in food and have begun exploring methodologies for microplastic risk assessment [44-45]. In 2016, the EFSA published a scientific opinion recognizing the need for more research to assess the potential risk of microplastics in food to establish an appropriate risk management measure [44]. The opinion emphasized the scarcity of data on microplastic toxicity and human exposure and called for improved analytical methods to detect and quantify microplastics in food matrices.

Similarly, the US-FDA has acknowledged the issue of microplastics in food and has conducted studies on their presence in various food items and potential health implications. However, specific regulations or guidelines solely targeting microplastics in food are still evolving [45]. Other international organizations, the World Health Organization (WHO) and the Joint Expert Committee on Food Additives (JECFA), have expressed concerns about microplastics in food but have primarily focused on understanding the exposure level and assessing the potential health risk rather than setting any stringent regulatory limits [46-47]. Given the complexities and challenges associated with assessing and regulating microplastics in food, a comprehensive and harmonized guideline or regulation addressing the presence and potential risk of microplastics in the food supply chain is still in the developmental stage. It is also essential to evaluate the effectiveness of current regulations, and proposing harmonized global standards would be beneficial in creating a more unified approach to managing microplastic contamination.

## 6. Preventive measures

### 6.1 *Strategies to mitigate microplastic contamination in food processing*

Mitigating microplastic contamination in food processing involves multifaceted approaches at different stages of the food supply chain, i.e., production to consumption, modifications in packaging, and processing techniques. The selection of alternative packaging materials or innovative biodegradable and compostable materials that reduce reliance on traditional plastics has gained attention. Bioplastics derived from renewable sources or biodegradable polymers offer potential alternatives to conventional plastics by minimizing the release of microplastics [48-49]. The improvement in packaging design to reduce abrasion and shedding of microplastics is also crucial. Implementing coatings or barrier layers on packaging materials may likely prevent the migration of microplastics into food products [13]. Furthermore, the development of packaging products that are less prone to fragmentation or wear during processing, storage, and transportation would also limit the microplastic release to a great extent [14].

Implementing strict manufacturing practices to minimize the use of additives or chemicals in plastics is essential. Regulations ensuring adherence to safety standards in the production and use of plastic packaging materials help to limit microplastic contamination [13]. Modifying food processing equipment and techniques to minimize the abrasion and wear of machinery parts made from plastic materials can reduce the shedding of microplastics into food products [14]. Regular maintenance and replacement of worn machinery parts also mitigate microplastic release during food processing. The enhancement in waste management practices, promotion of recycling practices, and reduction in plastic waste in food processing facilities indirectly reduce the presence of microplastics in the environment. Implementing effective recycling programs and circular economy practices can also minimize the generation and spread of microplastics from discarded packaging materials [13]. The education/training of consumers about proper disposal practices, responsible use of plastic-packaged products, and awareness about the environmental impact of microplastics may facilitate behavioral changes and reduce microplastic pollution [50]. Overall, comprehensive mitigation of microplastic contamination in food processing requires collaboration among stakeholders, including policymakers, manufacturers, researchers, and consumers, to implement strategies addressing the various facets of the food supply chain. Future research should also focus on field trials and real-world applications to validate these mitigation approaches.

### 6.2 *Advances in packaging technology for restricted release of microplastics*

The recent advances in packaging technology are focused on developing innovative solutions to limit the release of microplastics and address the environmental concerns associated with traditional plastic packaging materials. As highlighted in the previous section, developing biodegradable and compostable packaging materials has gained momentum. These materials, derived from renewable sources like plant starches, cellulose, or biopolymers, offer alternatives to conventional plastics and degrade into natural compounds, i.e., minimize microplastic pollution [48-49]. These advancements aim to mitigate the persistence of microplastics in the environment while maintaining packaging functionality. Active and intelligent packaging technologies incorporate functionalities beyond traditional packaging by including antimicrobial properties, an indicator for monitoring food quality and safety. Such technologies reduce the need for excessive plastic layers or preservatives, potentially decreasing the generation of microplastics and enhancing food preservation [51].

