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Preeti Khokhar
I.C. College of Community Science, CCS Haryana Agricultural University, Hisar, Haryana, India

Kanika Pawar
Centre of Food Science & Technology, CCS Haryana Agricultural University, Hisar, Haryana, India

Corresponding Author:
Kanika Pawar
Centre of Food Science & Technology, CCS Haryana Agricultural University, Hisar, Haryana, India

Chemical migration from packaging materials into consumable food matrices: A mini review

Preeti Khokhar and Kanika Pawar

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Abstract
The migration of chemical substances from food packaging materials into packaged foods presents a significant concern for food safety and public health. Packaging materials—such as plastics, metals, glass, and paper—often contain additives, residual solvents, and monomers that have the potential to migrate into the food, causing chemical contamination. This migration can occur through various mechanisms, including diffusion, volatilization, permeation, convection, solvent extraction, and heat transfer. Factors like temperature, food composition, contact time, and the characteristics of the packaging material influence these processes. A thorough understanding of the interactions between food and packaging is vital for assessing the extent of migration and its associated risks. Advanced analytical methods, such as chromatography and mass spectrometry, are used to detect and quantify migrating chemical compounds. Regulatory agencies like the European Food Safety Authority (EFSA) and the U.S. Food and Drug Administration (FDA) have established permissible migration limits for specific substances to safeguard consumer health. This review explores the factors influencing chemical migration, the mechanisms involved, and the techniques used for assessment. Addressing these issues can enhance food safety regulations, improve consumer protection, and foster the development of safer packaging materials.

Keywords: Chemical compounds, food packaging material, food safety, health concerns, migration mechanisms, packaging materials

Introduction

Food packaging usage has steadily increased over the past few decades as a result of (i) globalization, (ii) supermarket operations, and (iii) household dynamics. As a result, the food industry has become more and more dependent on packing, to the extent that practically all processed foods are now packed (Chakori *et al.*, 2021) [4]. The food industry chooses the most appropriate packaging materials for a product, considering the functional properties of the materials. Primary food packaging materials include materials like paper, paperboard, plastic, glass, aluminium or combinations of these (Dey *et al.*, 2021) [6]. Food packaging plays an integral role in preserving the safety, quality, and shelf life of products. Packaging materials like plastic, glass and metal are selected based on their ability to protect food from contaminants, moisture, and light (Gupta *et al.*, 2024) [12]. Although plastics are the most commonly used packaging materials because of their versatility and affordability, concerns have grown regarding the migration of chemicals from these materials into food (Gupta *et al.*, 2024) [12]. Chemicals such as plasticizers, solvents and monomers can leach from packaging materials into food under certain conditions (Rodríguez-Ramos *et al.*, 2024). Migration refers to the transfer of chemical substances frosm packaging materials into food, which can occur due to physical, chemical, or environmental factors (Zhao *et al.*, 2023) [22]. This process can involve various chemicals, including plasticizers, solvents, and stabilizers, potentially affecting food safety and consumer health (Gupta *et al.*, 2024) [12]. Understanding migration is crucial for ensuring food safety and meeting regulatory standards (Santos *et al.*, 2024) [19]. The study of chemical migration from packaging materials to food is critical for ensuring food safety and public health. With the growing use of synthetic materials, such as plastics, in food packaging, understanding the potential migration of chemicals like plasticizers, solvents, and stabilizers is vital (Zhao *et al*., 2023) [22]. These chemicals can have detrimental health effects, including endocrine disruption and carcinogenicity, especially with prolonged exposure (Chen *et al.*, 2023) [5].

As consumer demand for sustainable packaging rises, it is also essential to explore alternative materials that minimize migration risks while maintaining product integrity (Zhao *et al.,* 2023) [22]. This review not only supports the development of safer packaging but also strengthens consumer confidence and promotes innovations in the packaging industry (Gupta *et al.*, 2024) [12].

Chemical compounds in packaging materials

Plastic compounds

Plastic compounds, commonly used in food packaging, include materials like polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC), which offer flexibility, durability, and cost-effectiveness (Chen *et al.*, 2023) [5]. However, certain plasticizers, stabilizers, and additives used in these materials, such as bisphenol A (BPA) and phthalates, have raised concerns due to their potential to migrate into food and impact human health (Gao *et al.*, 2024) [9]. These chemicals are linked to long -term adverse effects, causing cancer, endocrine disruption and reproductive toxicity (Zhao *et al.*, 2023) [22].

