Letters in Food Science & Technology

Food Packaging Materials: Structure-Property Relationships, Food Preservation, Chemical Safety, and Life-Cycle Sustainability

A Narrative Review

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ABSTRACT

Food packaging is a functional part of food preservation. Its performance arises from interactions among material chemistry, molecular structure, transport properties, food composition and environmental conditions. Conventional materials (plastics, paperboard, glass and metals) are usually compared through lists of advantages and limitations, but a mechanistic understanding requires linking structure to barrier performance, mechanical integrity, food quality, chemical migration and end-of-life outcomes. This narrative review examines these links for conventional polymers, fibre-based materials, glass, metals, bio-based polymers and emerging packaging systems. It emphasizes polymer crystallinity, chain mobility, intermolecular interactions, multilayer architecture, moisture sensitivity, and the transport of gases, water vapour and chemical migrants. The consequences for oxidation, moisture-mediated deterioration, microbial stability and shelf life are discussed alongside active and intelligent packaging. Chemical migration is treated as a problem of diffusion, partitioning, contact conditions and exposure assessment. Environmental performance is considered through life-cycle assessment, including package mass, manufacturing energy, reuse, recycling and packaging-related food waste. The review argues that a material cannot be evaluated independently of the food it protects and the distribution system in which it operates, and it proposes an integrated framework that connects molecular structure to preservation efficacy, chemical safety and environmental performance. Priorities for future work include validated structure–property models, food-specific shelf-life testing, comprehensive migration assessment, recyclable high-barrier structures, and life-cycle comparisons based on equivalent packaging services.

Keywords: Food packaging; structure–property relationships; polymer crystallinity; gas permeability; chemical migration; shelf life; active packaging; biodegradable polymers; life-cycle assessment; food waste.

1. Introduction

Food packaging is integral to food processing, preservation, distribution, retail and consumption. Its basic purpose is to maintain food quality and safety from production to consumption while enabling handling, storage, transport and the communication of product information (Marsh & Bugusu, 2007; Han et al., 2018). Packaging can reduce exposure to oxygen, water vapour, light, dust and microorganisms, but the degree of protection depends on the material, closure system, package integrity and storage environment.

Its importance has grown with industrial food processing, international trade, convenience foods, chilled and frozen distribution, and longer supply chains. Appropriate packaging preserves sensory properties, slows oxidation, limits moisture loss or uptake, prevents physical damage and reduces post-process contamination. It cannot, however, compensate for poor hygiene, unsafe processing, temperature abuse or an unsuitable shelf-life strategy.

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Historically, packaging relied on glass, metal, paper and cellulosic materials. Synthetic polymers transformed the sector by offering lightweight, flexible and easily processed materials with a wide range of mechanical and barrier properties. Polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS), polyamide (PA) and ethylene–vinyl alcohol (EVOH) now serve distinct functions, alone or in multilayer structures.

Environmental concern and advances in materials science have stimulated interest in bio-based and biodegradable polymers, nanocomposites, edible coatings, antimicrobial packaging, oxygen scavengers, freshness indicators and digital traceability (Hussain et al., 2024; Kumari et al., 2024). Yet the terms “bio-based,” “biodegradable,” “compostable” and “recyclable” describe different attributes and are not interchangeable (Nilsen-Nygaard et al., 2021). A bio-based polymer may not biodegrade under ordinary environmental conditions, and a compostable package may need facilities that are unavailable in its intended market.

Food packaging should therefore be understood as a coupled material–food system rather than an isolated container. The contribution of this review is to connect molecular structure to material properties, to food preservation and chemical safety, and finally to life-cycle performance.

1.1. Central framework: from molecular structure to sustainability

The causal chain can be described in five linked stages: (1) material chemistry and structure, meaning polymer chemistry, molecular weight, crystallinity, cross-linking, fibre structure, coatings and interfaces; (2) functional properties, meaning gas and water-vapour permeability, mechanical strength, optical properties, thermal resistance and seal integrity; (3) package–food interactions, meaning oxygen transfer, moisture migration, aroma sorption, chemical migration, microbial ecology and food respiration; (4) food preservation and safety, meaning oxidation rate, texture retention, sensory quality, microbial stability, shelf life and consumer exposure; and (5) system-level environmental outcome, meaning material use, manufacturing impacts, transport, food losses, reuse, recycling and disposal (Figure 1).

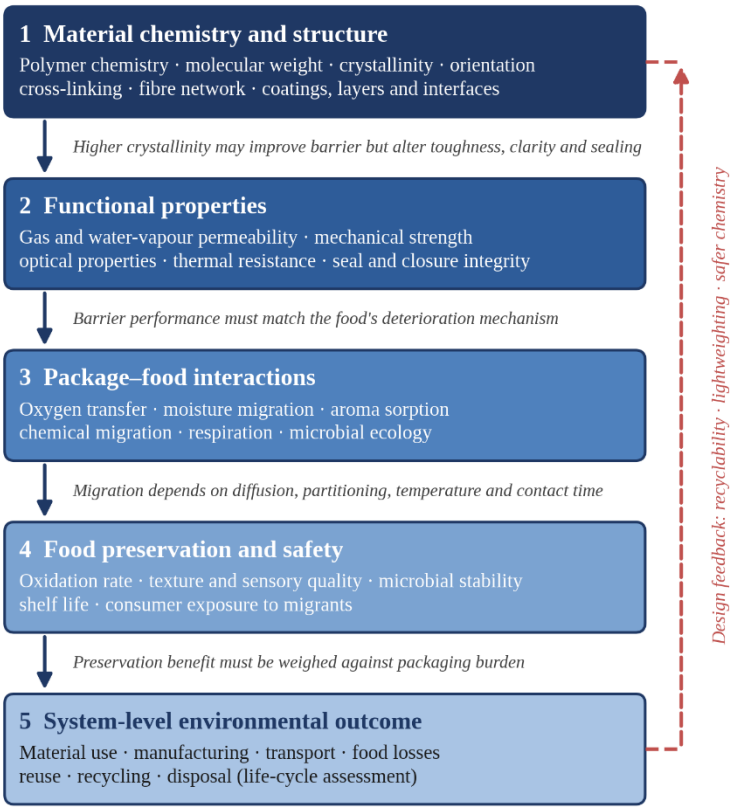


Figure 1. Integrated conceptual framework linking packaging-material structure to food preservation, chemical safety and life-cycle performance. Solid arrows show the causal sequence; the dashed arrow shows design feedback from environmental outcomes to material choice.

