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REVIEW

Food Packaging Materials: Risks of Contamination

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ABSTRACT

Food packaging performs multiple essential functions: it protects, preserves, contains, markets, stores, and facilitates the transport of food products. Throughout the food supply chain, packaging plays a critical role in maintaining food quality, safety, and shelf life. Growing consumer expectations and evolving market trends have contributed to the emergence of increasingly advanced and innovative wrapping systems. These innovations aim to improve functional performance while responding to sustainability and safety concerns. Despite these advantages, packaging materials pose environmental challenges due to their high production volumes, short lifespan, and waste management difficulties. Although recycling is essential for reducing waste, it may nevertheless lead to the accumulation of hazardous substances in packaging materials, which may migrate into food and present health risks to consumers. Mass transfer and chemical equilibrium govern the migration process, and this interaction can negatively affect human health when chemical substances from packaging penetrate food matrices. Potential migrants include compounds such as antioxidants, antimicrobial agents, deliberately added chemicals, unintended by-products, as well as monomers, oligomers, and nanoscale particles. The following paper reviews the potential hazards linked to materials

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used in food packaging, focusing on contamination mechanisms, migration phenomena, and the advancements in analytical techniques designed to identify packaging-derived hazardous substances in food.

Keywords: Food Packaging; Food Contaminants; Migration; Mechanism; Interaction

1. Introduction

Food wrapping plays a key role across all categories of food, contributing throughout the entire supply chain—from preservation and transport to storage, retail distribution, and final consumption [1,2]. Packaging fulfills both industry standards and consumer expectations, helps ensure food safety, and supports efforts to reduce environmental impact [3]. It also differentiates products in the marketplace and influences consumers psychologically by enhancing the visual appeal and perceived quality of the food [4].

Continuous innovation in packaging materials has led to the emergence of active and intelligent systems that enhance food protection and traceability. Modern smart and active packaging uses antimicrobial agents, oxygen scavengers, and sensors to control microbial activity, stabilize the packaging environment, and provide real-time updates on the quality and freshness of food products [5]. These materials also play a significant marketing role while remaining recyclable. Their compliance with food contact is evaluated according to the components used in their formulation, as stipulated by European Regulation No. 1935/2004 [6]. However, if proper hygiene is not upheld, packaging may serve as a pathway for contamination and allow microorganisms to be transferred to the food it contains [7].

Packaging needs differ widely according to the intrinsic properties of the food, such as its moisture level, fat content, acidity, and susceptibility to oxygen or light exposure. For instance, foods rich in lipids can encourage greater migration of fat-soluble compounds, while acidic products may accelerate corrosion or ion exchange in metallic packaging. Similarly, items sensitive to moisture require materials with strong water vapor barrier properties, and products prone to oxidation need packaging with low oxygen permeability. These variations underline the importance of selecting packaging solutions that are specifically designed for each type of food and its storage conditions [8].

Therefore, choosing packaging materials requires careful consideration of the possible interactions between the packaging and the food, as well as the associated health risks. Common materials include plastics, glass, metals, and paper, each offering different performance characteristics [9,10]. Several studies have reported contamination from packaging components. For example, Mazzoleni et al. (2023) [11] identified residual particles such as plastics, cellulose, and aluminum in old food products, whereas Guerreiro et al. (2018) [12] detected plastic-origin compounds like phthalic anhydride and diisooctyl phthalate in vacuum-packed meat samples. Such observations highlight the necessity of considering packaging safety alongside its functional characteristics.

Plastics are widely used in the food packaging sector because of their adaptability and range of applications, although biodegradable polymers are increasingly being developed as alternatives, paper and cardboard follow as the second most used materials [13]. It is well established that chemicals present in materials that come into contact with food can transfer into the food and may be ingested. Monitoring this migration has become essential to ensure food safety [9].

The choice of packaging should balance cost, performance, and its ability to maintain product freshness [4]. Plastics, in particular, are not chemically inert materials; low-molecular-weight substances such as plasticizers, monomers, and oligomers may migrate into food during processing or storage [4]. In addition, plastics can absorb contaminants from their surrounding environment, which may complicate recycling processes and increase the risk of secondary contamination. All types of packaging materials have the potential to release trace amounts of their constituents when in contact with food, which may raise toxicological concerns [14]. Migration and contamination processes are influenced by several factors, including temperature, contact duration, food composition, and the chemical nature of the packaging material [4,15].

