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# EDIBLE COATINGS: A COMPREHENSIVE REVIEW OF THEIR COMPOSITION, PREPARATION TECHNOLOGIES, AND ROLE IN FOOD PRESERVATION

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**ABSTRACT**

*Petroleum-based packaging persists in the environment for decades to millennia, and the microplastic particles it sheds have been detected in marine and terrestrial ecosystems and in the food chain. Edible coatings, thin layers of food-grade biopolymers formed directly on the product surface, offer a way to extend the shelf life of fresh produce while reducing dependence on synthetic packaging. This review assesses the chemical nature, structure, functional properties, preparation technologies, and preservation role of edible coatings, with particular emphasis on fruits and vegetables. Polysaccharide-, protein-, and lipid-based materials are compared in terms of barrier properties, gas permeability, and antimicrobial and antioxidant activity, and the advantages of composite and multilayer systems are discussed. The review explains how coatings regulate gas exchange, transpiration, and microbial spoilage, and it compiles quantitative evidence, including reductions in water-vapor permeability or transmission of up to 97%–98% in lipid-containing systems and a 21-day shelf life for coated fresh-cut melon. Conventional fabrication methods (solution casting, dipping, spraying, and extrusion) are evaluated alongside emerging approaches such as electrospinning, three-dimensional printing, reactive extrusion, nanotechnology, and layer-by-layer assembly. Finally, the review examines safety, migration, and regulatory requirements, identifies the main barriers to industrial scale-up, and outlines research priorities for next-generation edible coatings.*

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***Keywords:*** *biopolymers, microplastics, postharvest shelf life, water vapor barrier, electrospinning, reactive extrusion.*



## Introduction

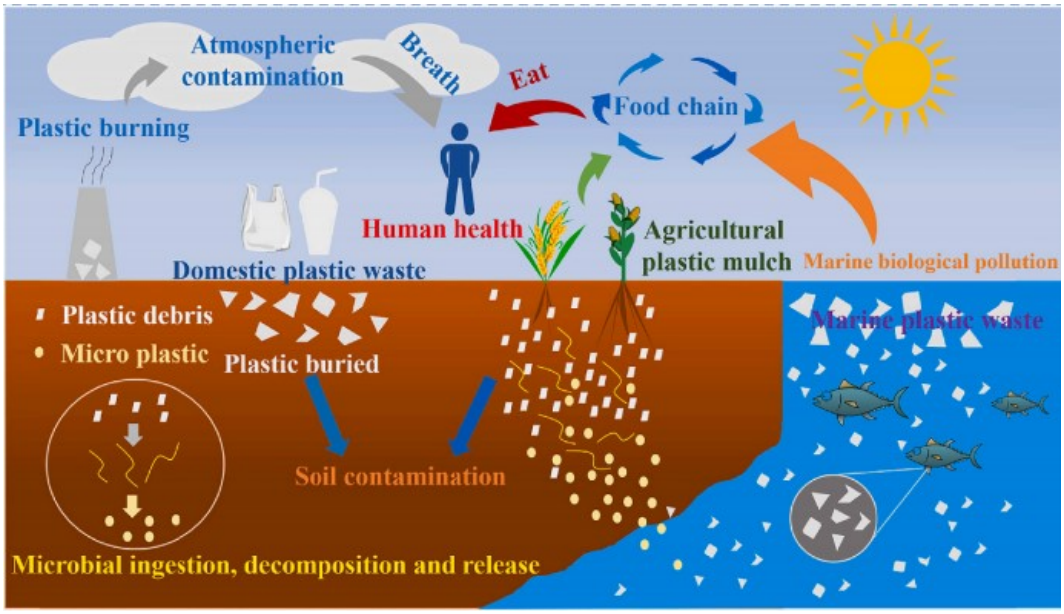
The era of synthetic polymers, which began with Leo H. Baekeland's invention of Bakelite at the start of the 20th century, marked a fundamental turning point in the material and technological development of human civilization (Crespy et al., 2008). Plastic products have since become integral to the packaging industry because they are lightweight, inexpensive, and mechanically strong and form excellent barriers to gases and moisture. Yet these very properties, particularly their near-total resistance to degradation under natural conditions, have turned plastic waste into a global environmental problem. Global plastic production has grown at an average annual rate of 8.4% since 1950, reaching approximately 435 million tonnes in 2025 and 450 million tonnes in 2026, nearly 225 times the 1950 level (Geyer et al., 2017; Plastics

Europe, 2025).

Because the covalent bonds between the monomers of plastic polymers are inherently stable, these materials resist natural physical, chemical, and enzymatic degradation. Plastic waste has consequently become a major pollutant, accounting for 60%–95% of the pollution of seas and oceans, and approximately 8 trillion microplastic particles enter natural water bodies through wastewater every day (Darwesh et al., 2026; Schnurr et al., 2018). These particles are taken up by marine organisms, including fish at the larval stage (Gove et al., 2019). Studies in natural areas of Switzerland detected microplastics in 90% of the soil samples examined (Scheurer & Bigalke, 2018), which shows that microplastic pollution is entrenched in terrestrial as well as aquatic ecosystems. Microplastics in soil can be transferred to soil-dwelling organisms such as earthworms and insects, impairing their physiological condition (Chae & An, 2018), and can then move along the food chain to larger animals, including birds and rodents (Figure 1).

**Figure 1**

*Pathways by Which Plastic Use and Disposal Pollute the Atmosphere, Soil, and Oceans and Ultimately Affect Human Health*




*Note.* From Cheng et al. (2021).

Over the past decade, the effects of microplastic particles on the human body have attracted substantial interest in medicine and food chemistry. Plastic particles accumulated in fish tissues have been shown to induce structural changes in liver tissue (Rochman et al., 2013) and to interfere with immune function (Limonta et al., 2019). Additives in plastic materials, including plasticizers, stabilizers, and pigments, may contribute to endocrine and immune disruption, reproductive abnormalities, and an increased risk of chronic conditions such as diabetes mellitus, precocious puberty, and obesity (Kumar, 2018). Because petroleum-derived plastics may take from several decades to thousands of years to degrade naturally (Dey et al., 2021), effective alternatives are urgently needed.