These relationships are interdependent rather than strictly linear. Higher crystallinity in a semi-crystalline polymer can reduce chain mobility and the volume available for diffusion, which may improve barrier performance. The processing conditions that alter crystallinity can also change toughness, transparency, sealing behaviour and dimensional stability. Likewise, a high-barrier multilayer structure may improve preservation while complicating recycling.

Three questions guide the review. How do material chemistry and structure determine packaging performance? How do these properties influence food deterioration, shelf life and chemical exposure? How should preservation benefits be balanced against manufacturing and end-of-life impacts?

2. Scope and methodology

This article is a narrative review that synthesizes established knowledge and selected literature on conventional, alternative and emerging food-packaging materials. It covers material properties, food preservation, food-contact safety, sustainability and functional packaging technologies. Because the approach is narrative, no claim is made of exhaustive database coverage, formal screening, risk-of-bias assessment or quantitative meta-analysis. The sources are mainly recent peer-reviewed reviews supplemented by standard textbooks and regulatory instruments; primary studies should be added where specific numerical values are quoted. If the target journal requires it, the databases searched, search dates, search strings, inclusion criteria and reference-verification procedure should be documented before submission.

3. Fundamental functions and performance requirements

Packaging performs several interconnected functions whose relative importance depends on food composition, processing history, storage conditions, distribution time and the dominant deterioration risks (Robertson, 2012).

Containment: holds the product and facilitates portioning, dispensing and transport.

Physical protection: limits damage from compression, vibration, impact, abrasion and handling.

Barrier protection: controls transmission of oxygen, carbon dioxide, water vapour, aroma compounds and other gases.

Chemical protection: limits oxidation, light-induced deterioration and unwanted interactions with the environment.

Microbiological protection: provides a physical barrier against post-process contamination; it does not necessarily kill microorganisms.

Shelf-life management: maintains quality through an appropriate combination of packaging, processing and storage.

Communication and traceability: conveys ingredients, allergens, nutritional information, date marking, batch identification and handling instructions.

Convenience: enables opening, resealing, portion control, reheating and disposal or reuse.

3.1. Critical material properties

Property	Scientific significance	Typical relevance
Oxygen transmission rate (OTR)	Oxygen transfer through a material under specified conditions	Oxidation-sensitive foods, meat, coffee, oils
Water-vapour transmission rate (WVTR)	Water-vapour transfer under specified conditions	Biscuits, powders, fresh produce, dried foods
Light transmission	Exposure to visible and ultraviolet radiation	Milk, oils, vitamins, light-sensitive beverages
Tensile strength and elongation	Resistance to stress and deformation	Films, bags and flexible pouches
Puncture and impact resistance	Resistance to physical damage	Frozen foods, sharp-edged products, transport
Thermal resistance	Suitability for hot filling, pasteurization, retorting or freezing	Ready meals and shelf-stable foods

Property	Scientific significance	Typical relevance
Seal integrity	Resistance to leakage and ingress through seals or closures	Vacuum packs, sterile packs, liquids
Chemical migration	Transfer of substances from packaging into food or simulants	All food-contact materials
Recyclability and reuse potential	Compatibility with actual collection and recovery systems	Circular packaging design

OTR and WVTR are not universal material constants. They depend on film thickness, temperature, relative humidity, pressure or concentration gradients and test method, so values obtained under different conditions should not be compared directly.

4. Conventional food-packaging materials

4.1. Plastic packaging materials

Plastics are widely used because their properties can be tailored through polymer selection, molecular structure, additives, orientation, coating and multilayer construction. Their low density and formability support flexible films, rigid containers, bottles, trays, closures and high-speed packaging operations.

4.1.1. Major polymer types

Polyethylene (PE: LDPE, LLDPE, HDPE). Applications include bags, films, liners, pouches, bottles and closures. PE offers good moisture resistance, chemical resistance, flexibility and heat-sealing capability. HDPE is generally stiffer than LDPE, which is useful for flexible films. Limitations include oxygen and aroma barriers that are poor relative to high-barrier polymers, grade-dependent heat deformation, and recycling difficulty for contaminated or multilayer formats.

Polypropylene (PP). Applications include food tubs, microwaveable containers, caps, films and snack packaging. PP offers useful stiffness, moisture resistance and heat resistance relative to many commodity plastics. Limitations include low-temperature brittleness in some grades, a limited oxygen barrier in unmodified form, and practical difficulty in recycling thin or contaminated flexible formats.

Polyethylene terephthalate (PET). Applications include beverage bottles, edible-oil bottles, trays and transparent containers. PET combines transparency, mechanical performance and a useful gas barrier for many beverages, and recycling pathways exist where collection and processing infrastructure are available. Limitations include thermal restrictions in some grades and reduced recycled quality caused by contamination or repeated processing.

Polyamide (PA) and ethylene–vinyl alcohol (EVOH). PA provides toughness and puncture resistance, whereas EVOH provides excellent oxygen-barrier performance under suitable humidity conditions. Both are often combined with PE or other polymers. Such multilayers can be difficult to separate and recycle, and EVOH barrier performance declines as humidity rises.

Polystyrene (PS and EPS). PS can be formed into rigid or foamed structures with useful stiffness and insulation. EPS is lightweight and can protect temperature-sensitive products in transport. However, its low density makes collection and transport for recycling difficult, food-contaminated formats may have limited recovery options, and restrictions vary by jurisdiction.

4.1.2. Advantages and limitations of plastic packaging

Advantages include low mass, design flexibility, high production rates, good sealing performance, transparent or opaque formats, potential reductions in transport energy, compatibility with vacuum and modified-atmosphere systems, and mature processing technology.

Limitations include environmental persistence when waste is poorly managed; recycling difficulties caused by additives, pigments, food residues, adhesives and multilayer structures; and the potential migration of monomers, oligomers, additives, degradation products, printing-ink constituents and other non-intentionally added substances (Geueke et al., 2018; Etxabide et al., 2022). Migration depends on chemical identity, food composition, time, temperature, package structure and regulatory compliance.