It is also crucial to note that these interactions can lead to various types of food contamination, such as the penetration of gases and volatile substances, moisture, microbial organisms, and additional low-molecular-weight substances [4]. These interactions are mainly governed by permeation, migration, and sorption phenomena [16].

Presented as a narrative review, this manuscript examines food packaging materials with a focus on potential contamination hazards. Key topics include interaction pathways, migration phenomena, safety assessment methodologies, and current challenges associated with modern packaging solutions.

2. Types of Packaging and Materials Used for Food Packaging

A wide range of packaging technologies and material systems has emerged in response to the functional and safety demands of modern food products. In addition to providing physical protection, contemporary packaging solutions are increasingly designed to play an active role in preserving food quality. Active packaging approaches focus on extending shelf life through the incorporation of components capable of scavenging oxygen, controlling moisture, or delivering antimicrobial effects. Intelligent packaging, on the other hand, is intended to monitor and communicate information related to product freshness, storage conditions, or potential breaches in package integrity throughout the distribution chain. At the same time, growing environmental concerns have accelerated the development of biodegradable and edible packaging materials as sustainable alternatives to conventional systems [17].

From a materials standpoint, food packaging systems are commonly categorized based on their chemical composition into three main groups: inorganic materials such as glass and metals, organic polymeric materials including plastics and paper-based substrates, and composite or multilayer structures that combine different materials to achieve specific functionalities. Each group is characterized by distinct physicochemical properties that govern barrier efficiency, mechanical performance, recyclability, and the nature of interactions with food products. To improve functional performance, packaging materials frequently incorporate additives such as antioxidants, plasticizers, and antimicrobial compounds; however, the presence of these substances may also increase the risk of chemical migration into food, raising potential safety and regulatory concerns [18].

Functional additives, especially nanoparticles (organic, inorganic, or hybrid), are being increasingly added to packaging materials to improve their mechanical strength and barrier performance, and antimicrobial activity. Nanoparticles can also block UV light and act as oxygen scavengers, thus helping to preserve food quality [19,20]. Advances in nanotechnology have therefore opened new opportunities for sustainable and high-performance packaging [21]. Nanotechnology-enabled packaging presents new opportunities for improving food preservation, enabling the development of packaging that is safer, more sustainable, and of higher quality. By enhancing both the performance and effectiveness of packaging, nanotechnology can provide significant advantages for manufacturers and consumers alike [21].

Despite their promise, the full potential of nano-based materials in food packaging remains largely untapped. Integrating these materials widely in the industry necessitates careful evaluation of critical factors, including costs, regulatory compliance, consumer acceptance, cytotoxicity, and migration behavior [22]. Over time, packaging materials have evolved from natural sources such as leaves, shells, and hollowed logs to cloth, ceramic, glass, metal, and plastic, with research focusing on their suitability for meeting the functional needs of the food packaging industry [23].

Selecting appropriate materials and technologies is essential for preserving a product's freshness and ensuring its safety during storage and distribution. Traditional materials-glass, metals (e.g., aluminum, tinplate), paper, cardboard, and plastics—each offer distinct advantages. Modern packaging often combines multiple materials to achieve optimal barrier properties and aesthetics [24].

Common food packaging materials used in the food industry are illustrated in **Figure 1**.

Figure 1. Common food packaging materials used in the food sector.

Illustrative examples of widely used food packaging materials, including glass containers, plastic packaging, metal cans, and paper-based materials, were selected for their role in protecting food products, maintaining quality, and ensuring safety along the food supply chain.

The sections below outline the primary types of food packaging materials, highlighting their chemical composition, key benefits, potential drawbacks, and their impact on both food safety and recyclability.

2.1. Glass

Glass container manufacturing involves heating a blend of silica (the primary component of glass), along with sodium carbonate as a flux, and stabilizing agents such as limestone, calcium carbonate, and alumina. This mixture is brought to very high temperatures. Until this mixture becomes a thick, molten mass that can then be shaped by pouring it into molds [24].