In response to these challenges, scientific attention has turned increasingly to biodegradable and bio-based polymers. The International Union of Pure and Applied Chemistry (IUPAC) recommends the term “bio-based polymer” over the broader “bioplastic,” because not every polymer derived from biomass is environmentally benign (Vert et al., 2012). Among bio-based materials, edible coatings represent a particularly promising research direction. An edible coating is a thin polymeric layer applied directly to the surface of a food product that can be eaten together with the food. Unlike a packaging film, which is manufactured separately and then wrapped around the product, an edible coating is formed on the product surface itself (Mensitieri et al., 2011). Edible coatings are therefore regarded as an environmentally friendly and consumer-safe alternative to petroleum-derived packaging that also extends shelf life and preserves


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quality (J. W. Han et al., 2018; Peelman et al., 2013).

Edible coatings can substantially extend the shelf life of fruits and vegetables by regulating key physiological processes, including respiration, moisture loss, and microbial deterioration (Food and Agriculture Organization of the United Nations [FAO], 2019; United Nations Environment Programme [UNEP], 2024). Many industrial sectors are now replacing petroleum-derived poly(vinylidene chloride) and other synthetic polymers with natural coatings based on polysaccharides, proteins, and lipids (Gaines, 2023; Rasheed & Parveez, 2021). Poly(vinyl alcohol) (PVOH) coatings, used for many years, are generally considered relatively benign (B. Liu et al., 2022), but protein coatings derived from zein (FloZein Products, n.d.), complex polysaccharides such as gum ghatti (Parija et al., 2001), and commercial biowax coatings such as Solenis TopScreen (Solenis, n.d.) have attracted considerable attention as fully bio-based and biodegradable solutions.

This review systematically analyzes the main classes of polymers used in edible coatings, their mechanisms of action in preserving fruits and vegetables, and the conventional and emerging technologies used to produce them.

**Polymer-Based Materials for Edible Coatings**

The biopolymers that form the chemical basis of edible coatings are broadly classified by origin and composition into polysaccharides, proteins, and lipids (Mohamed et al., 2020). Each class has a distinctive molecular structure and characteristic strengths and limitations, and in practice they are often combined in composite or multilayer systems to exploit complementary properties (Jahangiri et al., 2024). The classification used in this review is shown in Figure 2.

**Polysaccharide-Based Coatings**

Cellulose derivatives such as carboxymethyl cellulose, hydroxypropyl cellulose, and methylcellulose carry numerous hydroxyl groups that form hydrogen-bond networks with starch, improving the mechanical strength and thermal stability of the matrix (Jiang et al., 2020). Chitosan, the deacetylated derivative of chitin, is distinguished by its biocompatibility, low toxicity, and intrinsic antibacterial activity (Cazón et al., 2017). Its amino and hydroxyl groups interact with starch through hydrogen bonding, as confirmed by shifts in the main Fourier-transform infrared (FTIR) bands. In corn starch/chitosan films, elongation at break increased with chitosan content and peaked at 41 wt% chitosan (Ren et al., 2017), and the amylose content of the starch further modulates the properties of such composites (Domene-Lopez et al., 2019; C. Li et al., 2021; W.-C. Wu et al., 2019).

Alginate and carrageenan form relatively thick hydrogel layers on fruit surfaces that act as sacrificial moisture barriers until they become fully hydrated (Falguera et al., 2011; Kouhi et al., 2020). Pectin, obtainable from citrus peel and other fruit-processing by-products, is a naturally derived biopolymer that also modulates the structure and digestibility of starch-based matrices (L. Chen et al., 2019; Mohit et al., 2020).

**Protein-Based Coatings**

Protein-based coatings are classified as plant-derived (wheat gluten, corn zein, soy protein) or animal-derived (casein, whey protein, keratin, gelatin; H. Chen et al., 2019). The polar, cohesive polypeptide network of proteins provides better oxygen barrier properties than most polysaccharide and lipid films; the oxygen permeability of soy protein films has been reported to be approximately 260–670 times lower than that of low-density polyethylene, methylcellulose, starch, and pectin films. Protein coatings also generally show better mechanical properties than lipid- or polysaccharide-based coatings. Their main limitations are brittleness and hydrophilicity, which lead to poor water vapor barrier performance. These limitations have been addressed by cross-linking, by adding plasticizers such as glycerol and sorbitol, by incorporating natural antioxidants and antimicrobials such as vitamin E and nisin, and by surface modification (Fakhouri et al., 2012; Kouhi et al., 2020). For coatings that will be eaten, ionic cross-linking (e.g., with calcium chloride) or enzymatic cross-linking is preferable to glutaraldehyde,


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which is not a food-grade reagent and whose residues would require toxicological clearance.

Zein is notable for its flexibility, heat-sealability, and biodegradability (Kouhi et al., 2020), whereas gelatin forms thermoreversible gels on heating and cooling (Fakhouri et al., 2012). In starch–gelatin composites, hydrogen bonding between the components modifies water vapor permeability, mechanical strength, and transparency (Fakhouri et al., 2012), and gelatin/starch films have been used as orally disintegrating carriers of vitamin C (Garcia et al., 2018). Whey protein isolate (WPI) has excellent film-forming ability but relatively high water vapor permeability when plasticized, so it is frequently combined with lipids such as beeswax. In a paperboard coating study, a beeswax layer improved the water vapor barrier by approximately 89%, whereas an additional WPI/cellulose layer on top of the beeswax gave a smaller improvement than beeswax alone (J. Han et al., 2010; Jahangiri et al., 2025).

**Lipid-Based Coatings**

Lipids, including mono- and triacylglycerols, fatty acids, fatty alcohols, phospholipids, and natural waxes such as carnauba, candelilla, and beeswax, are the most effective moisture barriers because of their strong hydrophobicity (Yousuf et al., 2022; Zubair et al., 2021). The low water vapor permeability of waxes arises from their nonpolar long-chain constituents (*n*-alkanes, esters, alcohols, and fatty acids) and their dense, highly crystalline packing, and it correlates with the crystallinity of the individual constituents (Leyva-Gutierrez & Wang, 2021). Pure lipid layers, however, are mechanically weak and poorly cohesive, so they are usually combined with proteins or polysaccharides as bilayers or emulsions: the lipid phase provides the moisture barrier, and the hydrocolloid phase provides the supporting matrix and the gas barrier (Jahangiri et al., 2025; Yousuf et al., 2022). Starch–lipid inclusion complexes, such as those formed between debranched starch and stearic acid, are a further route to hydrophobization (Reddy et al., 2018), as is chemical modification of starch with octenylsuccinate groups (Gao et al., 2020).