4.2. Paper and paperboard

Paper and paperboard are cellulose-based materials used in bags, cartons, corrugated cases, wraps, cups, trays, labels and composite beverage cartons. Their advantages are low mass, printability, stiffness, renewable-fibre potential and compatibility with established paper-recycling systems. In uncoated form they are poor barriers to moisture, liquids, oil and gas. Coatings, sizing agents, waxes or polymer liners can improve performance but may complicate recycling. Inks, adhesives, recycled-fibre contaminants and mineral-oil hydrocarbons require attention in food-contact applications (Etxabide et al., 2022).

4.3. Glass packaging

Glass is used for beverage bottles, jars, sauces, preserves and other products that need strong barrier performance. Advantages include excellent barriers to gases and water vapour when properly sealed, high chemical inertness under intended conditions, transparency or coloured light protection, suitability for validated thermal processes, and reuse and recycling potential. Limitations include weight, fragility, transport impacts, high-temperature manufacture and thermal stress. Closures, liners and caps can still be sources of migration.

4.4. Metal packaging

Steel, tinplate and aluminium are used in cans, beverage containers, foil, trays, closures, tubes and flexible laminates. Advantages include excellent light and gas barriers, physical protection, hermetic sealing, suitability for validated thermal processing and established recycling streams. Limitations include potential corrosion, the need for suitable internal coatings, energy-intensive primary production, and recycling difficulty for inseparable foil-based laminates.

4.5. Wood and other traditional materials

Wooden crates, baskets, pallets and reusable transport boxes remain relevant for produce and bulk distribution. They give mechanical protection and ventilation, but porosity, moisture retention, splinters, contamination and cleaning requirements can limit direct food contact. Bamboo, leaves and other plant-derived materials are used traditionally in some regions; hygiene, standardization, durability and supply may constrain industrial use.

4.6. Comparative evaluation of conventional materials

Material	Principal strengths	Principal limitations	Typical applications
PE	Moisture barrier, flexibility, heat sealing	Limited oxygen barrier in common grades	Films, bags, liners
PP	Stiffness, moisture resistance, heat resistance in suitable grades	Low-temperature impact limits in some grades; recycling challenges	Tubs, trays, caps
PET	Transparency, strength, useful gas barrier	Thermal limits vary; contamination can affect recycling	Beverage bottles, trays
PA/EVOH multilayers	Toughness and high oxygen barrier	Humidity sensitivity of EVOH; difficult multilayer recycling	Meat, cheese, vacuum packs
PS/EPS	Formability, cushioning, insulation	Collection challenges and low-density waste	Trays, cups, transport protection
Paper/paperboard	Printability, stiffness, renewable-fibre potential	Weak moisture, grease and gas barriers unless treated	Cartons, cases, dry foods
Glass	Strong barrier, chemical inertness, reuse potential	Heavy and fragile; energy-intensive production	Jars, bottles, preserves
Aluminium	Excellent barrier, low mass as foil, recycling potential	Foil damage; energy-intensive primary production	Foils, cans, laminates
Steel/tinplate	Strength, hermetic sealing, retort compatibility	Corrosion potential, coating requirements, weight	Cans, closures
Wood	Reusable transport structures, mechanical strength	Porosity, cleaning and hygiene constraints	Crates, pallets

The table describes general characteristics, not measured universal rankings. Coatings, thickness, package geometry, closures, manufacturing conditions and local waste-management infrastructure can change the comparison substantially.

4.7. Structure–property relationships in conventional materials

4.7.1. Polymer molecular architecture and gas permeability

Transport of gases and vapours through a polymer is governed by the solubility and diffusion of the permeant within it. For a homogeneous material under idealized steady-state conditions, the permeability coefficient is the product of the diffusion and solubility coefficients (Robertson, 2012):

$$\mathbf{P = D \times S}$$

where P is the permeability coefficient, D the diffusion coefficient and S the solubility coefficient of the permeant in the polymer. Real packaging departs from this ideal because of orientation, crystallinity, humidity, additives, defects, interfaces and non-steady-state transport.

Diffusion depends on molecular size, free volume, chain mobility and local polymer structure. Solubility depends on the chemical compatibility of the permeant with the polymer, including polarity and intermolecular interactions. A polymer that resists one gas may therefore be a much weaker barrier to water vapour or organic aroma compounds.

In semicrystalline polymers, ordered crystalline regions generally exclude penetrant molecules, so transport occurs mainly through amorphous regions. Increasing crystallinity can thus improve the barrier to some gases and vapours, but the effect depends on morphology, orientation, crystal–amorphous interfaces and processing history. Polar functional groups can interact strongly with water and raise water sorption; a material with excellent oxygen-barrier performance when dry may perform much worse at high relative humidity. For this reason PE, PP, PET, PA and EVOH cannot be ranked by a single generic barrier value. Performance must be assessed for the specific permeant and under the temperature, humidity, thickness and processing conditions relevant to the food.

4.7.2. Mechanical properties, molecular mobility and package integrity

Mechanical performance depends on chain entanglement, intermolecular forces, crystallinity, molecular orientation, plasticization, and defects or reinforcing phases. A highly oriented film may gain tensile strength along the orientation direction but become anisotropic. A stiff material may resist deformation yet fracture in a brittle manner, whereas a flexible material may tolerate deformation but offer inadequate puncture resistance.

Packages can fail even when intrinsic barrier performance is excellent. Pinholes, flex cracking, damaged seals, poor closure design and transport-induced punctures create pathways for oxygen, moisture or microorganisms. Barrier measurements on intact laboratory specimens should therefore be complemented by package-level testing, including seal integrity, puncture resistance and distribution simulation.

4.7.3. Paper and paperboard

Paper and paperboard derive their mechanical properties from interconnected cellulose fibres, hydrogen bonding, fibre length and orientation, density and moisture content. Cellulose hydroxyl groups interact with water, and as humidity rises, water sorption alters fibre swelling and weakens fibre–fibre bonds, reducing stiffness and compression resistance, particularly in corrugated transport packaging.