Glass is among the oldest packaging materials and continues to be widely used thanks to its chemical stability and its resistance to permeation. It does not take up molecules from the foods it contacts, nor from the surrounding environment. Any potential migration substances from glass, governed by diffusion within its internal structure, are limited. Nevertheless, acidic foods can trigger an ion-exchange process between the cations present on the glass surface and the food, leading to some migration. In alkaline conditions, the Si-O bonds may undergo hydrolysis. Among the different glass types, soda-lime glass is the most prevalent, especially for food and beverage packaging [1].

Glass offers numerous benefits for food-packaging applications. It forms an effective barrier against gases and vapors, helping preserve products for extended periods without affecting their taste or aroma. Because it tolerates high processing temperatures, glass is well-suited for the heat sterilization of both low-acid and high-acid foods. Its inherent rigidity provides good structural protection, and it can be manufactured in a wide variety of shapes. The material's transparency allows consumers to see the contents, while colored glass variants help shield light-sensitive products. In addition, glass packaging is environmentally friendly, as it can be reused and is fully recyclable. On the downside, its significant weight and susceptibility to breakage increase transport costs and the likelihood of damage [24].

2.2. Metal

Metals, including aluminum and steel, are widely used because of their strength, recyclability, and barrier performance. It offers excellent physical protection, barrier properties, formability, decorative potential, recyclability, and consumer acceptance. Tin-based cans are used to hold foods and a variety of carbonated and non-carbonated drinks.

Aluminum is a light, silvery white metal derived from bauxite ore, where it exists in combination with oxygen in the form of alumina. Magnesium and manganese are often added to aluminium to improve its strength properties. They are commonly used to make cans, foil, and laminated paper or plastic packaging. Unlike many metals, aluminum is highly resistant to most forms of corrosion; its natural aluminum oxide coating provides excellent protection against the effects of air, temperature, moisture, and chemicals. It is inert to acidic foods and requires no lacquer or other protection. Although aluminum is easily recyclable [24].

Steel food packaging consists mainly of cans and other containers, lids, caps, and closures. Steel cans are made from tin-plated steel or electrolytic chromium-coated steel (ECCS). For most food categories, tinplate containers are usually lacquered with organic coatings to form a barrier between the metal and food; ECCS always requires an organic coating to resist corrosion. For light colored, acidic fruits and juices, tinplate cans are not coated with an organic coating, as tin oxidizes more easily than food, preventing darkening and flavor changes, but reducing shelf life to limit tin ion migration. Steel is a permanent material that can be infinitely recycled without loss of quality [1].

2.3. Paper and Board

Paper and cardboard are primarily used for dry food packaging and secondary or tertiary containment. When coated or waxed, they can also be used for moist or fatty foods. Their recyclability and renewability make them environmentally attractive [1].

2.4. Plastics

Plastics dominate the modern food packaging market. They come in a variety of forms, including bottles, films, trays, bags, pots, cups, pouches, bowls, and many more [1]. They can be molded into various forms, such as bottles, films, trays, cups, or pouches, and offer versatility, low cost, and chemical resistance. What's more, many plastics are heat sealable, easy to print, and can be integrated into production processes where the package is produced, filled, and sealed on a one-line production process. The major disadvantage of plastics is their variable permeability to light, gases, vapors, and small, low molecular weight [24]. Plastic packaging is mainly manufactured from fossil-fuel based. However, the source of raw materials has no impact on the recyclability of plastics, which depends on the type of plastic used [1].

The main types of films are represented in **Table 1**.

Table 1. Food package types [2,25].

Packaging Type	Product Type	Application*
Aseptic processing	Egg (whole liquid)/dairy products	Primary
Bags	Chips, apples, rice, canned tomato soup	Primary
Cans	Eggs, milk/fruit juices carton	Primary
Paper (cardboard, coated)	Bagged salad	Primary
Flexible packaging	Pieces of meat/fish	Primary
Trays	-	Primary
Boxes	Corrugated boxes for primary packaging: cereal boxes	Secondary
Pallets	A series of boxes on a single pallet for transport from the producing plant to a distribution station	Tertiary

Note: * Primary packaging is the main package used to hold food being processed; secondary packaging combines primary packages inside one box; tertiary packaging combines multiple secondary packages into one pack.