Quantitative data illustrate the size of the effect. Coating thermoplastic starch/poly(lactic acid) trays with 1%–3% beeswax reduced water vapor permeability from $7.9 \times 10^{-11}$ to $0.2 \times 10^{-11}$ g m$^{-1}$ s$^{-1}$ Pa$^{-1}$, a reduction of approximately 97% (Reis et al., 2018). In paper bilayer-coated with chitosan and beeswax, the water vapor transmission rate decreased from 2,877 g m$^{-2}$ d$^{-1}$ for uncoated paper to 52.8 g m$^{-2}$ d$^{-1}$ at 3.0 wt% chitosan (≈98%), while the required beeswax coat weight fell from 10.1 to 4.9 g m$^{-2}$ (W. Zhang et al., 2014). Vegetable oils such as sunflower, corn, and soybean oil are also incorporated into formulations; their ratio of saturated to unsaturated fatty acids, commonly expressed through the iodine value, affects oxidative stability and final coating properties (Zubair et al., 2021). Essential oils and their constituents, such as cinnamaldehyde and orange essential oil, add antibacterial, antifungal, and antioxidant functions (Cox et al., 2021; do Evangelho et al., 2019).

Paraffin and microcrystalline waxes are mixtures of aliphatic hydrocarbons obtained from petroleum fractions; they are mineral products rather than natural lipids and are therefore not counted among lipids in this review. In the European Union, microcrystalline wax (E 905) is authorized only for the surface treatment of fruits whose peel is not eaten (melons, papayas, mangoes, avocados, and pineapples), whereas beeswax (E 901), carnauba wax (E 903), and shellac (E 904) are authorized for a wider range of fruits, including citrus fruits, apples, pears, and peaches (Commission Regulation [EU] No 1147/2012, 2012; Regulation [EC] No 1333/2008, 2008).

**Composite and Hybrid Systems**

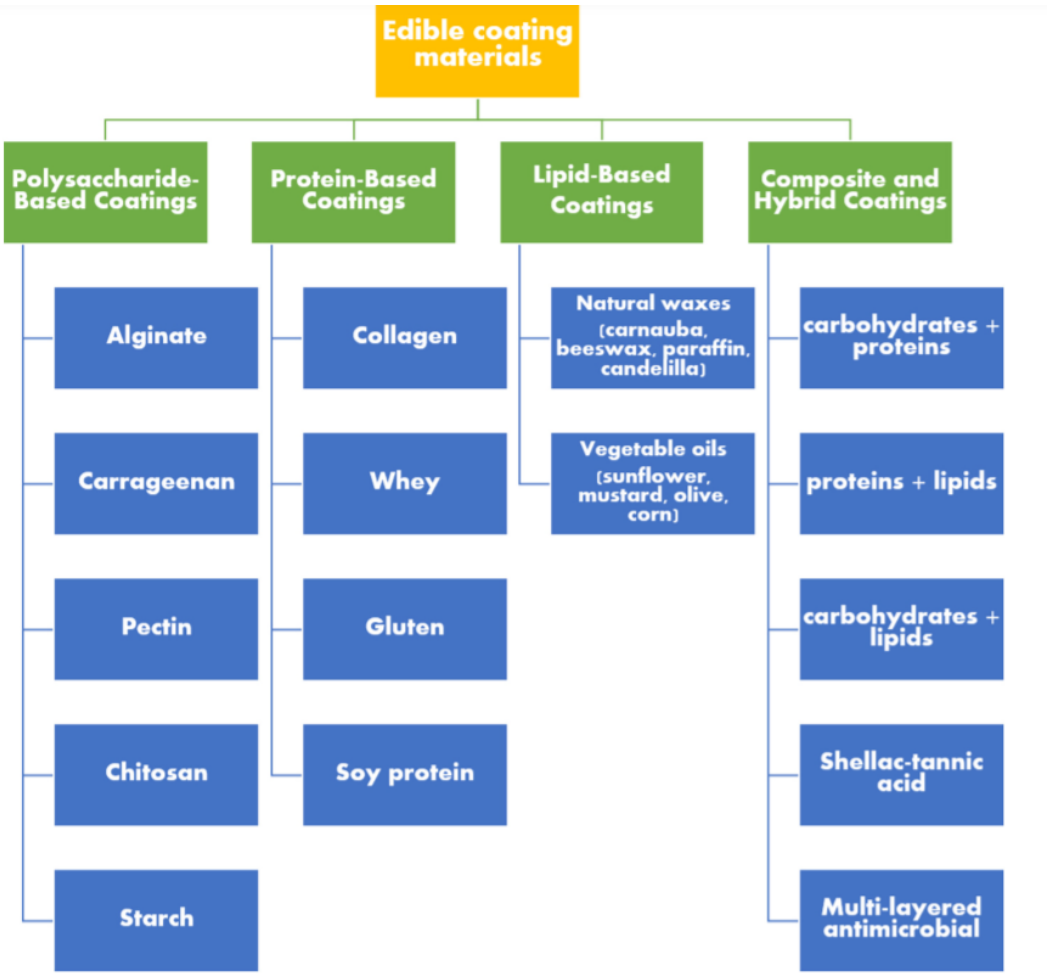
Pure polysaccharide, protein, or lipid coatings are rarely used alone because each class has inherent limitations: polysaccharides and proteins are hydrophilic and poor moisture barriers, whereas lipids have limited mechanical strength (Jahangiri et al., 2024). Modern formulations are therefore developed as composites of two or more biopolymer classes, such as chitosan–lipid systems, zein–chitosan Pickering emulsions, starch–protein blends, and nanostructured composites, which combine complementary properties and give synergistic improvements in barrier, mechanical, and antimicrobial performance (Adibi et al., 2023; Jahangiri et al., 2024). The chitosan–beeswax bilayer described above, in which the two layers


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formed an almost indistinguishable integrated structure, is a representative example (W. Zhang et al., 2014).

**Figure 2**

*Classification of the Major Biopolymers Used in Edible Coatings*




*Note.* The diagram groups edible coating materials into polysaccharide-based coatings (alginate, carrageenan, pectin, chitosan, starch), protein-based coatings (collagen, whey, gluten, soy protein), lipid-based coatings (natural waxes and vegetable oils), and composite and hybrid coatings (carbohydrate–protein, protein–lipid, and carbohydrate–lipid combinations; shellac–tannic acid; multilayered antimicrobial coatings). Adapted from Karnwal et al. (2025).