The porous structure allows gases and water vapour to pass unless it is modified. Surface sizing, polymer coatings, waxes, laminates and other treatments can improve liquid, grease or vapour resistance, but they may reduce repulpability or complicate recycling. The design challenge is to obtain adequate barrier performance while preserving fibre recovery and limiting incompatible materials.

4.7.4. Glass and metals

Glass is a continuous, nonporous barrier to gases and water vapour while the container and closure remain intact; its main limitations are fragility, weight, thermal stress and closure performance. Metals also have excellent intrinsic barriers, but food-contact performance depends on the metal, the food and any protective coating. Acidic or saline foods increase corrosion risk in unsuitable systems, and coating damage, seam defects and closure failure can compromise protection. The complete package assembly must therefore be evaluated.

5. Bio-based, biodegradable and compostable packaging materials

Bio-based and biodegradable materials have attracted interest as alternatives to fossil-derived polymers. Their performance varies with polymer chemistry, processing, additives, crystallinity, moisture and intended disposal conditions. "Bio-based" describes feedstock origin; "biodegradable" describes biological degradation under specified conditions; and "compostable" means meeting defined requirements under specified composting conditions (Nilsen-Nygaard et al., 2021). Several widely used matrices such as starch and cellulose are better described as semi-biodegradable than fully biodegradable (Weligama Thuppahige & Karim, 2022).

5.1. Starch-based materials

Starch from maize, cassava, potato and other sources can be processed into films, foams, coatings and blends. Advantages include renewable feedstock potential, availability and film formation. Limitations include moisture sensitivity, brittleness without plasticizers and storage-related changes in mechanical properties. Plasticizers improve flexibility but can increase water sensitivity or migrate, depending on the formulation.

5.2. Polylactic acid (PLA)

PLA is a bio-based polyester commonly produced from lactic acid obtained by fermentation of carbohydrate feedstocks. It can be processed into films, trays, containers and thermoformed structures. Advantages include transparency, rigidity in many formulations and compatibility with established processing methods. Limitations include limited heat resistance, brittleness, application-dependent barrier properties, and the need for industrial composting infrastructure for compostable grades. PLA should not be described as universally home-compostable or readily biodegradable in the natural environment.

5.3. Polyhydroxyalkanoates (PHAs)

PHAs are microbial polyesters whose properties vary with monomer composition and processing. Selected formulations can biodegrade under suitable conditions and are of interest for films and coatings. Limitations include production cost, processing challenges and variable mechanical properties. Environmental benefit depends on feedstock, fermentation, purification and end-of-life conditions.

5.4. Cellulose and cellulose derivatives

Cellulose films, nanocellulose and cellulose derivatives can serve as films, coatings and reinforcing components. Advantages include renewable feedstock potential and useful mechanical properties in selected structures. Limitations include hydrophilicity, moisture sensitivity, and processing and cost challenges. Chemical modification and composite design can improve performance but may complicate degradation and end-of-life assessment.

5.5. Chitosan, alginate, gelatin and other biopolymers

Chitosan is derived from chitin, alginate from algal polysaccharides and gelatin from collagen; whey and soy proteins have also been studied for edible films and coatings. These materials can carry antioxidants, antimicrobial compounds or colour-changing indicators (Agarwal et al., 2023; Biopolymer-Based Active and Intelligent Food Packaging, 2026). Many hydrophilic biopolymers resist moisture poorly and may lose mechanical integrity at high relative humidity. Antimicrobial activity in laboratory tests does not by itself establish efficacy in a real food matrix.

Material	Main strengths	Principal limitations	Potential applications
Starch	Renewable, available, film-forming	Moisture sensitivity; limited flexibility without modification	Dry-food films, foams, blends
PLA	Transparency, rigidity, processability	Heat sensitivity in some grades, brittleness, composting constraints	Trays, cups, selected films
PHA	Potential biodegradability, tunable chemistry	Cost, processing, variable performance	Films, coatings, selected containers
Cellulose derivatives	Renewable feedstock, film and coating properties	Moisture sensitivity and modification needs	Coatings, wraps, composites

Material	Main strengths	Principal limitations	Potential applications
Nanocellulose	Potential reinforcement and barrier improvement	Dispersion, moisture response, scale-up and cost	Reinforced films and coatings
Chitosan	Film formation, potential antimicrobial function	pH sensitivity, moisture resistance, formulation dependence	Active coatings and films
Alginate	Film formation and gelation	Moisture sensitivity and formulation requirements	Fruit coatings, composite films
Gelatin/protein films	Film formation in selected formulations	Moisture sensitivity and mechanical variability	Edible films and coatings

These are potential uses, not evidence of universal commercial suitability or environmental superiority.

6. Emerging and functional packaging technologies

6.1. Multilayer and composite packaging

Multilayer structures combine materials to balance mechanical strength, barrier properties, sealing, printability and appearance. A flexible package may combine an outer mechanical layer, a printed layer, an oxygen barrier and a heat-sealable inner layer; beverage cartons may combine paperboard with polymer layers and sometimes aluminium. The main advantage is functional integration, and the main disadvantage is end-of-life complexity when incompatible layers cannot be separated or recycled economically.

6.2. Vacuum packaging

Vacuum packaging removes much of the air before sealing. It reduces oxygen availability and can slow oxidative deterioration and the growth of some aerobic spoilage organisms. It is used for meat, cheese, coffee and other compatible foods. It does not sterilize food, and certain anaerobic pathogens can grow under favourable conditions, so hygiene, formulation, temperature control and validated shelf-life limits remain essential.

6.3. Modified-atmosphere packaging (MAP)

MAP replaces the initial headspace with a selected gas mixture, commonly carbon dioxide, nitrogen and oxygen. Benefits can include slowing selected spoilage organisms, reducing oxidation when oxygen is controlled, and maintaining appearance. MAP is used for fresh meat, fish, prepared foods, bakery products and fresh-cut produce. Gas composition must account for microbial hazards, respiration, gas solubility, package permeability and storage temperature.