3. Food Interaction with Packaging Materials

The interface between food and packaging materials involves various physicochemical processes that drive the transfer of substances. These interactions are critical, as they can influence both the quality of the food and the safety of consumers. The type of packaging material and the conditions under which the food is stored determine the mechanisms of mass transfer, which may result in chemical, sensory, or microbiological alterations in the packaged product.

One key mechanism through which foods interact with packaging materials is physisorption, also known as surface adsorption. This process is driven by weak intermolecular forces—such as van der Waals attractions and electrostatic interactions—between molecules in the food and the packaging surface. Because these forces are relatively weak, physisorption is usually reversible and predominantly involves lowmolecularweight compounds found in either the food or the packaging. While physisorption by itself does not necessarily lead to lasting contamination, it can serve as an initial interaction step that facilitates subsequent migration or diffusion of substances across the foodpackaging interface [16].

Another significant mechanism of interaction is sorption, in which components from food are taken up into the bulk of the packaging material. This phenomenon can induce swelling or plasticization of the material and, in certain situations, contribute to the deterioration of both the packaging and the food itself. Sorption is especially relevant for polymer-based packaging, as lipophilic compounds present in foods can penetrate the polymer matrix, gradually modifying its barrier properties and mechanical performance [16].

Permeation constitutes a third important interaction pathway, describing the movement of gases or volatile compounds through the packaging material. This mechanism may permit the entry of external contaminants or lead to the loss of desirable food aromas. The extent of permeation depends on the solubility and diffusivity of the molecules within the material and is significantly influenced by factors such as temperature, thickness of the packaging, and polymer structure [16].

The transfer of substances like plasticisers, antioxidants, or stabilisers from the packaging material to the food product is known as migration. This includes, for example, the migration of low molecular weight compounds, such as residual monomers, additives (antioxidants, plasticisers) or oligomers from polymeric packaging into food matrices, which can pose potential toxicity risks [18]. The presence of these migrating substances may present potential health hazards, especially when food is stored for extended periods.

Figure 1 provides an overview of the main interaction pathways between food and packaging materials, highlighting diffusion, sorption, and permeation as key processes controlling substance transfer. In real-world systems, these interactions are dynamic and often occur simultaneously, with their extent and rate affected by factors such as food composition, packaging structure, storage conditions, and processing parameters. A thorough understanding of these mechanisms is essential for accurately predicting migration behavior, designing safer and more effective packaging materials, and implementing comprehensive risk assessment strategies.

Figure 2 [16] illustrates the different mechanisms of interaction between food and packaging materials.