**Mechanisms of Action of Edible Coatings in Fruit and Vegetable Preservation**

After harvest, fruits and vegetables remain living systems that continue to respire, transpire, produce ethylene, and ripen, and the rates of these processes determine shelf life. Rather than isolating the produce completely, edible coatings work by selectively regulating these processes (Falguera et al., 2011). The four principal mechanisms are summarized in Figure 3.

**Regulation of Gas Exchange**

An edible coating forms a semipermeable layer on the surface of the produce that slows the diffusion of oxygen ($O_2$) and carbon dioxide ($CO_2$). A modified internal atmosphere with reduced $O_2$ and elevated $CO_2$ develops, which lowers the respiration rate, conserves metabolic reserves, and delays ripening (Falguera et al., 2011). Membranes with deliberately tuned gas permeation have been designed on this principle: a leaf-mimetic shellac membrane containing chitosan–poly(L-lactide) microspheres regulated $O_2$, $CO_2$, and $H_2O$ permeation and the $CO_2/O_2$ selectivity, prolonging the storage of several perishable fruits (Zhou et al., 2021). Excessively low oxygen permeability is nevertheless detrimental, because it induces anaerobic respiration, with accumulation of ethanol and acetaldehyde and the


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development of off-flavors (Falguera et al., 2011). An effective formulation must therefore balance gas permeability against the respiratory demand of the commodity.

**Moisture and Water Vapor Barrier Properties**

Weight loss, shriveling, and softening are caused mainly by transpiration, the transfer of water vapor from the produce to the surrounding air. Incorporating hydrophobic lipids such as waxes and oils markedly reduces water vapor permeability, as shown by the ≈97% reduction for beeswax-coated starch/poly(lactic acid) trays (Reis et al., 2018) and the ≈98% reduction in water vapor transmission for chitosan–beeswax bilayers (W. Zhang et al., 2014). On guavas, a corn starch (3%)–cassava starch (2%)–gelatin (5%) coating hydrophobized with 10% beeswax minimized weight loss during 15 days at 15 ± 2 °C and 90% ± 2% relative humidity while allowing normal ripening (Oliveira et al., 2018).

In starch-based coatings, plasticizers such as glycerol weaken the hydrogen bonding between amylose chains and loosen the network, increasing flexibility; the glycerol and water contents jointly determine the structural and functional properties of the films (Basiak et al., 2018; Saiah et al., 2007). Because plasticization also increases water vapor permeability, flexibility and moisture barrier performance have to be balanced during formulation. Acetylation of starch is another route to lower water sensitivity (Colussi et al., 2017).

**Antimicrobial and Antioxidant Protection**

Natural antimicrobial agents (chitosan, essential oils, organic acids, nisin) and antioxidants (vitamin E, tannic acid, plant extracts) incorporated into coatings inhibit bacteria, fungi, and yeasts on the surface of the produce and retard lipid oxidation and enzymatic browning (Kouhi et al., 2020). The protonated amino groups of chitosan interact electrostatically with negatively charged microbial cell surfaces and disrupt membrane permeability, giving broad-spectrum activity; rice starch/carboxymethyl chitosan films containing propolis extract have been developed as active packaging on this basis (Suriyatem et al., 2018). Cinnamaldehyde-functionalized surfaces showed high antibacterial efficacy (Cox et al., 2021), corn starch films containing orange essential oil were active against bacteria (do Evangelho et al., 2019), and self-assembled bovine serum albumin–chitosan oligosaccharide nanostructures produced a synergistic antimicrobial surface (Na et al., 2023). Such active components help maintain surface gloss, color, and biochemical stability during storage.

**Practical Applications**

Several studies demonstrate the effectiveness of edible coatings on fresh produce; selected quantitative results are collected in Table 1. A starch–gelatin–beeswax coating reduced moisture loss in guavas and improved sensory acceptability after 15 days of storage (Oliveira et al., 2018). A shellac membrane modified with chitosan–poly(L-lactide) microspheres controlled gas permeation and $CO_2/O_2$ selectivity for fruits such as oranges, mangoes, strawberries, and cherries (Zhou et al., 2021). A poly(lactic acid) film surface-modified with bovine serum albumin–chitosan oligosaccharide assemblies helped preserve the freshness of strawberries (Na et al., 2023). A xanthan gum coating containing β-carotene nanocapsules (122–220 nm) extended the shelf life of fresh-cut cantaloupe melon to 21 days at 4 °C, with firmness loss not exceeding 2% and changes in whiteness index of 10% or less (Zambrano-Zaragoza et al., 2017). A cassava starch–zinc nanocomposite film was evaluated for tomato packaging (Fadeyibi et al., 2017).


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**Table 1**

*Selected Quantitative Evidence on the Performance of Edible Coatings and Related Bio-Based Films*

| Material or system | Product or format | Conditions | Key quantitative outcome | Source |
|---|---|---|---|---|
| Corn starch 3% + cassava starch 2% + gelatin 5% + beeswax 10% | Guava (whole) | 15 ± 2 °C, 90% ± 2% RH, 15 d | Minimized weight loss; film elasticity +80%, solubility −15%; normal ripening | Oliveira et al. (2018) |
| Xanthan gum + β-carotene nanocapsules (122–220 nm) | Fresh-cut cantaloupe | 4 °C | Shelf life up to 21 d; firmness loss ≤ 2%; whiteness change ≤ 10% | Zambrano-Zaragoza et al. (2017) |
| Thermoplastic starch/PLA tray + beeswax (1%–3%) | Packaging tray | — | WVP 7.9 → 0.2 × $10^{-11}$ g $m^{-1}$ $s^{-1}$ $Pa^{-1}$ (≈ 97% lower); tensile strength 11.5 MPa (1% beeswax) | Reis et al. (2018) |
| Chitosan (1–3 wt%)/beeswax bilayer | Paper | — | WVTR 2,877 → 52.8 g $m^{-2}$ $d^{-1}$ (≈ 98% lower); beeswax demand 10.1 → 4.9 g $m^{-2}$ | W. Zhang et al. (2014) |
| Beeswax layer (± WPI/cellulose top layer) | Paperboard | — | Water vapor barrier improved by ≈ 89% | J. Han et al. (2010) |
| Corn starch/chitosan (0–81 wt% chitosan) | Cast film | — | Maximum elongation at 41 wt% chitosan; hydrogen bonding confirmed by FTIR | Ren et al. (2017) |
| Soluble potato starch nanofibers + carvacrol (20%–40%) | Electrospun mat | 75% formic acid as solvent | Fiber diameter 73–95 nm; bacterial reduction 49%–89% (30% carvacrol); antioxidant inhibition 83.1% (40%); activity ≥ 30 d | Fonseca et al. (2019) |
| Wheat, potato, and corn starch gels | 3D-printed gel | — | Wheat starch: lowest viscosity, best extrudability and dimensional fidelity | Zheng et al. (2019) |

*Note.* RH = relative humidity; WVP = water vapor permeability; WVTR = water vapor transmission rate; PLA = poly(lactic acid); WPI = whey protein isolate; FTIR = Fourier-transform infrared spectroscopy; 3D = three-dimensional.