6.4. Active packaging

Active packaging incorporates components that deliberately interact with the package environment or the food. Examples include oxygen scavengers, moisture absorbers or regulators, ethylene scavengers, antimicrobial and antioxidant systems, and carbon-dioxide regulators (Amin et al., 2022). Effectiveness depends on the food, temperature, humidity, package permeability, active-agent concentration and release mechanism. Regulatory assessment is needed when substances are released into food or interact with food-contact surfaces.

6.5. Intelligent and smart packaging

Intelligent packaging monitors or communicates information about the food, the package or surrounding conditions. Examples include time–temperature indicators, oxygen indicators, freshness indicators, and sensors that respond to selected gases or metabolites. Anthocyanin-based colourimetric systems respond to pH change in selected foods, but pH change is not a universal measure of safety (Amin et al., 2022). RFID and QR codes support traceability and product information. Current reviews stress that signal stability and selectivity in humid headspaces, together with validated links between sensor response and food quality, determine whether such systems are translatable (Agarwal et al., 2026). Intelligent packaging is a monitoring and decision-support tool, not a substitute for validated food-safety controls.

Technology	Primary mechanism	Potential benefit	Principal limitation
Vacuum packaging	Removes much of the headspace air	Reduced oxygen exposure	Not sterilizing; anaerobic hazards remain
MAP	Changes headspace gas composition	Product-specific shelf-life extension	Requires correct gas mix and temperature control
Oxygen scavenging	Removes residual or permeating oxygen	Reduced oxidation	Capacity and activation conditions matter
Moisture control	Absorbs or regulates water	Reduced condensation or texture change	Can over-dry if poorly designed
Antimicrobial packaging	Presents or releases an antimicrobial agent	Suppression of selected microorganisms	Efficacy, migration, sensory effects and safety require validation
Ethylene management	Removes or controls ethylene	Slower ripening in selected produce	Crop and storage conditions determine efficacy
Time–temperature indicator	Responds to cumulative temperature exposure	Cold-chain monitoring	Requires food-specific calibration
Freshness indicator	Responds to selected metabolites or environmental changes	Additional quality information	May not establish microbiological safety
RFID/QR traceability	Encodes and communicates data	Improved tracking and information access	Depends on data accuracy and implementation

7. Linking packaging properties to food deterioration and shelf life

Packaging properties matter only insofar as they control a deterioration mechanism that is relevant to the food, so the relationship between material performance and shelf life is food-specific.

7.1. Oxygen transfer and oxidative deterioration

Oxygen entering a package can promote lipid oxidation, pigment degradation, vitamin loss and changes in flavour or aroma. The extent depends on oxygen concentration, food composition, temperature, light exposure, catalytic components and antioxidant activity. A low-OTR material reduces oxygen availability, but actual exposure also depends on residual headspace oxygen, package area, film thickness, seals, closure permeability and oxygen trapped in the product.

7.2. Water transfer and texture changes

Water-vapour transfer can cause moisture uptake in dry foods, leading to loss of crispness, caking or reduced flowability. Conversely, moisture loss from fresh produce causes wilting and mass loss. The appropriate barrier depends on the direction of the moisture gradient and the desired equilibrium moisture content: a package designed to keep moisture out of biscuits may be unsuitable for produce that needs controlled water loss and gas exchange.

7.3. Gas exchange and respiration

Fresh fruits and vegetables remain metabolically active after harvest, and respiration depends on species, maturity, temperature and atmosphere. Packaging must balance oxygen and carbon-dioxide transfer with product respiration. Excessively low permeability can cause oxygen depletion and undesirable anaerobic metabolism, whereas excessive permeability may fail to sustain a beneficial modified atmosphere. Design should be based on measured respiration and gas-transfer behaviour.

7.4. Microbial stability

Packaging can prevent post-process contamination and modify conditions for microbial growth, but it does not independently establish microbiological safety. Vacuum and MAP can suppress selected spoilage organisms while allowing others to persist or grow. Package selection must therefore be integrated with hygiene, processing, formulation, storage temperature and validated shelf-life assessment.

7.5. Shelf life as a system outcome

Shelf life emerges from the interaction of food, package, processing method, storage environment and the quality or safety endpoint used to define acceptability. Credible shelf-life claims require product-

specific testing, which may include microbiological analyses, oxidation indices, moisture content or water activity, sensory assessment, colour, texture and nutritional quality.

8. Food-contact safety and chemical migration

Food-contact safety is central for plastics, recycled paper, coated paperboard, metal cans, glass closures, adhesives, inks and emerging biopolymer systems. Migration is the transfer of substances from packaging into food or food simulants, and its significance depends on the identity and concentration of the substance, exposure, toxicological properties and the intended conditions of use (Alamri et al., 2021; Gupta et al., 2024). Food–package interaction is commonly divided into migration, permeation and sorption, which may occur simultaneously and in both directions.

8.1. Factors affecting migration

Temperature: elevated temperature accelerates diffusion and other transfer processes.

Contact time: longer contact can increase migration until equilibrium or another limiting condition is reached.

Food composition: fatty, aqueous, acidic or alcoholic foods interact differently with packaging constituents.

Material composition: residual monomers, additives, oligomers, degradation products, inks and adhesives differ among materials.

Package structure: coatings, barrier layers, surface treatments and seals affect transfer.

Storage and processing: heating, refrigeration, freezing and repeated use can alter migration behaviour.

Recycled feedstock: contaminants from previous uses need particular attention, because recycled materials can increase the number and possible sources of substances present (Etxabide et al., 2022).

Migration is not synonymous with toxicity. Detecting a chemical does not by itself establish harm; assessment requires reliable measurement and toxicological interpretation. Conversely, the absence of a known migration problem does not establish safety for every food and temperature condition.

8.2. Material-specific considerations and regulation

Plastics may require assessment of residual monomers, additives, oligomers, degradation products and non-intentionally added substances. Paper and paperboard may require assessment of inks, adhesives, recycled-fibre contaminants and coatings. For metals, the metal, internal coating, closure and seam must be evaluated. Glass is generally chemically inert in common food uses, but pigments, treatments, closures and liners may need assessment. Biopolymers raise further questions about residual processing chemicals, plasticizers, nanoparticles, active agents and degradation products (Geueke et al., 2018; Zhang et al., 2025).