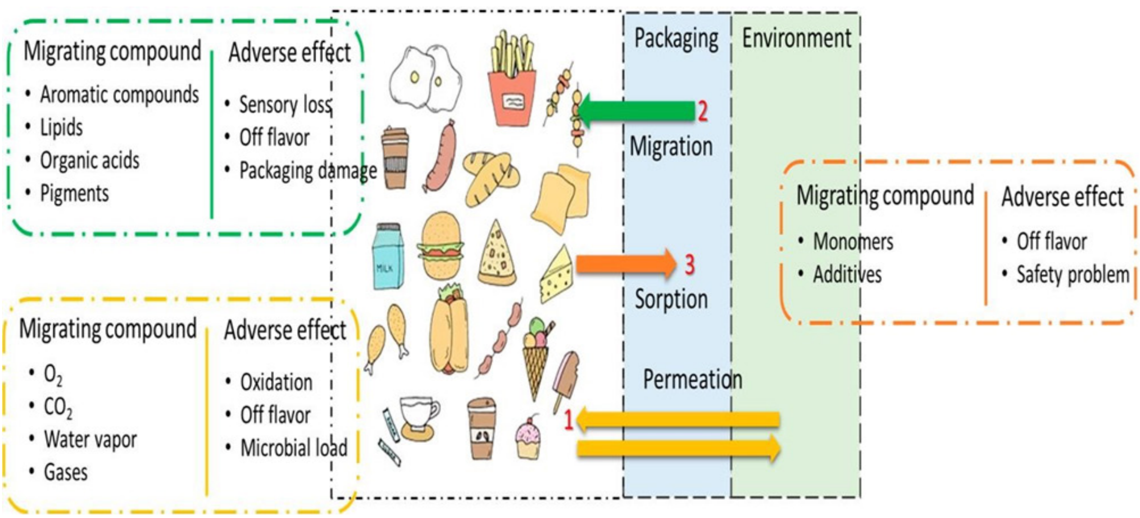

Figure 2. Interaction between packaging material and food [16].

4. Food Simulant

Throughout the food supply chain, numerous chemicals can unintentionally enter food. These include additives, pesticide residues, environmental pollutants, mycotoxins, and micronutrients. Packaging systems and other food-contact materials are also a source of chemicals in food and beverages. Monitoring exposure to these chemicals has become an integral part of ensuring the safety of the food supply [8].

Migration is a widespread concern because thousands of potential substances can transfer from packaging into food. Additives are the most common group of potential migrants, as they are not bound to the polymer mesh and are a likely source of neoformed substances [6].

There are several types of potential migrants, which are not considered in the same way by public authorities or at the quality control level:

- Residual monomers used during polymerization;
- Technological additives such as stabilizers and colorants;
- Monomer reaction or degradation products, polymers, and processing aids (neoforms);
- Unlisted substances, including impurities, auxiliary agents, or contaminants from recycled materials.

Many chemicals are used in food contact materials, and to date, over 3000 indirect food additives, including chemicals used in food contact materials, have been listed [26,27].

5. Migration Mechanism

Migration refers to the diffusion of molecules from packaging into food, potentially altering the properties of both. It is influenced by factors such as the packaging material, chemical nature of the migrants, food composition, contact conditions, temperature, light, agitation, and storage or processing parameters [2].

Various chemical substances are generally found in foodstuffs during the different phases of the supply chain, such as micronutrients, flavorings, antimicrobials, antioxidants, pesticides and mycotoxins, etc. In addition, additives such as plasticizers, mono- and oligomers present in packaging materials can also be transferred to foods by contact during the processing or packaging; this transfer of chemicals compounds between the food and packaging is known as "migration". Migration can lead to off-flavors or the transfer of unwanted substances into food products. Understanding this process is essential for predicting and controlling contamination [2].

The substances that migrate from food packaging to foods are highly complex. Diffusion phenomena are the main migration mechanism, where macroscopic mass movement of molecules occurs from a higher to a lower concentration gradients until an equilibrium is reached [28].

The rate of molecular diffusion is mathematically represented by Fick's second law [2]:

$$dC_p/dt = D\ (d^2C_p/dx^2)$$

where,

C_p: concentration (mg/g) of migrant in packaging material.

D: coefficient of diffusion (cm^2/s). t(s): time of diffusion.

x: distance (cm) between food and packaging material.

While these mathematical models continue to be refined, they offer valuable estimates for evaluating chemical contamination and for identifying the key factors that govern migration. A better assessment of the migration of chemicals from packaging to food would help limit and control food contamination, thereby promoting food security [2].

6. Type of Migration

Two main terms are used when describing migration phenomena: overall migration and specific migration. Overall migration refers to the total mass of all substances transferred from a unit area of packaging material into food. It measures the cumulative amount of chemical transfer. Specific migration, on the other hand, represents the transfer of a particular chemical compound or class of substances from the packaging into the food [2].

7. Hazards of Packaging Materials in Contact with Foods

The substances that can migrate into food and affect its safety depend on the nature and composition of the packaging material. The constant introduction of new packaging materials has increased the number of specific hazards to which humans are exposed through migration from packaging to food [8].

Mass transfer has been categorized as:

(a) Physical interactions at the food–packaging interface;
(b) Chemical interactions, such as corrosion of metallic packaging by food components;
(c) Microbiological contamination of food caused by contact with contaminated packaging material [2,10].

Understanding these hazards is crucial for risk assessment and for the development of packaging systems that minimize contamination and ensure consumer safety.

