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Advancements in post-harvest techniques for preserving fresh produce: a comprehensive review

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ABSTRACT
One of the biggest constraints in the food industry is the economic transportation of healthy food products with reduced post-harvest losses. Edible coatings are bio-based films applied to fruits and vegetables to enhance their shelf life during post-harvest storage and distribution. This review critically evaluates recent advances in edible coating and packaging technologies for post-harvest preservation of fruits and vegetables. Food packaging designed from nature's building blocks, such as sugars, amino acids, and fats, has long reflected exemplary success in maintaining the freshness and quality of fresh foods. The literature is categorised into polysaccharide, protein, lipid-based, and composite edible coatings, as well as active and intelligent packaging systems. Emerging technologies, especially 3D printing, hold great promise for developing unprecedented surface topography and tailored features, enabling the controlled addition of beneficial compounds. In contrast, food packaging is a functional barrier, offering essential protection against environmental assailants such as UV light, oxygen, microbial penetration, and water vapor. Freshness-retaining packaging technologies employ agents such as antioxidants, charcoal for gas management, and moisture managers, which play a valuable role in preserving the quality and nutritional content. Across the reviewed studies, these systems demonstrated shelf-life extensions ranging from several days to multiple weeks, along with reduced weight loss, delayed microbial spoilage, and improved physicochemical quality. Further, the growing use of intelligent packaging with sensors and freshness indicators enables real-time quality and safety inspections along the supply chain. Despite these advancements, challenges remain regarding large-scale applicability, cost-effectiveness, sensory acceptance, and regulatory standardisation. This study concludes that a sensible, well-designed blend of tailored food wraps and advanced storage protocols forms a strong alliance with high potential to jointly provide robust protection, conserve nutrients, and substantially prolong the freshness of a variety of fresh produce.

Keywords: Post-harvest technology, edible coating, active packaging, intelligent packaging, storage.

INTRODUCTION
A balanced diet rich in fruits and vegetables plays a central role in preventing chronic diseases due to its diverse nutritional composition, including carbohydrates, proteins, lipids, fibres, minerals, and vitamins **[1]**. This nutritional profile is associated with reduced risks of cancer, cardiovascular disorders, diabetes, obesity, and various degenerative diseases **[1]**, **[2]**. Consequently, the global fresh produce market has grown substantially, underscoring the need to maintain its quality and safety throughout the supply chain **[1]**, **[3]**.
Addressing these issues requires innovative preservation strategies to reduce losses and ensure the availability of high-quality produce. Historically, preservation techniques such as drying, salting, and pasteurization can extend shelf life but often compromise texture, flavour, or nutritional integrity **[4]**.

Given the complexities, post-harvest measures have emerged as an indispensable cornerstone in the ongoing efforts to enhance the quality of fresh produce, significantly reduce waste, and optimize the utilization of agricultural output **[5]**, **[6]**, **[7]**. These measures encompass a wide array of interventions, broadly categorized into physical and chemical methods. Physical approaches frequently involve leading-edge packaging technologies, including active, intelligent, and composite packaging systems, as well as the application of various edible and non-edible coatings **[8]**. Chemical methods typically involve the judicious incorporation of antioxidants and antimicrobials to effectively inhibit spoilage.

Among these innovations, edible coatings represent a particularly promising eco-friendly strategy. These thin, biodegradable films reduce transpiration and moisture loss, suppress microbial growth, and extend shelf life without altering the physiological or metabolic properties of the produce **[9]**. Their ability to incorporate antioxidants, antimicrobials, or other functional additives enhances both protection and visual appeal **[10]**.
Modern packaging technologies further contribute to quality preservation. Beyond basic containment, contemporary designs emphasize convenience, reusability, and compatibility with consumer lifestyles **[11]**. Active packaging modifies the surrounding environment using components such as oxygen scavengers or moisture absorbers, while intelligent packaging monitors freshness through indicators and sensors **[11]**, **[12]**. Although many of these technologies are under active development, their commercial integration is still emerging.

Several studies have addressed edible coatings, edible films, active packaging, and intelligent packaging as individual methods for post-harvest preservation. But these reviews often focus on specific material or technologies, with limited emphasis on their combined application, commercialisation readiness, and regulatory considerations. This review uniquely combines edible coating technologies with active and intelligent packaging systems, while critically measuring their practical feasibility, scalability, and significance to real-world post-harvest supply chains.