Ink and Coatings

In food packaging, inks and coatings are essential for branding, product information, and protection. These inks and coatings often contain chemicals such as solvents, pigments, and heavy metals (Santos *et al.*, 2024) [19]. Solvents like toluene and xylene are used to dissolve inks, while pigments often contain heavy metals such as lead, cadmium, and chromium, which can migrate into food under certain conditions (Gao *et al.*, 2024) [9]. These substances are of particular concern due to their toxicological effects, including carcinogenicity and neurotoxicity, especially when food is in prolonged contact with the packaging (Zhao *et al.*, 2023) [22].

Additives and Plasticizers

Additives and plasticizers are commonly used in food packaging to enhance the flexibility, durability, and processing properties of plastics (Gao *et al.*, 2024) [9]. Substances like phthalates, adipates, and citrates are often added to plastics such as PVC, PET, and polypropylene to improve their performance (Chen *et al.*, 2023) [5]. However, many of these compounds can migrate into food products, raising concerns due to their potential toxicity, including endocrine disruption and developmental effects (Zhao *et al.*, 2023) [22]. Migration from materials such as glass, metals, and paper-based packaging is also a concern, though generally to a lesser extent than plastics. Glass containers are typically inert but may leach trace amounts of metals like lead or cadmium from certain types of glass or coatings (Gao *et al.*, 2024) [9]. Metal packaging, such as cans, can release substances like tin or aluminium, which can interact with acidic foods (Chen *et al*., 2023) [5]. Paper-based packaging, often treated with waxes, resins, or inks, can migrate chemicals, including solvents and heavy metals, into food under specific conditions (Su *et al.*, 2023) [21].

Antioxidants

Antioxidants are commonly used in packaging materials to prevent the oxidation of the packaging itself or the food within, thereby extending shelf life. However, these compounds can migrate into the food over time, especially under certain conditions like high temperatures or prolonged contact. Antioxidants such as butylated hydroxyl anisole (BHA), butylated hydroxyl toluene (BHT), and other phenolic compounds can leach into food, potentially altering its flavor, aroma, and safety (Fasihnia *et al.*, 2020) [8]. Fatty and oily foods are particularly susceptible to antioxidant migration, as these compounds are lipophilic, making them more likely to be transferred from packaging to food. High temperatures, common in storage and transportation, can accelerate the migration of antioxidants from packaging into food (Alamri *et al.*, 2021) [1].

Monomers and Oligomer

Monomers and oligomers, which are often used as building blocks in the production of food packaging materials, can migrate into food under certain conditions. These substances are typically residual components from the polymerization process or degradation products that can leach from packaging materials into food. These compounds can migrate more readily when the packaging is exposed to elevated temperatures, prolonged storage, or acidic or fatty foods, which can facilitate the release of monomers like styrene from polystyrene or bisphenol A (BPA) from polycarbonate plastics (Zulkifli *et al.*, 2021) [24]. Both monomers and oligomers, due to their smaller molecular size, have higher mobility, making them more likely to migrate into food, especially in high-fat or high-temperature conditions (Arvanitoyannis & Kotsanopoulos, 2014) [3]. Such migration raises concerns about the potential health effects of exposure to these substances, which have been linked to endocrine disruption, carcinogenicity, and other adverse health effects.

Factors affecting migration rates through packaging material

The migration of chemicals from food packaging into food products is influenced by various factors:

Physical and Chemical Factors

The migration of chemicals from food packaging into food products is influenced by various physical and chemical factors. One key factor is temperature; higher temperatures can increase the rate of migration by enhancing the diffusion of chemicals from the packaging material into the food. This is especially critical during transportation and storage under non-optimal conditions. The composition of the food itself also plays a significant role in migration. Fatty foods, for example, tend to absorb lipophilic substances more effectively, leading to higher migration of fat-soluble compounds such as plasticizers and solvents. Higher temperatures result in increased migration rates and a faster attainment of equilibrium.