Innovative nanostructured coatings and barrier films have also been developed to provide enhanced protection for food products without extensive use of plastics. These coatings, derived from natural compounds or nanomaterials, offer improved barrier properties against oxygen, moisture, and microbial contamination by reducing the reliance on multiple plastic layers in packaging [52]. Efforts are being made to design packaging products that facilitate easier recycling and promote reusability. Designing packaging materials compatible with existing recycling systems or developing innovative recycling methods for complex packaging structures can minimize plastic waste and reduce microplastics' release into the environment [49]. Bio-based polymers and polymer blends derived from renewable resources are alternatives to conventional plastics. These materials offer biodegradability or improved recyclability towards reduced microplastic contamination while maintaining the necessary functionalities required for packaging [53]. These technological advancements in the packaging sector demonstrate a shift towards more sustainable and environment-friendly alternatives for mitigating microplastic release and reducing the ecological footprint associated with conventional plastic packaging materials. Although advancements in packaging technology, such as the development of bioplastics and coatings, show promise in restricting microplastic release, future studies must assess these technologies' long-term effectiveness and environmental impact to ensure they are viable solutions.

### 6.3 *Best practices and innovative approaches*

Minimizing microplastics in packaging materials involves adopting best practices and innovative approaches across various stages of material development, production, use, and disposal. Opting for materials less prone to microplastic generation is essential. Designing packaging materials focusing on reduced shedding and fragmentation during manufacturing limits the microplastic release. Selecting durable materials that are less prone to mechanical wear and tear mitigates microplastic generation [53]. Innovations in processing methods are crucial in minimizing microplastics in packaging materials. Advanced manufacturing processes, such as precision molding or extrusion techniques, produce packaging materials with improved structural integrity and reduced potential for microplastic shedding [54].

Nanotechnology offers potential solutions for developing packaging materials with enhanced barrier properties by reducing the need for multiple plastic layers. Nanocomposites or nanoparticle-based coatings generally strengthen the packaging materials by improving the resistance to environmental stressors and reducing microplastic generation during use and disposal [52]. A key strategy is to adopt bio-based and biodegradable materials as alternatives to traditional plastics. These materials, derived from natural sources, degrade more readily by reducing the persistence of microplastics in the environment. At the same time, the design of biodegradable packaging materials possesses the necessary functional properties crucial for sustainability [51]. A circular economy model by prioritizing recyclability in packaging design is pivotal [55]. Developing packaging materials that are easily recyclable and compatible with existing recycling systems can significantly reduce the generation of microplastics from discarded packaging [48-49]. The comprehensive lifecycle assessments of packaging materials aid in identifying potential sources of microplastics and guiding the improvements. Integrating findings from such assessments into regulatory frameworks may facilitate the development and adoption of standards that prioritize reducing microplastic generation in packaging products [56]. There is a wealth of proposed best practices and innovative approaches to minimize microplastic contamination, but their adoption could be more consistent across the industry. Future studies should identify barriers to adoption and develop strategies to encourage widespread implementation of these best practices.

## 7. Detection and analysis methods

### 7.1 *Microplastics in food products*

The detection and quantification of microplastics in food products involves various analytical techniques for identifying and measuring these particles. Commonly utilized methods include visual inspection, microscopy, and spectroscopic analyses [57]. Visual identification is an initial step, particularly for larger microplastics (> 1 mm), which involves manual sorting and observation based on particle characteristics like size, shape, and color. The microscopy techniques, such as optical, stereo-zoom, and scanning electron microscopy (SEM), allow microplastics to be visualized and characterized based on morphological features and surface characteristics [57]. However, FTIR and Raman spectroscopy provide molecular and chemical identification, helping to differentiate the plastic polymers from other materials in food samples. Combining these techniques enables a more comprehensive analysis by visualizing, characterizing, and chemically identifying the microplastics in food matrices [58].

The pyrolysis-gas chromatography-mass spectrometry (Py-GC-MS) is also used to analyze microplastic polymers by breaking down the particles into smaller fragments for identification. This method involves microplastics' thermal decomposition (pyrolysis) and GC-MS analysis to identify the released fragments. It offers insights into the polymer composition of microplastics and their identification and quantification within food samples [57].