Despite their promising potential, several unresolved problems hinder the widespread adoption of advanced coating and packaging technologies. These include regulatory uncertainties surrounding nano-enabled systems, concerns regarding material migration and toxicity, variable consumer acceptance, reliability of sensing components, cost–benefit constraints, and difficulties in large-scale industrial implementation. Addressing these difficulties is essential to bridge the gap between laboratory-scale innovations and commercial deployment **[13]**.
In this context, the present review aims to: (i) examine sustainable, next-generation preservation strategies for fresh produce; (ii) categorize key packaging and coating materials and their applications; (iii) evaluate coating mechanisms in post-harvest preservation of fruits and vegetables; and (iv) explore the potential of advanced active and intelligent packaging systems in improving food safety and extending shelf life.

1. COATING AND PACKAGING:

Coating and packaging are innovative post-harvest techniques that preserve the quality and shelf-life of fruits and fresh produce. Coatings, a type of edible packaging, are made of edible substances such as polysaccharides, proteins, and lipids, ensuring a protective barrier to reduce moisture loss, respiration rate, and microbial growth (Figure 1) **[12]**. Each component used in the production of edible coatings ought to be GRAS (Generally Recognized As Safe) and have been authorized to be utilized in food products **[14]**. Compared to the other measures, these have grown in popularity over the years owing to their benefits on produce quality and environmental sustainability **[15]**. On the other hand, the packaging consists of two techniques: active and intelligent packaging. Active packaging systems use antimicrobial agents or oxygen scavengers to maintain product quality, while intelligent packaging systems use sensors and indicators to maintain the freshness of the produce. Table 1 reflects the differences between food coatings and packaging and Table 2 describes the important findings and types of edible coatings that are commercially used.

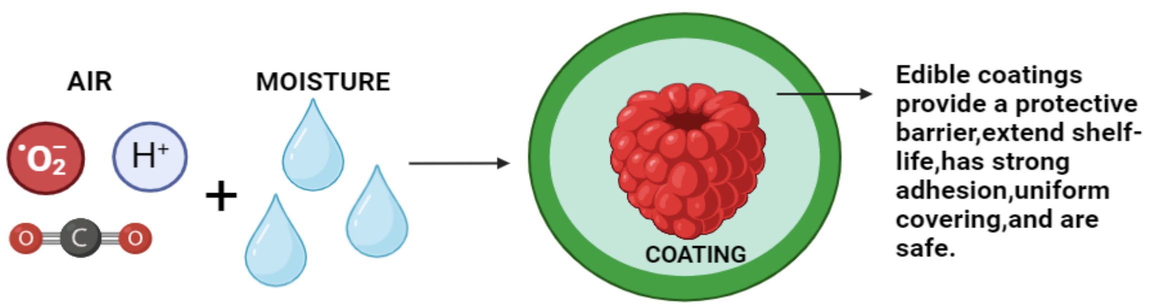

Figure 1 Functional role of edible coating in food packaging.

Table 1 Distinct entities of consumable packaging and coatings.

DESCRIPTION	EDIBLE PACKAGING	EDIBLE COATINGS
Definition	Use of Bio-based and biodegradable materials due to their film-forming qualities.	Liquid, emulsion, or powder-based and is applied directly to food surfaces.
Vital properties	Enhance organoleptic properties of sealed products by incorporating aromas, colors, and surface modifications.	Edibility, non-toxic, and cost-effectiveness in comparison with alternative synthetic coatings
Packaging methods	Different forms include coatings and films.	Main techniques include spraying, dipping, and spreading.
Moisture characteristics	Polysaccharides and proteins are less moisture-resistant and exhibit lower barrier properties than lipids due to their hydrodynamic properties.	Offering a moisture barrier on produce surfaces will minimize moisture loss.
Materials employed	Polysaccharides, proteins, lipids, and composites (multi-stack, conglomerates, blends of the other three components)	Proteins, polysaccharides, lipids, and natural resins (including shellac, terpene, wood rosin)

Note: source **[16]**, **[17]**.

With regard to the above table, edible coating is used for goods that require a basic, affordable method to enhance lifespan and effectiveness, whereas dietary packaging has greater potential to improve product appearance while offering maximum protection and value. The decision between edible coating and edible packaging depends on the product's specific requirements.