Regulatory compliance depends on the intended market, food type and use conditions. In the European Union, Regulation (EC) No 1935/2004 sets the general framework for food-contact materials, and Commission Regulation (EU) No 10/2011 sets specific requirements for plastics, including specific migration limits and an overall migration limit. In the United States, food-contact substances are regulated under the Federal Food, Drug, and Cosmetic Act and FDA requirements. In India, the Food Safety and Standards (Packaging) Regulations, 2018, issued by the FSSAI, govern food-contact packaging. Current official texts, including amendments, must be checked before submission, and recycled materials, active substances, inks and novel materials may require additional assessment.

8.3. Migration as a structure–property and exposure problem

Migration links the molecular characteristics of packaging to potential consumer exposure. Migrants may include residual monomers, oligomers, antioxidants, plasticizers, stabilizers, printing-ink constituents, adhesive components, degradation products and substances formed unintentionally during manufacture or use. Two processes are involved: diffusion within the material, which determines how quickly a substance moves through it, and partitioning between packaging and food, which determines how the substance is distributed between the two phases (Tehrany & Desobry, 2004).

For an idealized planar material, Fick's first law describes steady-state diffusive flux (Crank, 1975):

$$\mathbf{J = -D\,(\partial C/\partial x)}$$

where J is the mass flux, D the diffusion coefficient, C the concentration and x the distance through the material. The negative sign indicates transport down the concentration gradient. Migration is rarely steady-state, so prediction usually relies on Fick's second law,

$$\partial C/\partial t = D\,(\partial^2 C/\partial x^2)$$

combined with a partition coefficient at the package–food interface, K = C(polymer)/C(food) at equilibrium, together with boundary conditions describing the food, the contact time and the package thickness. Mathematical models and their key parameters are reviewed by Zhang et al. (2025), and techniques for measuring sorption and migration by Kadam et al. (2015). The diffusion coefficient typically increases with temperature, often following an Arrhenius-type relationship, because molecular mobility rises.

Food composition influences partitioning: Fatty foods may favour certain lipophilic substances, while other migrants behave differently in aqueous or acidic foods. Polymer crystallinity, free volume, molecular size and chemical compatibility further influence transfer. Chemical safety therefore cannot be inferred from a polymer's general reputation or renewable origin.

Migration testing should be designed around the intended application, including foreseeable temperature and contact-time conditions. Appropriate food simulants, analytical detection limits, toxicological interpretation and regulatory requirements are essential. The objective is to determine whether exposure under intended conditions complies with applicable requirements and presents an acceptable level of risk.

9. Environmental sustainability and life-cycle assessment

Environmental performance cannot be judged by package weight, renewable origin or apparent ease of decomposition alone. Life-cycle assessment (LCA) considers raw-material extraction, manufacturing, transportation, packaging efficiency, food preservation, reuse, recycling and final disposal. Relevant indicators include greenhouse-gas emissions, energy, water use, resource depletion, eutrophication and waste generation. A recent systematic review of 51 LCA studies found that global warming potential was the most frequently used indicator and that functional units and methodologies differed widely between studies (Vuk & Bauerné Gáthy, 2026).

9.1. Why packaging comparisons require care

Comparing one kilogram of glass with one kilogram of plastic is often misleading, because the materials may not provide equivalent packaging services. A meaningful comparison packages the same quantity of food, delivers equivalent protection and maintains equivalent shelf life. A lightweight package may reduce transport impacts, but if it causes additional spoilage its total environmental result may be unfavourable.

Reusable packaging can offer benefits when enough reuse cycles offset production and cleaning impacts. Performance depends on actual rotations, washing, return transport, breakage and losses in the reuse system. Where comparisons are made consistently, reusable and recycled packaging have often performed better than single-use alternatives (Vuk & Bauerné Gáthy, 2026).

9.2. Strategies for improving sustainability

Source reduction: eliminate unnecessary material without compromising integrity.

Lightweighting: reduce package mass while maintaining barrier and mechanical performance.

Reuse: develop durable systems where collection, cleaning and redistribution are practical.

Design for recycling: use compatible material combinations, suitable labels and adhesives, and structures that can be sorted effectively.

Recycled content: use appropriately assessed recycled material where technically and legally feasible.

Bio-based feedstocks: assess renewable sourcing, land use, energy, water and processing impacts.

Composting: use certified compostable materials where they serve a defined purpose and suitable collection and processing infrastructure exists.

Food-loss prevention: include the environmental consequences of spoilage when evaluating alternatives.

9.3. Linking material selection to life-cycle performance

Life-cycle performance depends on production route, processing requirements, mass, transport efficiency, service life, preservation effectiveness and end-of-life pathway. Crystallinity and orientation may improve barrier or mechanical performance and permit thinner packages, but lightweighting is beneficial only if integrity and food protection are maintained.

Glass offers reusability and an excellent barrier, but its mass and manufacturing energy must be considered, and its relative performance may improve when bottles are reused many times within an efficient local return system. Paperboard may use renewable fibre and fit established recycling systems, but coatings and laminates can change recovery potential. Bio-based polymers can reduce dependence on fossil feedstocks, yet production inputs and actual end-of-life conditions determine their net impact.

Food preservation must be part of the comparison. Packaging that prevents spoilage can avoid the impacts of producing food that would otherwise be wasted. A scoping review of LCAs that explicitly accounted for packaging-related food waste found only 23 such studies, with shelf-life extension the most frequently evaluated packaging function, and called for broader coverage of food categories (Hemachandra et al., 2024). A meaningful comparison should define a functional unit that captures the service provided, such as delivery of a specified quantity of food at acceptable quality and safety, and should disclose system boundaries, transport assumptions, reuse cycles, recycling rates, energy mix and the treatment of food waste.

The scientifically defensible question is therefore not which material has the lowest impact per kilogram, but which packaging system delivers the required preservation service with the lowest overall environmental burden under specified conditions.

10. Framework for selecting food-packaging materials

The selection process can be organized in five steps (Figure 2), which should be iterated if validation shows that requirements are not met:

1. Characterize the food: water activity, pH, fat content, oxygen sensitivity, respiration and microbial risks.

2. Define preservation requirements: barrier levels, light protection, mechanical strength, temperature and target shelf life.