Several research articles have investigated microplastic contamination in food from packaging products, employing qualitative and quantitative methods to understand the mechanisms involved. For instance, Xu et al. [59] utilized FTIR microscopy to identify microplastics in bottled water, highlighting physical abrasion and leaching as key contamination pathways. They also applied Raman spectroscopy and Py-GC-MS to quantify microplastics in seafood, revealing significant contamination due to packaging material degradation. Singh and Kumar [60] discussed Thermal Extraction & Desorption-GC-MS to measure microplastics in various foods, demonstrating the impact of thermal degradation during processing and storage. Further, combined uses of visual inspection, FTIR, and SEM were recommended to assess the microplastics in canned foods by linking mechanical stress during canning to contamination [59, 61]. Substantial microplastic contamination in beverages from bottle caps and closures was also found using FTIR and Raman spectroscopy, suggesting improved packaging designs [18]. These techniques, whether used individually or in combination, contribute to understanding microplastic presence and characteristics in food products despite the challenges associated with detecting particles of varying sizes and types [7]. There is still a need for more sensitive, standardized, and cost-effective techniques, so future research should focus on enhancing detection accuracy and developing standardized protocols for industry-wide use.

### 7.2 *Challenges and limitations*

The analysis of microplastics in food packaging materials poses several challenges and limitations due to the intricate nature of packaging matrices and the minute size of microplastics. One significant challenge involves the diverse composition of packaging materials, which often contain multiple polymers, additives, and coatings, complicating the extraction and identification of microplastics. The complex matrix of food packaging requires meticulous sample preparation techniques to isolate the microplastics without altering their characteristics or introducing contaminants, thus posing a challenge in ensuring the accuracy and reliability of results [62]. However, the detection and identification of microplastics in food packaging could be improved by the broad range of particle sizes and forms, including fibers, fragments, and films. The analytical techniques must encompass this particle morphology and composition diversity by necessitating sophisticated methodologies to differentiate microplastics from other materials in the packaging matrix. Additionally, the absence of standardized protocols and reference materials for microplastic analysis in food packaging materials adds complexity to the field by hindering the comparability and reliability of data obtained from various studies [62].

The existing studies on microplastic contamination in food from packaging materials exhibit several limitations. Many investigations predominantly focus on the presence and quantification of microplastics without exploring the mechanisms behind their migration from packaging into food [14, 63]. There is often a need for standardized methodologies for microplastic detection and characterization, leading to data inconsistencies and difficulty in comparing results across studies. The potential health impacts of microplastics still need to be fully addressed, with limited toxicological assessments. The influence of different environmental factors, such as UV radiation and temperature, on the degradation of plastics and subsequent microplastic formation is not comprehensively studied. Future research should adopt standardized detection and quantification methods to overcome these limitations, investigate the migration mechanisms in various food matrices, and conduct detailed toxicological studies. Studies should also explore the effects of environmental factors on microplastic formation and consider the development of alternative, safer packaging materials.

# 8. Industry and regulatory responses

## 8.1 *Initiatives undertaken by the food industry*

The food industry has been increasingly active in addressing plastic contamination by implementing various initiatives to mitigate the presence of these particles in food products and packaging materials. One significant focus area involves reducing plastic usage in food packaging products. It may be noted that food companies are exploring alternative materials, such as biodegradable polymers, compostable packaging, and bio-based plastics derived from renewable sources, to minimize the environmental impact of packaging materials and to decrease the potential for microplastic contamination in food products [49]. Furthermore, food industry stakeholders invest in innovative technologies and manufacturing processes to limit microplastic release during food processing and packaging stages. Some advanced techniques also aim to produce packaging materials with improved durability and reduced shedding of microplastics. As highlighted in the previous section, the recent developments also include the change of coatings and barrier films that prevent the migration of microplastics into food products. These initiatives aim to enhance packaging integrity while mitigating the risk of microplastic contamination throughout the food supply chain [14]. Stringent quality control measures are being implemented across the food industry to detect and minimize microplastic contamination in food products. The comprehensive monitoring of raw materials, production processes, and final products is conducted to ensure compliance with safety standards and regulations. In some instances, collaborative efforts among food industry stakeholders are being made to develop guidelines and protocols for microplastic analysis to improve food safety and reduce cases of microplastic presence in food [49].