1.1 Protein Coatings and Packaging

Proteins are macromolecules, consisting of single or multiple long chains of amino acid residues. These amino acids are combined together by a peptide bond and are stabilized by various covalent and non-covalent interactions. Proteins such as gelatin, maize zein, wheat gluten, soy protein, meat-derived proteins, and milk protein are commonly used for coating due to their molecular interactions, good film-forming ability, high nutritional value, and gas barrier properties **[18]**. To enhance their barrier and mechanical capabilities, a variety of techniques have been used, including physical approaches in conjunction with hydrophobic materials, and enzymatic modification of protein features **[19]**. Despite their advantages, these coatings face several limitations, including water sensitivity of protein films, allergenicity concerns associated with gluten-containing materials, consumer hesitancy toward animal-derived proteins such as gelatin, and challenges related to cost, large-scale processing, and industrial scalability.

1.1.1 Wheat Gluten

Gluten is a protein found in wheat and related grains, such as barley and rye. The wheat kernel is composed of 12-16% of the gluten protein **[20]**. Along with water and other ingredients such as plasticizers, a film coating is manufactured that imparts good barrier and mechanical properties. Various experimental studies were conducted to analyze the effectiveness and the physicochemical properties of gluten-based coatings on food products **[21]**. One such study was the fabrication of wheat gluten on strawberries to prolong their shelf life, delay the deterioration process, and boost firmness retention **[22]**. Based on Jingwen et al., gluten-based coatings prolong the life span of fresh green chilies, tomatoes, potatoes, apples, and strawberries by slowing weight loss and delaying senescence under storage conditions. However, the application of gluten-based coatings is limited by gluten allergenicity concerns and regulatory restrictions for sensitive consumer groups **[23]**.

Table 2 Coatings overview.

POLYMER TYPE	ACTIVE INGREDIENT INCORPORATED	APPLICATION METHOD	PRODUCE TYPE	STORAGE CONDITIONS	MAIN MEASURED OUTCOMES	SHELF-LIFE EXTENSION	REFERENCES
			POLYSACCHARIDES-BASED COATINGS				
Alginate	Asparagus waste extract (Phenolic-rich)	Dipping	Fresh-cut Papaya	5 ± 1 °C, 85-90% RH	Reduced weight loss, delayed firmness loss, lower microbial growth, and maintained colour	Shelf life extended by 4-6 days compared to the control	**[42]**
Cellulose	Asparagus waste extract	Dipping	Strawberry	25 ºC, 80% RH	Reduced weight loss, delayed colour change (ΔE), higher phenolics and flavonoids, and antifungal activity	Shelf life extended by ≈ 5 days	**[43]**
Chitosan	Aloe vera gel	Dipping	Mango	12 ± 1 ºC (28 days) + 25 ºC (5 days), 80-85% RH	Reduced decay incidence, lower respiration and ethylene production, maintained firmness and ascorbic acid	Shelf life extended by ≈7–10 days	**[44]**
Pectin	Plasticized with glycerol	Dipping	Plum	19 ± 2 °C, 65% RH	Higher antioxidant capacity, increased POD activity, reduced PPO activity, preserved anthocyanins	Shelf life extended by ≈4–6 days	**[45]**
Starch	Basil Essential Oil + Cellulose Nanofibers	Dipping	Mandarin Orange	Room Temperature, 12 days	Reduced weight loss, better color retention (L*), maintained organic acids and ascorbic acid	Weight loss reduced by ≈4–5%, shelf life extended by ≈3–4 days	**[46]**
Carrageenan	None	Dipping	Cavendish Banana	25 ºC, ambient RH	Reduced respiration rate, delayed peel browning, and maintained firmness	Shelf life extended by 3–5 days	**[47]**
			PROTEIN-BASED COATINGS				
Wheat Gluten	None (functional coating without added antimicrobials	Dipping/immersion	Strawberries and Cherries	Ambient Storage (~24–25 °C, 50–55% RH)	Reduced weight loss and decay rate, delayed softening, improved colour retention, reduced oxidative damage	Shelf life extended by 2-3 days vs control at room temperature	**[48]**
Maize Zein	Resveratrol (2-10% w/w)	Direct electrospinning of nanofibers onto produce surface	Fresh-cut apple slices	Ambient temperature (~25–30 °C)	Reduced moisture loss, improved colour retention, enhanced antioxidant activity, controlled	Quality retention evaluated over 6 hours; effective short-term preservation	**[49]**