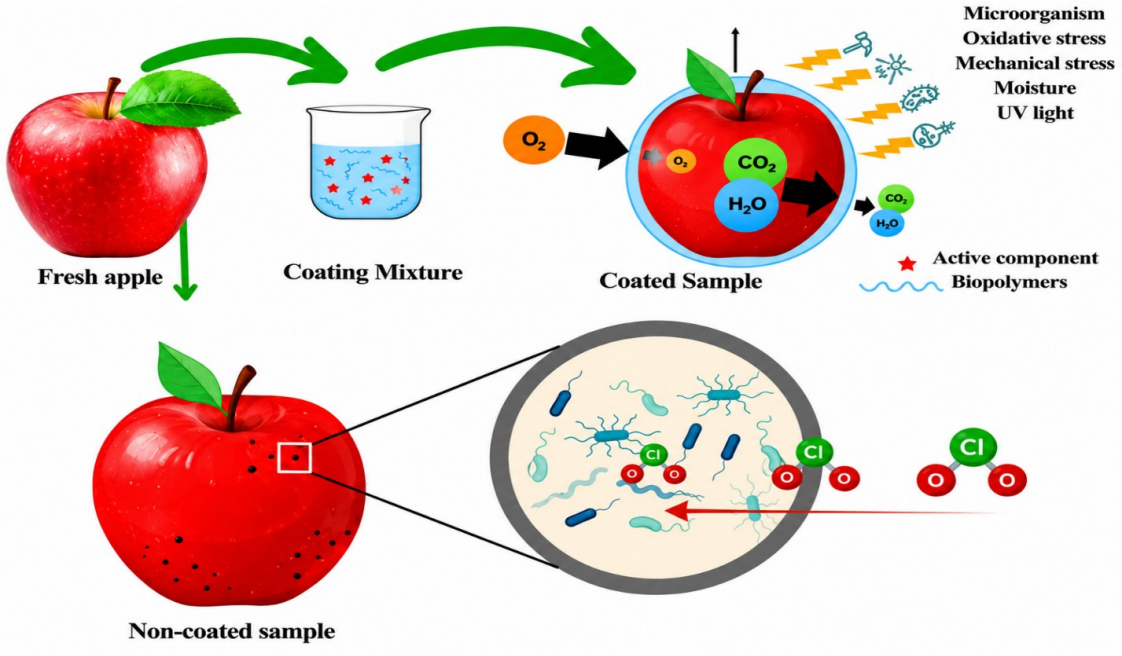
These examples show that edible coatings are not universal preservation solutions: formulations must be tailored to the physiology of each commodity (its respiration rate, peel structure, and whether the peel is eaten) and to its storage conditions.



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**Figure 3**

*Mechanism by Which an Edible Coating Extends the Shelf Life of Fruits and Vegetables*




*Note.* The coating layer regulates gas exchange ($O_2/CO_2$), water vapor diffusion, and microbial activity at the surface of the produce. Adapted from Guan et al. (2021) and Maan et al. (2021).

**Conventional and Emerging Techniques for Producing Edible Coatings**

Technologies for producing edible coatings and biodegradable films fall into two groups: conventional methods and emerging, often nanotechnology-enabled, approaches that have developed rapidly over the past decade. The two groups differ in production rate, degree of structural control, energy consumption, and industrial scalability (Figure 4).

**Conventional Methods**

Solution casting is the simplest and most widely used laboratory method. A film-forming polymer such as gelatinized starch is dissolved or dispersed in water or another solvent, cast onto a flat glass or plastic plate, and dried to evaporate the solvent (do Val Siqueira et al., 2021). Although simple and inexpensive, the method is poorly suited to continuous industrial production because of its high water consumption, long drying times, and high energy demand (Jiang et al., 2020).

Dipping and spraying are the most widely used methods for applying coatings directly to produce. In dipping, the product is immersed in the coating dispersion, excess liquid is drained, and the coating is dried; the method is rapid and inexpensive and gives full coverage, and coating thickness is governed mainly by viscosity and drainage time (Falguera et al., 2011). In spraying, the formulation is atomized through a pressurized nozzle onto the product surface. This minimizes material consumption and allows controlled dosing, but uniform thickness on large or irregular surfaces is harder to achieve at industrial scale (Adibi et al., 2023). In both cases, adhesion between the coating and the substrate determines coating integrity (Verma et al., 2020).