8. Analytical Evaluation of Contaminants in Foodstuffs

Quantifying and identifying potential contaminants are fundamental for maintaining food safety. Detecting the origin of contaminants, whether from processing, packaging, or storage, remains a major analytical challenge. The differences between food additives (direct) and substances migrating from packaging (known as "indirect additives" in the US context) are such that they require different methodologies when assessing consumer [8]. To harmonize analytical approaches, research now focuses on developing traceable and standardized methods for quantifying contaminants and identifying their sources throughout the production and packaging chain. Detecting compounds from food packaging in food is difficult, as these compounds are often unknown, present in trace amounts and have a wide variety of physico-chemical characteristics. The development of rapid and reliable analytical methods, suitable for detecting the largest possible number of potential contaminants, is necessary to implement effective controls. The following table (**Table 2**) shows the analytical techniques used to detect migration in foodstuffs.

Table 2. Examples of analytical techniques commonly used to identify scattering compounds after solid/solid or solid/liquid contact experiments [29].

Analysis Technique	Analyzed Samples	Analyzed Molecules	References
Chromatography			
Gaz (GC)	Extraction solution	Depending on the nature of the detector	Karaiskakis and Gavril [30]
Liquid (HPLC)			Nerín et al. [31]
Spectrophotometry			
Ultraviolet (UV)	Extraction solution or polymer	UV probe, aromatic	Ferrara et al. [32]
Visible		Dye	Feigenbaum et al. [33]
Infrared (IR)		IR probe, carbonyl compound	Moisan [34]
µ Spectrophotometry			
Ultraviolet (UV)	Polymer	UV probe, aromatic	Dudler and Muiños [35]
Infrared (IR)		IR probe, carbonyl compound	Riquet et al. [36]
Gravimetry (µbalance)	Polymer	All types of molecules	Aminabhavi et al. [37]

9. Factors Influencing the Migration Phenomenon

Migration is a multifactorial process affected by the intrinsic properties of both the food and the packaging material, as well as by environmental conditions. The most significant parameters include the nature of the food, the type of contact, duration, temperature, and the structural characteristics of the packaging.

- **Nature of Food**

The chemical composition of food has a major influence on migration levels. For example, fatty foods tend to exhibit higher migration rates than aqueous products, as lipophilic substances dissolve more easily in fats. Numerous studies have been conducted to examine the mass transfer of substances between packaging and food by applying solubility parameters, which have helped test the extent of migration during real-time food production [2,38].

- **Contact Type**

Migration is associated with the type of contact (direct or indirect) between food and packaging. More specifically, direct contact between food and packaging increases the mass transfer rate, while with indirect contact, the gaseous medium between the food and packaging results in a relatively slower migration [2].

- **Time and Duration**

The duration of contact strongly affects the extent of migration. According to some experimental data, the mass transfer of a substance is directly related to the square root of the time during which food and packaging materials are in contact. Conversely, temperature influences the equilibrium time of migration, following an inverse logarithmic relationship [39].

- **Temperature**

The relationship between temperature and migration is directly influenced by the storage temperature of food. Higher storage or processing temperatures accelerate molecular diffusion and increase migration rates [40].

- **Packaging Material**

The thickness and intrinsic properties of the packaging material, such as its plasticization, greatly influence the potential migratory transfers to food. Additives and recycled fillers may also modify permeability and chemical reactivity [41,42].

10. Conclusions

Food packaging is essential for ensuring convenience and extending shelf life by protecting products from microbial, chemical, and biological spoilage. The past decades have seen significant advancements in packaging materials to meet the growing needs of the food industry. Choosing the right packaging requires careful evaluation of food composition, potential interactions with the material, and their effects on quality and safety, with monitoring of overall and specific migration being critical for consumer protection.

Future developments in the sector will benefit from stronger collaboration between researchers, manufacturers, and stakeholders to create environmentally sustainable and safe packaging solutions. Key research directions include the design of biodegradable and intelligent packaging, the improvement of analytical methods for faster and more accurate assessment of food–material interactions, and the development of predictive models for chemical migration. These approaches will support safer, more sustainable, and functionally optimized food packaging systems.

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