					release of resveratrol		
Soy Protein	Calcium Chloride (10g/L)	Dipping (5 min immersion)	Fresh-cut peaches	Refrigerated (0 ºC)	Inhibited browning, reduced Polyphenol Oxidase & Peroxidase activity, lower microbial growth, reduced respiration & ethylene	Shelf life maintained up to 10 days with acceptable quality; control showed severe browning and quality loss earlier → ≈ 2–4 days functional extension	**[50]**
Gelatin	Argentinian propolis ethanolic extract (direct or zein-encapsulated)	Dipping (film-forming dispersion)	Raspberries (Rubus idaeus L.)	Refrigerated Storage (5 ºC)	Reduced fungal decay, antifungal activity against *Botrytis cinerea* and *Penicillium* spp., improved microbial stability	Shelf life extended for 4-5 days during cold storage compared to uncoated fruit	**[51]**
LIPID-BASED COATINGS							
Carnauba Wax	Carnauba Wax Emulsion (0.5-1.5%, w/v)	Dipping	Orange	4 ± 1 °C, cold storage	Reduced weight loss, delayed firmness loss, reduced decay, maintained antioxidant activity	Extended up to 80 days	**[52]**
Essential Oil	Aloe vera gel (25%) + lemongrass essential oil nanoemulsion (1-5%)	Dipping	Date fruit	Ambient storage	Reduced microbial load, delayed spoilage, improved texture	Extended up to 4 weeks	**[53]**

1.1.2 Maize Zein

Zein constitutes about 45-50% of the overall protein content in maize; other proteins include albumin, globulin, and glutelin. Zein is an edible protein due to the presence of hydrophobic amino acids, relaying zein-based coatings and water vapor barrier properties **[18]**. It is used in the manufacturing of nanoparticles, which wrap up bioactive substances by improving their stability under processing and storage conditions **[20]**. In research, Belay et al. **[24]** dipped half-damp apricots in the organic maize protein zein and observed that this coating prevented microbial development. Additionally, these coatings have prolonged the shelf life of apples and pears and reduced weight. Contrary to other protein-based coatings, zein-based coatings exhibit good barrier properties and protect food products from oxygen, moisture, and other environmental factors responsible for the loss of their quality **[25]**. Nevertheless, the relatively high cost of zein extraction and processing may limit its widespread industrial adoption.

1.1.3 Soy Protein

Soy proteins are obtained from soybeans by dehulling, flaking, or defatting. Soy protein isolate (SPI) is used in crafting a soy protein-based coating. SPI-based edible coatings reveal good flexibility, oxygen barrier properties, optical transparency, and affordability. Pineapples coated with soy protein isolate successfully reduced moisture loss and microbiological development **[26]**. Research explained the ability of the SPI to form Biodegradable, edible films as it blends soy protein with plasticisers or bioactive compounds, emphasising flexibility, antimicrobial activity, and preservation of the produce **[27]**. The SPI consists of hydrogen bonds, hydrophobic bonds, ionic bonds, and disulfide bonds, demonstrating better film-forming properties but poor waterproofing and mechanical properties. Additionally, they exhibit high water sensitivity, which restricts their performance under high-humidity storage conditions unless modified through composite or nanofiller incorporation. This challenge was rectified by supporting the coating with nanofibers or nanocrystals. One instance was a combination of cellulose nanocrystals and Cedrus deodara pine needle extract in SPI, which showcases a high tensile strength **[25]**. Majumder et al. (2023) revealed that tannic acid-loaded halloysite clay conjugated with silver nanoparticles improved the performance of these isolation films, making them ideal for food coating applications **[28]**.

1.1.4 Milk Protein

Milk consists of 80% casein and 20% whey proteins. Casein is obtained by precipitating milk with acid at pH 4.6. It exhibits various characteristics like biodegradability, chemical resistance, non-toxicity, high nutritional value, and the ability to aggregate to form micelles, stabilized by coupling with calcium phosphate, making it an excellent material for biodegradable films **[21]**. Because native casein is insoluble, it is converted into sodium caseinate using sodium hydroxide, improving film-forming capacity and barrier properties, which can be further enhanced with zein coatings **[20]**. Casein-based films are transparent, flavorless, flexible, and can be formulated with glycerol, citric acid, pectin, or calcium caseinate to improve tensile strength and elasticity, thereby extending food shelf life by limiting microbial growth **[25]**, **[29]**. Whey proteins, although negatively charged, offer comparable functional properties and have been incorporated into composite coatings, for example, with rice bran oil and plasticizers to maintain firmness and storage quality in kiwi fruit. Despite their favourable film-forming properties, these coatings may have limitations, including moisture sensitivity and higher formulation costs than polysaccharide-based alternatives.