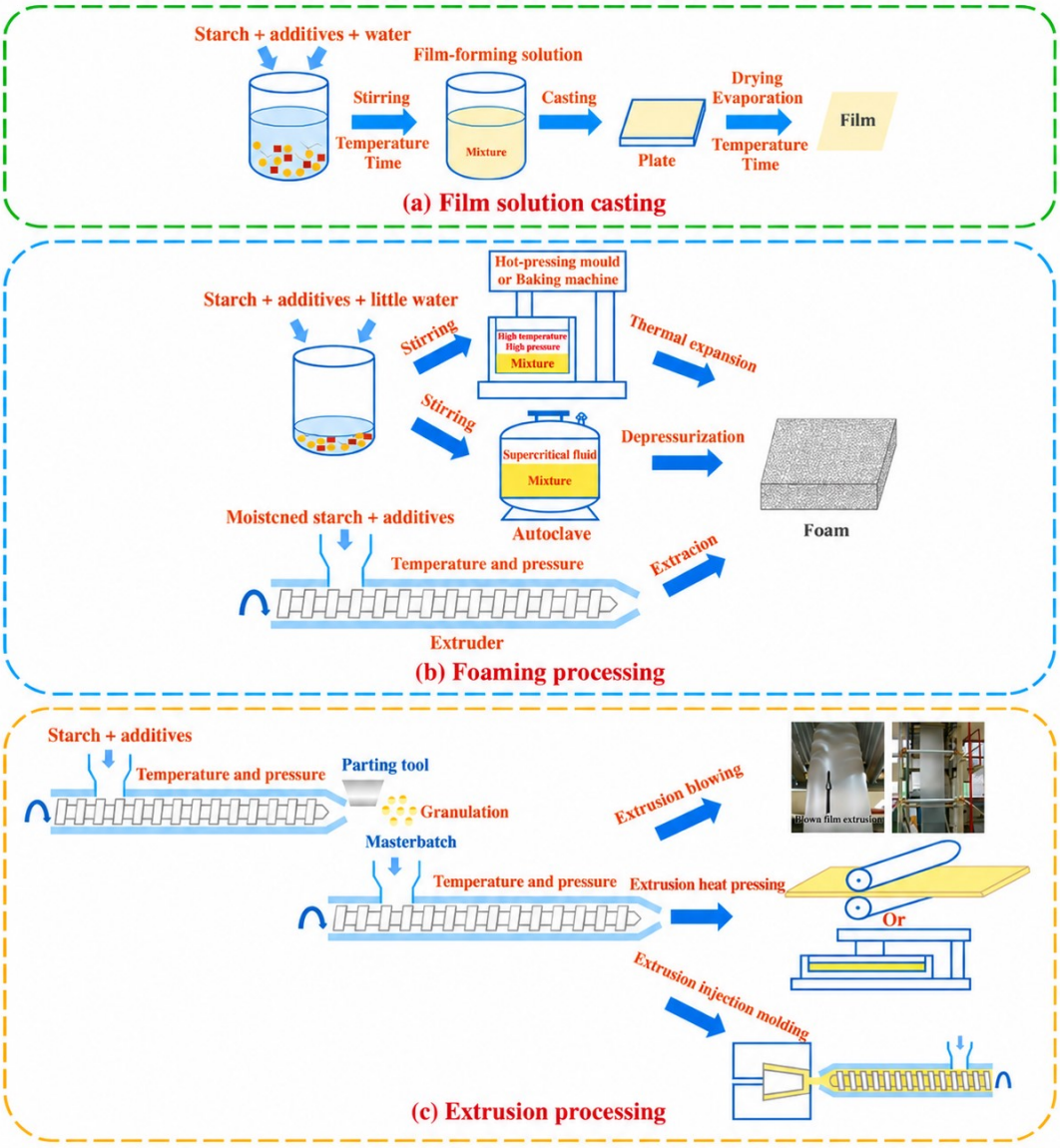
Extrusion is a dry process that exploits the thermoplastic behavior of biopolymers. The formulation is fed into a screw extruder, heated to the processing temperature under shear, and forced through a die; extrusion blowing, extrusion–compression molding, and injection molding are derived techniques (do Val Siqueira et al., 2021). Extrusion offers high throughput and is widely used industrially, for example for starch/poly(butylene adipate-*co*-terephthalate) (PBAT) blends (Dammak et al., 2020; C. Zhang et al., 2021), but the combined thermal and mechanical stress can alter molecular organization and reduce starch crystallinity. Foamed starch materials are produced by baking or molding, extrusion cooking, and


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supercritical $CO_2$ foaming (Barbosa et al., 2019; Combrzyński et al., 2019; Peng et al., 2018; Zeng et al., 2019); starch foams reinforced with grape stalks are one example developed for food packaging (Engel et al., 2019).

**Figure 4**

*Conventional Techniques for Processing Starch-Based Biodegradable Materials*




*Note.* (a) Film solution casting. (b) Foaming processing. (c) Extrusion processing. The schematic of extrusion blowing is adapted from Domene-Lopez et al. (2019).

### Emerging and Nanotechnological Methods

Electrospinning uses a high-voltage electric field to draw nano- to micrometer-scale fibers from polymer solutions or melts. A droplet at the needle tip deforms into a Taylor cone, and when the electrostatic force exceeds the surface tension, a charged jet is ejected toward the collector while the solvent evaporates (G. Liu et al., 2017). Carvacrol-loaded soluble potato starch nanofibers with diameters of 73–95 nm reduced *Listeria monocytogenes*, *Salmonella* Typhimurium, *Escherichia coli*, and *Staphylococcus aureus* by 89%, 68%, 62%, and 49%, respectively, and retained activity for at least 30 days (Fonseca et al., 2019). Electrospinning can also produce aligned or multilayer structures with good adhesion between hydrophilic and hydrophobic layers (Mondragon et al., 2020; H. Wang et al., 2019).

The safety of electrospun materials intended for food contact depends largely on the solvent and the cross-linker. Starch is commonly spun from dimethyl sulfoxide (DMSO) or aqueous formic acid (G.



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Liu et al., 2017); the carvacrol fibers described above, for example, were produced from 75% formic acid. Neither solvent is added to the food intentionally, but residues can remain in the fibers. Both DMSO and formic acid belong to Class 3 (low toxic potential) of the ICH Q3C guideline, for which residues of up to 5,000 ppm (0.5%) are acceptable without further justification (International Council for Harmonisation [ICH], 2024). Residual solvent should nevertheless be removed by drying or vacuum treatment and quantified, for example by headspace gas chromatography, before food-contact use. Cross-linking with glutaraldehyde vapor, used to improve the water stability of starch fibers (W. Wang et al., 2016), raises greater concern because glutaraldehyde is not food-grade. For edible applications, water- or ethanol-based spinning systems and food-grade cross-linking strategies are therefore preferred (G. Liu et al., 2017).

Three-dimensional (3D) printing is a computer-controlled, layer-by-layer technology for producing objects of predefined geometry. Because starch forms gels, starch dispersions can serve as printable “inks” (Maniglia et al., 2019; Perez et al., 2019). Of the gels of three starches compared, wheat starch showed the lowest viscosity, the best extrudability, and the closest agreement with the designed dimensions, outperforming potato and corn starch (Zheng et al., 2019). Adding pea protein (Feng et al., 2018) and ozone modification of cassava starch (Maniglia et al., 2019) further improve printability, and starch has also been blended with acrylonitrile–butadiene–styrene (ABS) for printing filaments (Kuo et al., 2016). 3D printing is expected to support coatings and foods with customized shapes and architectures, although its cost currently limits it to specialized products (Perez et al., 2019).