3. Screen candidate materials: plastic, paperboard, glass, metal, bio-based materials or combinations.

4. Validate performance and safety: migration, seal integrity, shelf-life testing, transport simulation and regulatory compliance.

5. Evaluate the full life cycle: cost, manufacturing, distribution, food waste, reuse, recycling and disposal infrastructure.

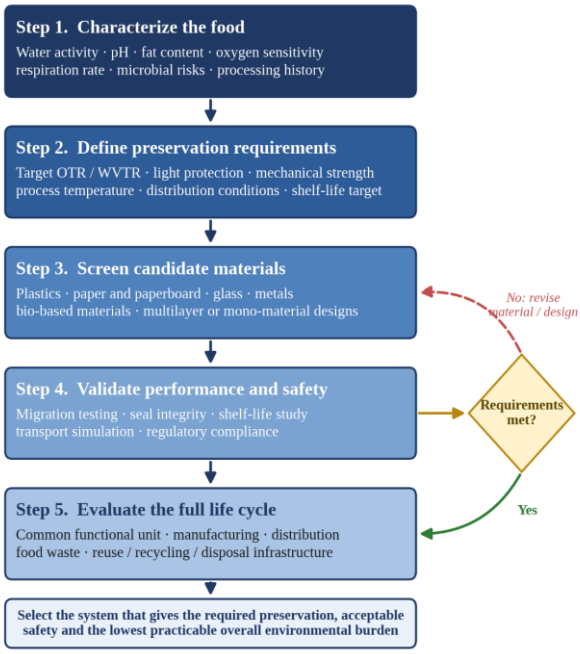


Figure 2. Decision framework for selecting food-packaging materials. Candidates that fail validation return to the screening step. The framework is conceptual and is not a validated numerical model.

The table below gives example starting points for common food categories.

Food category	Major deterioration concerns	Candidate approach	Critical validation
Edible oils	Oxidation, light exposure	Opaque/coloured glass, metal or suitable barrier plastic	Light transmission, oxygen ingress, closure integrity
Biscuits/crackers	Moisture uptake, texture loss	High-moisture-barrier film or laminate	WVTR, seal integrity, texture retention
Fresh meat	Microbial growth, oxidation, colour change	Vacuum or MAP with suitable barrier materials	Microbiological safety, gas composition, temperature
Fresh-cut produce	Respiration, moisture loss, microbial spoilage	Permeable films or selected MAP systems	Respiration, condensation, microbial shelf life
Milk/beverages	Microbial spoilage, oxidation, light sensitivity	Suitable glass, carton, metal or polymer package	Process compatibility, light barrier, closure
Canned vegetables	Microbial stability, corrosion	Coated metal can with validated thermal process	Seam integrity, coating compatibility, process validation
Dry powders	Moisture uptake, oxygen sensitivity	Barrier laminate or rigid container	WVTR, OTR, seal integrity
Frozen foods	Moisture loss, oxidation, puncture damage	Low-temperature-compatible film or container	Low-temperature toughness, seals
Bakery products	Moisture migration, mould, texture changes	Film, paper–polymer combination or selected MAP	Moisture balance, mould control, sensory quality
Ready-to-eat meals	Post-process contamination, temperature abuse	Validated tray, pouch or process-compatible container	Seal integrity, process and shelf-life validation

These are starting points, not universal recommendations. Final packaging must be tested for the actual formulation, processing method, storage temperature, distribution conditions and shelf-life target.

10.1. Integrated comparison: chemistry, performance, safety and sustainability

Material class	Structural/chemical feature	Functional behaviour	Food-quality and safety implications	Life-cycle consideration
PE and PP	Semicrystalline hydrocarbon polymers	Useful moisture barrier, heat sealing; flexible or rigid formats	Moisture control and integrity; oxygen protection may be insufficient for some foods	Lightweighting and recycling depend on format and infrastructure
PET	Aromatic polyester; orientation and crystallinity depend on processing	Transparent, strong, useful gas barrier	Suitable for many beverages; heat and contact suitability depend on grade	Recycling pathways exist; quality and contamination matter
PA/EVOH	Polar amide or hydroxyl-containing polymer structures	Toughness or high oxygen barrier; EVOH humidity-sensitive	Useful for oxygen-sensitive foods in suitable structures	Multilayers complicate recycling
Paperboard	Porous cellulose-fibre network	Stiffness, printability, compression performance	Moisture can affect integrity and food texture	Fibre recovery depends on coatings and infrastructure
Glass	Continuous inorganic silicate network	Excellent barrier and high chemical inertness	Good protection when closure intact	Heavy transport; reuse may help with efficient returns
Aluminium/steel	Metallic structure with high intrinsic barrier	Excellent light, gas and moisture protection	Suitable for shelf-stable foods with validated coatings and processes	Recycling potential; primary production energy-intensive
PLA	Aliphatic polyester, often bio-based	Transparent, rigid in suitable grades	Heat, barrier and use conditions require validation	Compostability and recycling depend on grade and infrastructure

Material class	Structural/chemical feature	Functional behaviour	Food-quality and safety implications	Life-cycle consideration
Starch	Hydrophilic polysaccharide chains	Film-forming, often limited moisture resistance	Water sensitivity may compromise barrier and mechanical performance	Renewable feedstock must be balanced with processing and end of life
Cellulose/ nanocellulose	Hydrogen-bonded polysaccharide structures	Film formation or reinforcement	Moisture sensitivity and coatings need attention	Renewable potential; treatments affect recovery
Chitosan/ other biopolymers	Functional groups enabling interactions and potential bioactivity	Film formation and possible active function	Efficacy and migration need food-specific validation	Feedstock, additives, processing and degradation determine impact

These are qualitative relationships, not universal performance rankings. Structural features alone do not establish safety or sustainability.

10.2. Research hypotheses

Structure–barrier hypothesis: Polymer morphology, crystallinity, orientation and humidity-dependent chain mobility may predict transport more reliably than polymer identity alone.

Preservation–environment hypothesis: For some perishable foods, reduced food loss may outweigh the extra impact of higher-barrier packaging; the outcome depends on the food, storage and system boundaries.