1.1.5 Gelatin

An animal-derived protein, produced by the hydrolysis of collagen **[25]**. Gelatin is used for various applications owing to different attributes such as high gas and oil resistance, non-toxic, affordable, and biodegradable**[20]** . It is used in the fabrication of food coatings, prepared by casting from its aqueous solution, disclosing high tensile properties, improving longevity, antimicrobial, and antioxidant properties **[21]**, **[18]**. Their antimicrobial properties were evident in chitosan-gelatin-ZnO nanocomposite and chitosan-gelatin-Silver nanoparticle coatings on red grapes, reducing microbial growth and extending their longevity by 14 days without affecting their nutritional content. However, consumer concerns related to animal origin, dietary restrictions, and ethical considerations may limit the acceptance of these coatings in certain markets.

1.2 Lipid Coatings and Packaging

Lipids are organic substances that are partially soluble in water but soluble in a few natural solvents such as methanol, hexane, diethyl ether, chloroform, and benzene. They are categorized as simple (fats and oils, and waxes), derived (phospholipids, and glycolipids), and compound lipids (steroids, terpenes, and carotenoids). Fats and oils, which are triglycerides, are the most prevalent lipid structures in food sources. Lipids are used in coatings as they prevent moisture loss, minimize packaging costs, enhance the visual appearance of food products, enhance hydrophobicity, and inhibit water vapor permeability **[30]**. Although these coatings have been widely used on entire vegetables and fruits, they have several drawbacks, including the potential for crack development, a lack of uniformity, changes in sensory perception, poor adherence to the produce, and, in certain situations, the establishment of a high gas barrier that may restrict respiration and result in anaerobic conditions during storage **[31]**.

1.2.1 Waxes

Waxes, water-insoluble molecules, are composed of alcohol or esters of a long-chain acid. Concerning origin, waxes are grouped as Animal waxes, Vegetable waxes, and Mineral and synthetic waxes **[32]**. The most commonly used waxes are Carnauba wax, paraffin wax, Bee's wax, and Candelilla wax. These are applied as edible coatings or films on foods owing to reduced moisture permeability. Carnauba wax, the hardest of the commercial natural waxes, serves as a carrier, glazing agent, acidity regulator, bulking agent, and anticaking agent in food surface conditioning. Studies have shown that a carnauba wax wrapping and 2% montmorillonite nano-clay increase the durability during storage and the aroma of blood oranges **[18]**. Paraffin wax (PW) is a solid hydrocarbon made from crude petroleum, serves as an obstruction to moisture loss, and provides a lustrous and glossy appearance to fruits and vegetables. A candelilla wax coating was shown to improve strawberry freshness and quality when combined with biocontrol bacteria. These organic waxes are considered in the food industry as they enhance their surface appearance and decrease their stickiness **[32]**.

1.2.2 Essential Oils

Essential oils, evaporative substances derived from plants, exhibit various biological activities. According to the Food and Drug Administration (FDA), essential oils are generally recognized as Safe (GRAS), facilitating their use as alternatives to synthetic additives; however, regulatory acceptance may vary by region and intended application. Moreover, its use in the fabrication of edible films and coatings prevents microbial growth and lipid oxidation, owing to its constituents, such as terpenoids, terpenes, and other aromatic compounds **[32]**, **[33]**. Along with monoterpenes and sesquiterpenes, essential oils are incorporated into films and coatings, increasing the shelf life, improving mechanical properties, and reducing moisture loss in fresh fruits and vegetables **[31]**.However, the application of essential oils in edible coatings may be limited by strong sensory impacts, migration into the food matrix, volatility, and challenges related to controlled release and organoleptic acceptability. The vital ingredients include spices and herbs, particularly thymol, cinnamaldehyde, carvacrol, and eugenol, owing to antimicrobial (coconut or cinnamon oil) and antioxidant properties (grapeseed and olive oil) **[34]**. Thymol, an antifungal agent, has several limitations, including a strong odor, low water solubility, high volatility, and reduced antibacterial activity over time. This issue was resolved by introducing a chitosan-thymol composite coating on peaches, resulting in enhanced freshness and storage life **[18]**. Research is being conducted on edible coatings for organic foods, such as flaxseed or sesame oil, to enhance the quality and stability of healthy fruits and veggies during storage **[35]**.

1.3 Polysaccharides

Polysaccharides are organic polymers used to wrap fresh produce. The most frequently employed polymers are starch, chitosan, cellulose, alginate, pectin, pullulan, xanthan gum, and carrageenan **[36]**. These are used as standard coatings in the food industry as thickeners and gelling agents, to inhibit crystal formation, as stabilizing agents, and as encapsulating agents, due to their ability to reduce oxygen permeability, delay surface browning, and improve the storage stability of coated produce. Yet, these molecules are not able to function as moisture barriers because of their hydrophilic characteristics **[37]**.