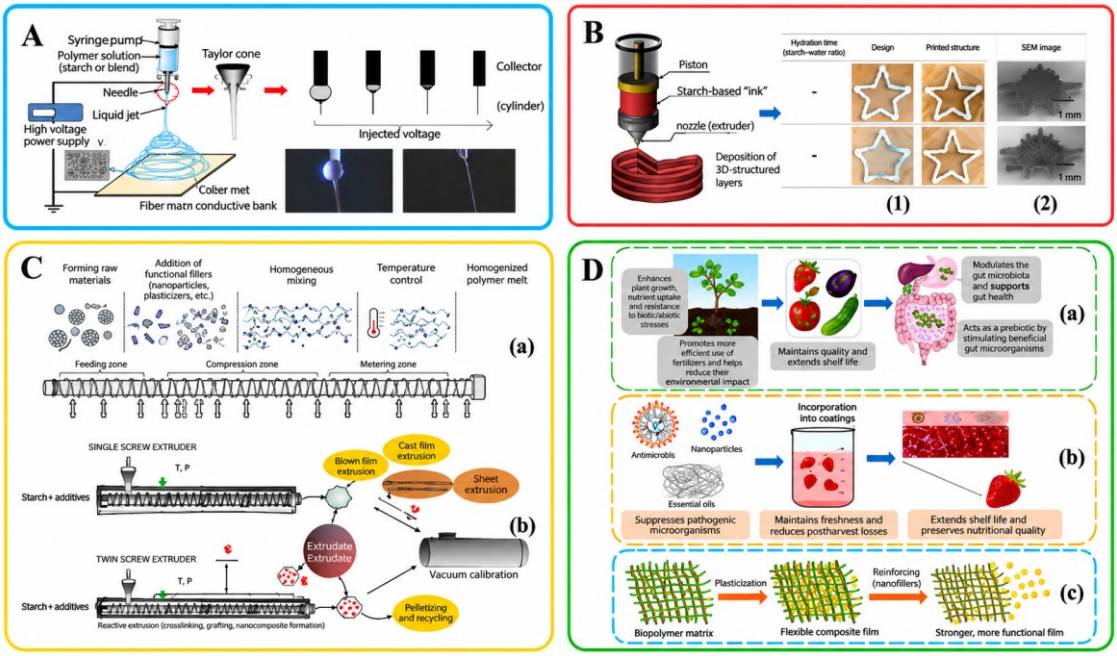
Reactive extrusion (REX) combines chemical or enzymatic reactions, such as grafting, cross-linking, and polymerization, with extrusion, so that the extruder acts as a continuous chemical or biocatalytic reactor (Siyamak et al., 2020; Xu et al., 2020). Adding exogenous enzymes (enzymatic reactive extrusion, eREX) improves process efficiency and offers more sustainable modification routes (Gatt et al., 2018; Xu et al., 2015). REX has been used for in situ plasticization and succinylation of cassava starch and to make biodegradable films from cellulose acetate/corn starch blends (Fonseca-Florido et al., 2019; Julien et al., 2019). Its main limitations are the complexity of process modeling and the short residence time of the reacting melt, typically only 1–5 min, which restricts it to fast reactions (Xu et al., 2020).

Nanotechnology concerns materials with at least one dimension of approximately 1–100 nm and can substantially enhance the functionality of coatings (Rodrigues & Emeje, 2012; Sampathkumar et al., 2020). Nanofillers such as cellulose nanofibrils, montmorillonite, and bentonite modify crystallization, morphology, and particle size, improving mechanical and barrier properties (Issa et al., 2018; Merino et al., 2019). Cellulose nanofibrils increase the tensile strength and Young’s modulus of starch films (Fourati et al., 2020; Lomeli-Ramirez et al., 2018), although excessive loadings can promote agglomeration that impairs performance. $TiO_2$ nanoparticles modify the physicochemical and thermal properties of starch films (Oleyaei et al., 2016), silver nanoparticles and chitosan have been used to impart antibacterial activity (Batool et al., 2019), and starch–chitosan nanocomposites have even been developed as substrates for flexible green electronics (Miao et al., 2018). Layer-by-layer (LbL) assembly builds dense multilayers with high gas barrier performance through the sequential deposition of oppositely charged polyelectrolytes, such as polyethyleneimine or chitosan and sodium alginate, driven by electrostatic interactions and hydrogen bonding (Rocca-Smith et al., 2019; F. Wu et al., 2021).


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**Figure 5**

*Emerging Techniques for Producing Edible Coatings and Biodegradable Films*




*Note.* (A) Electrospinning: group drawing adapted from G. Liu et al. (2017); schematic of electrospinning (left) adapted from http://weistron.com.cn/newsitem/277119212; Taylor cone formation (right) adapted from Sill and von Recum (2008). (B) 3D printing: extrusion process (left) adapted from Godoi et al. (2016); 3D-printed starch products (right): (1) 3D-printed cassava starch gel (Maniglia et al., 2019) and (2) samples printed with (a) potato, (b) wheat, and (c) corn starch (Zheng et al., 2019). (C) Reactive extrusion: (a) change of starch structure from ordered to disordered during reactive extrusion, adapted from Fonseca-Florido et al. (2019); (b) sequential reactive extrusion–enzymatic hydrolysis (REX-EH) and enzymatic reactive extrusion (eREX), adapted from Xu et al. (2020). (D) Nanotechnology: (a) applications in agriculture, food, and drug delivery and (b) nano-delivery systems in edible food coatings, adapted from Sampathkumar et al. (2020); (c) drug loading and delivery by biopolymer nanocomposites, adapted from Jacob et al. (2018).

**Comparative Analysis of Conventional and Emerging Methods**

Conventional methods are simple and inexpensive and require little equipment, but casting in particular is suited mainly to laboratory or small-scale production because of its energy demand and long processing times. Emerging methods offer much greater control over structure and function, including delivery of nanoencapsulated active agents, defined geometries, and enhanced barrier performance, but they require greater capital investment, more complex processing, and specialized equipment. For direct application to fresh produce, dipping and spraying remain the industrial standard, whereas extrusion, electrospinning, and LbL assembly are more relevant to active packaging layers. Manufacturers should therefore select technologies according to product type, required functionality, and available resources.

**Safety, Migration, and Challenges in Industrial Application**

Because edible coatings are eaten together with the food, their safety must be assessed as rigorously as that of any food ingredient (Figure 6). Legally, coatings applied directly to food are regulated in the European Union as food additives: glazing agents such as beeswax (E 901), carnauba wax (E 903), and shellac (E 904) are authorized only for listed fruits, and microcrystalline wax (E 905) only for fruits with inedible peel (Commission Regulation [EU] No 1147/2012, 2012; Regulation [EC] No 1333/2008, 2008). Coatings on packaging materials are instead regulated as food-contact materials; for plastic materials, the overall migration limit is 10 mg of substances per $dm^2$ of contact surface, or 60 mg $kg^{-1}$ of food (Commission Regulation [EU] No 10/2011, 2011).