Policymakers developing regulations and guidelines to address microplastic contamination in food processing should focus on creating stringent regulations that limit the use of plastics in packaging materials. They should establish clear standards for acceptable microplastic levels in food, support research funding to enhance detection and mitigation techniques, and promote public awareness campaigns about the risks of microplastics. The development of collaboration among industry stakeholders, researchers, and regulatory bodies is crucial for developing innovative solutions and ensuring compliance through effective monitoring and enforcement mechanisms.

## 8.2 *Regulations and policies*

The regulatory frameworks to directly control microplastic contamination in food are in the early stages of development, focusing on understanding and monitoring rather than direct regulations. However, several governments and international bodies have taken steps towards addressing microplastic concerns through broader environmental and food safety regulations that indirectly target microplastic contaminant minimization. Governmental agencies, such as EFSA and US-FDA, are working to assess the risks associated with microplastics in food to understand the extent of contamination. These initiatives are essential to establish guidelines and regulations for safe levels of microplastics in food products. For instance, EFSA conducted risk assessments to evaluate the potential health risks of microplastic exposure through food consumption. At the same time, the US-FDA assessed the occurrence of microplastics in the U.S. food supply [44].

International bodies, like WHO and the United Nations Environment Programme (UNEP), are raising awareness and guiding the risks posed by microplastics in food and the environment [64]. While direct regulations specifically targeting microplastics in food are currently limited, existing regulations on food safety, packaging materials, and environmental protection indirectly contribute to microplastic contamination control. The policymakers continually review and update standards and regulations to address emerging concerns about microplastics in food and packaging materials. At the same time, monitoring official government websites, environmental agencies, and food safety authorities can provide the most current information on regulations related to microplastic contamination in food.

Consumers can play a vital role in reducing microplastic contamination by adopting safe handling and disposal practices and avoiding certain types of plastic packaging. It is advisable to prefer products packaged in eco-friendly materials such as glass, metal, or certified biodegradable options [65]. Consumers should follow proper disposal methods by recycling plastics correctly and reducing single-use plastic consumption. They can also support brands that prioritize sustainable packaging and stay informed about the types of plastics most prone to releasing microplastics, such as plastic films and thin plastic wraps, to make more conscious purchasing decisions. Consumers can contribute significantly to mitigating microplastic pollution in the food supply chain through these efforts.

## 9. Consumer awareness and perception

### 9.1 *Influence of consumer awareness*

The food industry has begun implementing various initiatives to address microplastic contamination in food products and packaging materials. These initiatives primarily focus on sustainable practices, innovation in packaging, and stringent quality control measures. The existing regulations and requirements on the social responsibility of packaging products and material manufacturers often include mandates to minimize environmental impact, such as reducing plastic waste and ensuring materials are recyclable or biodegradable. These regulations may require manufacturers to adhere to specific standards for sustainable sourcing and production practices and disclose their products' environmental impact. Manufacturers are also expected to engage in corporate social responsibility initiatives, such as supporting recycling programs and investing in research for eco-friendly packaging solutions, to address their products' broader environmental and health implications. One notable initiative involves adopting sustainable packaging practices aimed at reducing plastic usage. The food companies are exploring alternatives to traditional plastic packaging, such as biodegradable materials, compostable polymers, and bio-based plastics derived from renewable sources. These initiatives aim to minimize the environmental impact of packaging materials and to reduce the potential for microplastic contamination in food products [49].

In addition to sustainable packaging, the food industry is investing in innovative technologies to limit microplastic release during food processing and packaging stages. Advanced manufacturing processes are being employed to produce packaging materials with improved durability and reduced shedding of microplastics. The development of coatings and barrier films that prevent the migration of microplastics into food products is gaining traction. These innovative approaches aim to enhance packaging integrity while minimizing the risk of microplastic contamination throughout the food supply chain [14]. The rigorous monitoring of raw materials, production processes, and final products must be undertaken in future research to comply with safety standards and regulations.