1.3.1 Chitosan

Chitosan is a linear polymer obtained by deacetylation of chitin. It is predominantly synthesized from the cell walls of fungi and other pathogens, as well as from crustacean shells. The molecular structure of chitin consists of glucosamine and N-acetylglucosamine chains, imparting characteristics such as non-toxicity, non-allergenicity, biodegradability, biocompatibility, antifungality, antibacteriality, and film-forming ability. These serve as the basis for food coatings and films by reducing microbial spoilage, delaying firmness loss, limiting nutrient degradation, and extending the shelf life of food products during storage **[38]**. Chitosan coatings selectively inhibit the movement of gases, possess good tensile properties, and are highly decomposable on blending with other polymers, plasticizers, and cross-linkers **[29]**. Moreover, research was conducted by incorporating Essential oils, such as thyme oil, cinnamon oil, and clove oil, into chitosan coatings, resulting in a significant extension of shelf life and a reduction in microbial load across different varieties of fruit. Additionally, the coating of chitosan solution on the guava fruit could delay its ripening by reducing its respiration rate and degradation of chlorophyll **[39]**.

1.3.2 Pectin

Pectin is a complex and emulsifiable fiber found in the cell walls of plants, comprising high molecular glycan galacturonan chains. It is predominantly derived from veggies and fruits such as citrus peel and apples **[39]**. Pectin-based coatings are responsible for exceptional mechanical properties, reduced gas permeability, high transparency, and the ability to extend the storage period of fresh produce **[38]**. An examination of plums coated with pectin was carried out, in which the activity of the oxidative enzyme polyphenol oxidase decreased, while the antioxidant activity of the peroxidase enzyme increased, resulting in enhanced fruit quality **[40]**. Moreover, pectin-based coatings on pear wedges were reported to maintain their physical quality for up to 2 weeks under refrigerated storage **[36]**.

1.3.3 Starch

Starch, a vital storage carbohydrate with linear chains of amylose units, is found in cereals, cassava, potato, wheat, and corn. It possesses adequate mechanical strength, moderate gas barrier properties, oil resistance, flexibility, and water solubility. Those subunits in starch contribute to edible coatings because of their biodegradability and affordability **[41]**. Starch-based coatings on fruits and vegetables are odorless, non-toxic, colorless, exhibit reduced oxygen permeability, and decrease respiration rate, thereby extending postharvest life **[38]**. The incorporation of gelatin on starch-coated avocado fruits elevated the retention period of the fruit by decreasing its respiration rate. The main disadvantage of this coating is the phenomenon of retrogradation, which has been reduced by combining it with xanthan gums or gellan gums **[36]**.

1.3.4 Alginate

Alginate is a structural polysaccharide produced from brown seaweed. It is an unbranched, linear copolymer of β-d-mannuronic acid and α-l-guluronic acid residues **[39]**. Its hydrophilic nature and colloidal properties, like stabilizing emulsions, thickening, and gel-forming, play a role in coating fruits and veggies **[37]**. Alginate-based coatings exhibit limited moisture-barrier properties but effectively preserve color and extend the shelf life of food products, particularly plums and guava, by reducing dehydration and respiration rates. Besides this, the coating inhibits oxygen, which helps reduce lipid oxidation and weight, and minimizes aging during storage. It was suggested that sodium alginate coated on lemon, orange, and grapefruit decreased oxygen consumption and carbon dioxide production **[38]**.

1.3.5 Cellulose

Cellulose is the predominant natural polymer, with D-glucose units arranged in a crystalline structure. It can tolerate mechanical stress and temperature, but is less prevalent in moisture resistance, solubility, and high hydrophilicity **[38]**. Cellulose derivatives such as carboxymethylcellulose, hydroxypropyl cellulose, hydroxypropyl methylcellulose, and methylcellulose are used as edible films and coatings on fresh produce **[37]**. Cellulose-based coatings exhibit anti-rancidity effects and provide effective barriers against oxygen and carbon dioxide, while offering limited resistance to moisture transfer. This led to the crafting of an edible coating with collagen, starch, and chitosan, along with carboxymethylcellulose, which was proposed to improve vapor permeability and act as a carrier for probiotic strains. Chitosan/cellulose nanofiller-based coatings on curcumin prevent the growth of microbes by preserving the quality of kiwi fruit for up to 10 days **[40]**.