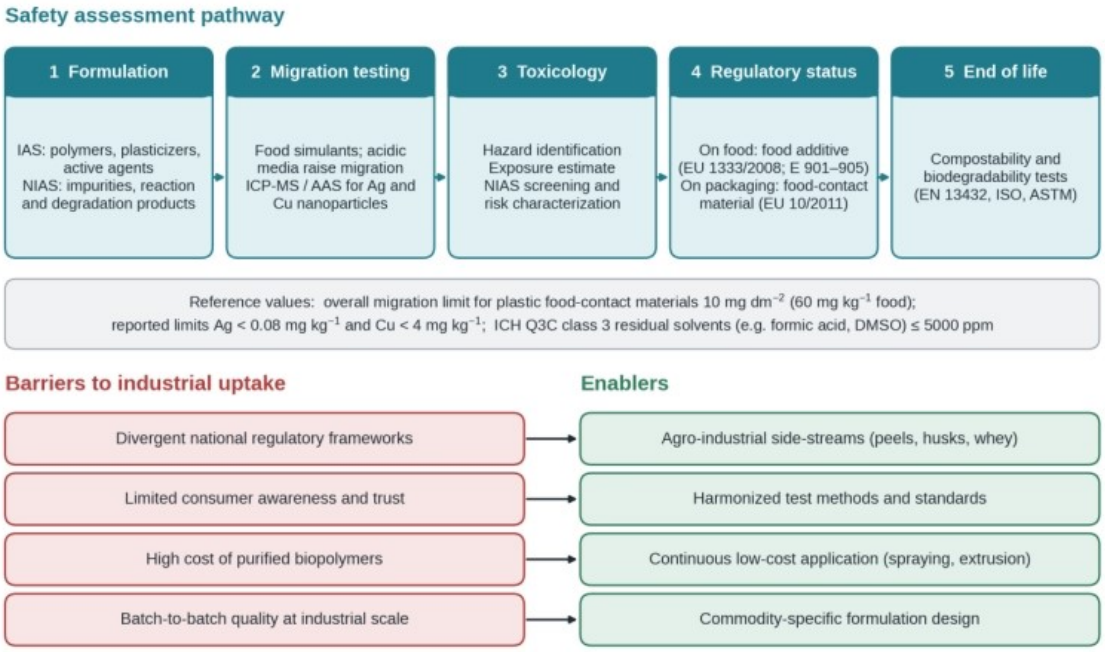
Both intentionally added substances and non-intentionally added substances (NIAS), such as impurities, reaction by-products, and degradation products, must be identified and toxicologically assessed. Harmonized guidance exists for selecting analytical techniques for NIAS in food-contact materials (Nerín et al., 2022), and an interlaboratory study has validated a combined chemical and in vitro testing protocol for packaging coatings (Marin-Kuan et al., 2023). For nanomaterials, inductively coupled plasma mass spectrometry (ICP-MS) and atomic absorption spectroscopy (AAS) are the principal techniques for quantifying the migration of silver and copper nanoparticles. Migration increases in acidic media; reported values for polyethylene nanocomposites range from 0.003 to 0.005 mg $dm^{-2}$ for Ag and from 0.024 to 0.049 mg $dm^{-2}$ for Cu, and limits of < 0.08 mg $kg^{-1}$ for Ag and < 4 mg $kg^{-1}$ for Cu have been reported (Ahari & Lahijani, 2021).

Large-scale implementation is further constrained by divergent regulatory frameworks across countries, limited consumer awareness and trust, the high cost of purified biopolymers, and the difficulty of maintaining consistent quality at industrial scale (Cloete et al., 2023; Din et al., 2020). Seal integrity and adhesion become critical when coatings are applied to flexible packaging (Ilhan et al., 2021), and the barrier performance of biodegradable polymers under high humidity remains a key technical gap (Adibi et al., 2023; F. Wu et al., 2021). Biodegradability claims must be supported by standardized tests, such as ISO and ASTM methods and EN 13432 for industrial compostability (Jahangiri et al., 2024; Meereboer et al., 2020). Biodegradation has been demonstrated, for example, for poly(vinyl alcohol)/starch composite films (Kaur et al., 2019), acetylated rice starch films (Colussi et al., 2017), and nanoclay-containing starch mulch films (Merino et al., 2019).

Future priorities include harmonizing international regulatory requirements, standardizing biodegradability and migration testing, and integrating low-cost raw materials from agricultural residues and food-processing by-products (fruit peels, cereal husks, whey) into production chains. These measures would improve the economic feasibility, regulatory acceptance, and environmental sustainability of edible coating technologies.

**Figure 6**

*Safety Assessment Pathway for Edible Coatings and the Main Barriers to and Enablers of Industrial Uptake*




*Note.* The pathway runs from formulation through migration testing, toxicology, and regulatory status to end of life. Reference values are from Commission Regulation (EU) No 10/2011 (2011), Ahari and Lahijani (2021), and ICH (2024). Original schematic prepared by the authors.



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## Conclusions

This review shows that edible coating technology is an environmentally sustainable, functionally versatile, and realistic complement to petroleum-based packaging. Polysaccharides and proteins provide good gas barrier and film-forming properties, proteins contribute mechanical strength, and lipids provide superior resistance to moisture transfer, as reflected in reductions in water vapor permeability or transmission of up to 97%–98% in lipid-containing systems. Hybrid combinations compensate for the limitations of individual components and yield multifunctional materials; coated fresh-cut melon, for example, retained its quality for 21 days at 4 °C. Conventional technologies (casting, dipping, spraying, and extrusion) remain the most cost-effective routes, while electrospinning, 3D printing, reactive extrusion, and nanotechnology add controlled release, customized geometry, and enhanced barrier performance, provided that residual solvents, cross-linkers, and nanoparticle migration are rigorously controlled.

Future research should focus on (a) cost-effective recovery of functional raw materials from agricultural and food-processing residues such as fruit peels, cereal husks, and whey; (b) adaptation of nanotechnological approaches to industrial-scale, food-grade manufacturing using green solvents; (c) harmonized methods for evaluating the biodegradability and safety of edible coatings in line with international standards; and (d) intelligent coatings, such as anthocyanin-based pH-indicator films that signal freshness through a color change (Choi et al., 2017). Progress in these areas will strengthen the role of edible coatings in reducing food loss, mitigating plastic pollution, and supporting the Sustainable Development Goals.

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