### 9.2 *Communication strategies*

Effective communication strategies are pivotal in educating/training consumers about the risks associated with microplastic-contaminated food and fostering awareness regarding its potential impact on health and the environment. One approach involves using various communication channels, including social media, websites, and educational campaigns, to disseminate accurate and comprehensible information to the public. The clear and concise messaging, supported by scientific evidence, helps articulate the risks associated with microplastics in food. Communication through easily accessible platforms and using graphics, videos, and informative content aids in engaging consumers and enhancing their understanding of the issue [39].

The collaboration between government agencies, Non-Governmental Organizations (NGOs), and health organizations would play a crucial role in designing and implementing effective communication strategies. The coordination among these entities enables the development of standardized information materials and guidelines for communicating risks associated with microplastics in food. The partnerships with media outlets and influencers can also amplify the reach of educational messages, ensure broader dissemination, and increase awareness among diverse demographics. Consumers with knowledge about reducing exposure to microplastics, such as through informed food choices or lifestyle changes, can further contribute to shaping responsible consumer behavior and fostering a more informed society [39].

## 10. Future perspectives and recommendations

To minimize microplastic contamination in food processing, future trends and research directions offer promising avenues for progress. Advancements in material science have heralded the development of innovative, biodegradable, and compostable packaging materials that can minimize microplastic release. The nanotechnology-based solutions present potential breakthroughs in creating effective barriers against microplastic migration from packaging to food. Furthermore, enhancing detection methods and standardizing protocols for quantifying microplastics in food products will aid in comprehensive risk assessment and regulation. The collaborative interdisciplinary research focusing on the lifecycle of packaging materials and their interactions with food will provide invaluable insights into reducing microplastic contamination.

To effectively mitigate microplastic exposure in food processing, concerted efforts from policymakers, industry stakeholders, and consumers are imperative. Policymakers should enact stringent regulations that mandate using environmentally friendly and low-microplastic-release packaging materials. Additionally, supporting research on alternative materials and incentivizing their adoption is essential. The industry stakeholders must prioritize investing in innovative, sustainable packaging technologies while ensuring transparent labeling to inform consumers about microplastic-free products. The collaborative initiatives among industries, research institutions, and regulatory bodies can foster the development of standardized microplastic detection methods, ensuring quality control and compliance. Consumers also play a pivotal role by advocating for and supporting products packaged with environmentally responsible materials, thereby driving market demand. The enhanced consumer awareness campaigns can empower informed choices and encourage a shift towards products with reduced microplastic exposure by promoting a sustainable and healthier food ecosystem.

## 11. Conclusions

Examining microplastic contamination from packaging materials in food processing reveals critical insights. The key findings emphasize the pervasive presence of microplastics in various stages of food production and consumption. These microplastics pose risks to food safety and human health and warrant immediate attention. This review paper highlights the pressing need for stringent regulations, innovative packaging solutions, and heightened consumer awareness to mitigate microplastic release. By emphasizing the urgency of proactive measures, this study accentuates the need for collaborative efforts among industries, policymakers, researchers, and consumers to curtail microplastic contamination in the food chain. The microplastic contamination in the food processing sector demands proactive and concerted action on multiple fronts. Timely intervention through stringent regulations governing packaging materials and investment in innovative technologies for eco-friendly alternatives is important. It is also equally vital to ensure consumer awareness of sustainable packaging. In conclusion, microplastic contamination in food processing, primarily from various packaging materials, emphasizes a multifaceted challenge with far-reaching implications. This review has highlighted the intricate interplay between packaging materials and the release of microplastics into the food chain by emphasizing the potential risks posed to food safety, human health, and environmental sustainability. So, the pervasive presence of microplastics in food packaging materials poses significant food safety risks by emphasizing the urgent need for stringent regulations, innovative packaging solutions, and informed consumer choices. By adopting sustainable packaging practices and being vigilant about plastic use, the consumer can collectively mitigate the impact of microplastic contamination on their health and the environment. Exploring preventive measures, innovative technologies, regulatory approaches, and consumer awareness initiatives suggests a collective need for proactive interventions across the food industry.

## Conflict of interests

The author declares there is no conflict of interest at any point with reference to research findings.

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