1.4 Composite Packagings and Coatings

Composite coating or packaging is a blend of the active and matrix materials that are blended by covalent and non-covalent interactions through chemical or enzymatic reactions and are themselves biodegradable. The most common covalent interactions among such molecules are esterification, etherification, amidation, and glycosylation. Hydrophobic and electrostatic interactions are non-covalent interactions. Two methods for the preparation of this film- dry and wet processes, or otherwise known as Extrusion and Solvent-casting processes. These films play a significant role in the food sector as they improve the integrity and respiratory stability of fruits and vegetables and boost their antioxidant and antibacterial activities **[54]**. Current studies have focused on creating edible films from surplus antimicrobial extracts, e.g., rosemary and cinnamon, which have been observed to exhibit superior antibacterial activity and increased mechanical strength. Following this, Studies have reported that the combination of Aloe vera gel and Chitosan results in composite edible coatings by enhancing the antimicrobial activity, longevity of the fruits and veggies, and reducing the moisture content **[55]**. Ternary films of proteins, chitosan, and glucomannan were analyzed for antimicrobial, antioxidant, mechanical, physical, optical, and barrier properties, and can be used for the preservation of fresh potatoes **[18]**.

1.5 Edible Nano-Coatings

Edible films and coatings serve as a matrix for the incorporation of nanoparticles to maximize interaction with food microorganisms. Silver, copper, titanium dioxide, and zinc nanoparticles are added to the chitosan, kefiran, shellac, cyclodextrin, or starch matrix to fabricate nano-coatings and films **[12]**.

The various benefits of coatings consist of enhanced nutrient delivery, reduced dehydration, nutrient retention, inhibition of microbial growth, enhanced nutraceutical value, and maintenance of overall fruit quality (Figure 2) **[10]**. For fresh keeping of food for extended storage periods, nanoemulsion-based coatings are used, with direct control over such characteristics as gas transfer and water vapor permeability **[56]**.

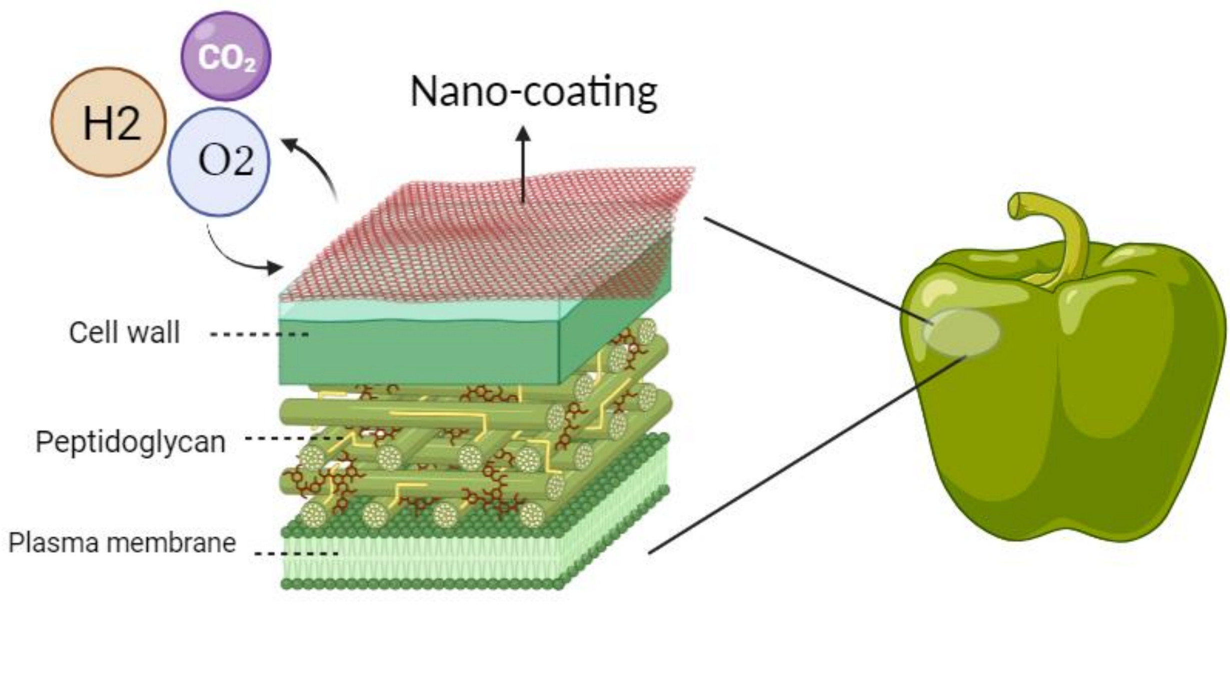

Figure 2 Edible Nanocoating uses nanoparticles in the form of film/sheet.