Food composition

Food composition significantly influences the migration of chemicals from packaging materials. For instance, fatty foods, such as oils, cheeses and meats, are more likely to absorb fat-soluble compounds like plasticizers and solvents from packaging materials (Gao *et al.*, 2021) [9]. The pH, moisture content, and fat content of the food affect the solubility and diffusivity of chemicals, thereby influencing migration rates (Zhao *et al.*, 2022) [22]. Dry foods, such as crackers and cereals, typically have lower moisture content, which can reduce the migration of water-soluble chemicals, but they may still absorb volatile substances. The need for packaging materials to be evaluated with respect to the specific food types they will contact, to ensure safety and minimize potential risks from chemical migration (Triantafyllou *et al.*, 2007) [22].

Properties of packaging materials

The properties of packaging materials significantly influence the migration of chemicals into food. Materials like plastics, metals, glass, and paper have different levels of permeability, which influence the rate at which chemicals migrate. Plastics like polyethylene and polypropylene are more prone to releasing additives such as plasticizers, solvents, and stabilizers, especially under conditions of high temperature or prolonged contact with food. Glass and metal packaging, on the other hand, have lower permeability, but can still leach certain substances like metals or chemicals from coatings (Nerin *et al.*, 2007) [15]. The structural design of packaging materials, such as multi-layered films, can act as barriers, reducing migration rates by limiting chemical diffusion. The presence of recycled ingredients showed no correlation with migration.

Interaction of food matrices with food packaging material

As packaging materials come into direct contact with food, various mechanisms of migration, leaching, and chemical reactions can occur, transferring substances from the packaging to the food. These interactions can affect the food's sensory attributes, nutritional content, and safety. A physical interaction may occur when chemical substances are transferred between foods through the food-package interface. A chemical interaction can take place if a food item causes corrosion in a metal package. Additionally, a microbial interaction may happen when food becomes contaminated by microorganisms due to contact with unsuitable packaging materials (Lee, 2010) [14].

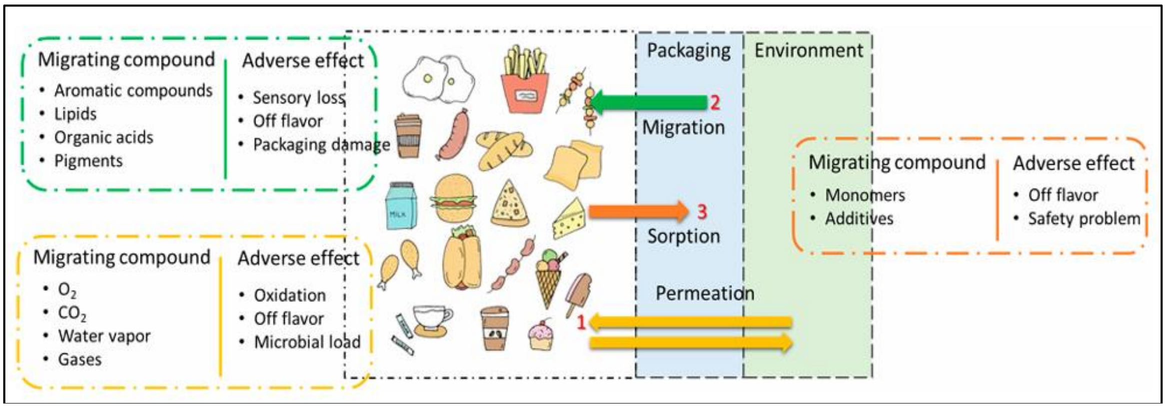

Fig 1: Interaction between packaging material and food (Gupta *et al.*, 2024) [12].

Migration mechanism

The migration mechanisms are influenced by factors such as temperature, time, food composition, and the characteristics of the packaging. The primary migration mechanisms include:

Diffusion

Diffusion is the most common migration mechanism, where chemical compounds move from the packaging material into the food due to concentration gradients. When the concentration of a substance is higher in the packaging material than in the food, the substance will naturally migrate to the area of lower concentration in an attempt to reach equilibrium. This process is typically driven by the physical properties of the packaging material (e.g., permeability) and the food product (e.g., fat content, acidity, moisture). For example, hydrophobic substances like plasticizers and antioxidants may diffuse more readily into fatty foods, as they tend to interact with the lipid content (Simoneau, 2008) [20].