Migration–design hypothesis: Combining diffusion coefficients, polymer–food partitioning and realistic storage conditions may improve migration prediction and exposure assessment.

Circularity–barrier hypothesis: Recyclable mono-material structures with engineered barrier layers may balance preservation and recovery better than some conventional multilayers, provided performance is maintained.

Biopolymer–function hypothesis: Reinforcements or coatings may improve biopolymer performance, but the net benefit depends on additives, manufacture, protection and end-of-life pathway.

These are proposed hypotheses, not established findings.

11. Current challenges and research priorities

11.1. Balancing barrier properties and biodegradability

Many naturally derived polymers are hydrophilic and resist water vapour poorly. Coatings, blending, cross-linking or nanofillers can improve performance but may introduce additional substances or complicate end-of-life processing.

11.2. Recyclability of high-barrier structures

High-barrier packaging often relies on multiple layers. Replacing them with recyclable mono-material designs requires sufficient oxygen and moisture barrier, reliable sealing and adequate mechanical strength.

11.3. Chemical safety of innovative materials

Nanocomposites, natural extracts, antimicrobial compounds and recycled feedstocks may improve functionality, but their migration, exposure, toxicology and environmental fate must be characterized. “Natural” and “bio-based” are not substitutes for safety testing.

11.4. Standardized environmental comparisons

Environmental studies should use transparent system boundaries, functional units, recycling assumptions and food-waste scenarios (Vuk & Bauerné Gáthy, 2026). Packaging and the food it protects should be assessed together where appropriate (Hemachandra et al., 2024).

11.5. Industrial scalability and cost

Laboratory films may show strong tensile performance or antimicrobial activity yet fail to reach consistent quality at industrial speeds. Scale-up requires assessment of raw-material variability, energy, processability, sealing, storage stability, migration and cost per unit of food protected.

11.6. Integrating sensors with practical decisions

Intelligent packaging requires reliable indicators, calibration, validated relationships between sensor response and food quality, and communication systems that support meaningful decisions (Agarwal et al., 2026). Research should distinguish quality indicators from indicators that can support safety decisions.

12. Data requirements and recommended quantitative analyses

Figure 1 presents the structure–property–preservation–sustainability framework and Figure 2 the material-selection decision framework. Further figures could compare qualitative performance across material classes, illustrate packaging technologies and preservation mechanisms, or show LCA system boundaries. A publishable quantitative comparison needs verified data, common functional units and compatible system boundaries; invented barrier values, shelf-life extensions, carbon footprints, recycling rates or percentage improvements must not be presented as findings.

12.1. Recommended analyses

Analysis A, structure–property comparison: compare oxygen permeability, water-vapour permeability, tensile properties and thermal behaviour for selected grades, reporting temperature, relative humidity, thickness, test standard and units.

Analysis B, migration and food-contact safety: compare migration behaviour for selected substances or material systems using published diffusion coefficients, partition coefficients or measured concentrations, keeping experimental and modelled values separate.

Analysis C, preservation performance: compare shelf-life outcomes for a specific food under defined packaging and storage conditions, distinguishing microbiological endpoints from sensory, oxidative and nutritional endpoints.

Analysis D, life-cycle comparison: compare packaging systems using a common functional unit, such as delivery of 1,000 kg of food meeting specified quality and safety criteria, including packaging production, distribution, food losses, reuse, recycling and disposal as appropriate.

These analyses should not be combined into a single numerical ranking unless the data are sufficiently comparable. If suitable data cannot be assembled, a transparent qualitative evidence table is preferable to a misleading graph.

13. Conclusions

The performance of food packaging is governed by the interaction of material chemistry, molecular structure, macroscopic properties, food composition and environmental conditions. Evaluation should therefore go beyond listing advantages and limitations and explain the mechanisms by which materials protect food, influence chemical exposure and affect environmental outcomes.

For polymers, molecular architecture, crystallinity, chain mobility, polarity and multilayer design influence gas and water-vapour transport, mechanical behaviour and chemical migration. For fibre-based materials, porosity, cellulose interactions and moisture sorption determine structural stability and barrier requirements. Glass and metals provide excellent intrinsic barriers, but overall performance depends on closures, coatings, mechanical integrity, manufacturing and reuse or recycling systems.

These characteristics influence preservation through oxidation, moisture transfer, respiration, microbial ecology and physical damage. No single barrier property determines shelf life independently of food composition, processing, storage temperature and the endpoint used.

Chemical safety must be treated as a mechanistic, exposure-based question. Diffusion, partitioning, contact conditions and migrant identity determine whether chemical transfer is relevant, and compliance requires application-specific assessment rather than assumptions based on whether a material is conventional, recycled, natural or biodegradable.

Environmental sustainability must be evaluated at the packaging-system level. Material reduction, reuse, recycling and bio-based alternatives can bring benefits under appropriate conditions, but these must be weighed against manufacturing impacts, distribution, food waste and end-of-life infrastructure. The central design objective is to provide the required preservation service with acceptable safety and the lowest practicable overall environmental burden.

Future research should integrate predictive structure–property modelling, food-specific shelf-life validation, migration assessment, recyclable high-barrier design and life-cycle analysis. Such integration can support packaging choices that are scientifically justified, commercially feasible and environmentally responsible.

Declarations

1. Use of AI-Assisted Tools: AI-assisted tools were used in the preparation of this manuscript for organising scientific information, developing the review structure, improving language and readability, and refining the presentation of technical concepts. The author(s) critically reviewed, verified, and edited all AI-assisted content and take full responsibility for the accuracy, originality, scientific integrity, interpretation of the literature, and final content of the manuscript.

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4. Ethical Approval: Ethical approval was not required for this narrative review, as it is based on previously published scientific literature, technical publications, regulatory documents, and publicly available information. No experiments involving human participants or animals were conducted.

5. Informed Consent: Not applicable. This manuscript does not involve human participants, patient information, or personally identifiable data.

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7. Author Contributions: The author contributed to the conceptualization, visualization and development of the review, identification and collection of relevant scientific literature, examination of food packaging materials and their structural characteristics, evaluation of structure–property relationships, analysis of food preservation mechanisms, manuscript preparation, revision and approval of the final version.

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