Volatilization

Volatilization occurs when volatile chemicals in the packaging material evaporate and migrate into the food. This typically happens with volatile compounds like solvents, fragrances, or certain additives used in food packaging. The rate of volatilization depends on the temperature and humidity conditions, with higher temperatures accelerating the evaporation of substances from packaging into food (Lee *et al.*, 2010) [14].

Permeation

Permeation refers to the process by which small molecules move through the packaging material itself, bypassing any protective layers or barriers. This process is particularly important for plastic packaging materials, where small molecules like monomers or oligomers may migrate over time through microscopic pores in the material (Jickells *et al.*, 2005) [13]. For example, monomers such as styrene from polystyrene packaging can permeate into food, especially under conditions of prolonged contact or high temperature.

Convection

Convection refers to the migration of chemical compounds facilitated by fluid movement, such as the movement of gases or liquids in packaging. This can happen when food products contain liquids or are stored under conditions where fluid movement inside the packaging (e.g., gases or water vapour) helps carry chemicals from the packaging material into the food. This mechanism is especially relevant in vacuum-sealed or modified atmosphere packaging, where fluid dynamics can influence the rate of chemical migration (EFSA, 2008).

Chemical Reactions

Chemical reactions between the food and packaging materials can also contribute to migration. For instance, acidic or alkaline foods can react with metals in the packaging, leading to the release of metal ions into the food. A well-known example is the corrosion of aluminium cans, where acids from the food can cause the release of aluminium ions into the food product (Arvanitoyannis and Stratakos 2011). Similarly, reactive chemicals in the packaging can degrade over time, releasing potentially harmful by-products into the food.

Migration testing methods

Food Simulants

Food simulants are employed to replicate the conditions that packaging materials would encounter when in contact with real food. These simulants are selected based on the characteristics of the food being tested, such as its fat content or acidity. Regulatory bodies like the EFSA and FDA set guidelines for simulant selection and testing conditions to ensure that migration tests accurately reflect potential real-world scenarios (EFSA, 2008) (Grob 2008).

Common simulants include

- Water (for aqueous foods)
- Ethanol or isooctane (for fatty foods)
- Acidic solutions (for acidic foods like vinegar or fruit juices)

Specific Migration Testing

Specific migration testing evaluates the migration of individual substances, such as monomers, oligomers, plasticizers, and additives, from food packaging materials into food. This type of testing is essential for assessing substances that may pose specific health risks, such as bisphenol A (BPA) and phthalates. Advanced analytical techniques, including high-performance liquid chromatography (HPLC), HPLC with fluorescence detection (HPLC-FLD), liquid chromatography-tandem mass spectrometry (LC-MS/MS), gas chromatography-mass spectrometry (GC-MS), and gas chromatography coupled with Orbitrap mass spectrometry, are utilized to detect and quantify these substances at trace concentrations. (Garcia *et al.*, 2006; Gupta *et al.*, 2024) [12]. Regulatory authorities, including the European Food Safety Authority (EFSA) and the FDA, set migration limits to ensure the safety of food products, establishing safe thresholds for specific chemicals (EFSA, 2008) (Grob 2008).

Conclusion

The migration of chemical compounds from packaging materials into packaged foods is a critical focus in food safety and regulatory science. Packaging materials, commonly composed of plastics, metals, or paper, often contain chemical additives such as plasticizers, monomers, antioxidants, and stabilizers, which can transfer into food under specific conditions. Factors influencing this migration include temperature, time, food composition, and the chemical characteristics of both the packaging and the food. Migration is typically evaluated through comprehensive testing methods, including overall and specific migration tests, which replicate real-world conditions to quantify substance transfer. Recent research highlights the health risks posed by compounds like bisphenol A (BPA) and phthalates due to their endocrine-disrupting effects. Consequently, regulatory agencies such as the European Food Safety Authority (EFSA) and the U.S. Food and Drug Administration (FDA) have established strict migration limits to safeguard public health. While significant advancements have been made in understanding and managing chemical migration, ongoing research, innovation in testing methodologies, and robust regulatory frameworks remain essential to ensure consumer safety.

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