1.5.1 Safety, Migration, and Regulatory Considerations for Nano-Enabled Coatings and Packaging

Nanomaterials in food-contact applications require toxicological evaluation due to potential migration into food. Silver and zinc nanoparticles provide antimicrobial benefits but pose leaching risks, with EU overall migration limited to 10 mg/dm² (Regulation 10/2011) and titanium dioxide subject to specific migration limits. Recent journal studies (2022–2025) report low migration rates in standardized tests (EN 1186 for overall, EN 13130 for specific migrants) using simulants like 10% ethanol or 3% acetic acid at 40°C for 10 days, though nano-scale particles raise bioaccumulation concerns**[57]**, **[58]**, **[59]**, **[60]**.

Risk assessments apply threshold of toxicological concern (TTC) principles; in vitro data show dose-dependent cytotoxicity for Ag and ZnO nanoparticles, necessitating balanced benefit-risk profiles. EU's EFSA mandates nano-specific authorizations under Novel Food Regulation (EU 2015/2283), while the US FDA uses GRAS with nanomaterial-specific data requirements. Persistent challenges include particle agglomeration in food simulants, long-term exposure gaps, and regulatory validation costs, hindering widespread adoption **[61]**, **[62]**, **[63]**.

2. Dipping and Bilayer Coating

The methods and techniques for applying coatings are vital to ensure the product is properly packed in accordance with the proper procedure. Various coating application techniques are brushing, spreading, individual wrapping, dipping coating, bilayer coating, dripping, multilayer or layer-by-layer coating, and fluidized-bed handling **[64]**.

2.1 Dipping Coating

By dip or immersion coating, fruits and vegetables are immersed in a solution for a specified duration before drying, with implications for thickness, homogeneity, and textural attributes. The brittleness of the coating material can be reduced by adding plasticizers such as sorbitol, mannitol, sucrose, and glycerol. Surfactants lower surface tension, allowing a uniform coating to form. While dip coating is usually used on smooth-skinned fruits and vegetables, it is not ideal for thin membranes or skin. It's an inexpensive, simple-to-use process that may be up-scaled for industrial use. Fruit or vegetable shelf life can be enhanced by incorporating an antioxidant or antimicrobial extract into a biopolymer mixture. Dip coating has three stages: dwelling, layering, and dehydration **[65]**.

2.2 Bilayer Coating

Bilayer coatings provide an effective method to regulate moisture and gas exchange in fresh produce, helping delay ripening, reduce water loss, and improve storage stability **[36]**.

Biopolymer coatings derived from lipids, carbohydrates, and proteins protect against microbial, mechanical, and chemical degradation, thereby extending shelf life **[66]**. Hydrocolloids such as chitosan and alginate form strong gas-barrier films with antimicrobial activity, while lipid-based coatings reduce moisture loss due to their hydrophobicity **[35]**. Composite coatings combine these materials to achieve enhanced barrier performance **[67]**. A key advantage of bilayer systems is the ability to control the thickness and composition of each layer, enabling targeted protection and controlled release of active agents **[68]**. EVOH is commonly used for berries due to its excellent gas-barrier properties that regulate respiration and prevent over-ripening **[69]**. PLA, a biodegradable polymer, is applied to citrus fruits for its mechanical strength and balanced oxygen barrier, supporting freshness while remaining environmentally sustainable **[70]**.

3. 3-D Coating and Packaging

Advances in 3D food printing are introducing new possibilities for food preservation, enabling highly precise and consistent application of food-grade coatings on fruits and vegetables. The layer-by-layer deposition characteristic of 3D printing ensures uniform, optimized protective barriers. A major advantage of this technology is its ability to accurately incorporate active compounds directly into the coating matrix, improving preservation efficiency **[65]**. Ahmadzadeh et al. (2023) demonstrated this by combining 3D printing with sodium alginate and natural bioactives to produce effective barriers for fresh produce; embedding green tea extract and grape seed polyphenols into soy protein films also improved mechanical strength and barrier properties. However, industrial feasibility remains limited by high equipment costs (often exceeding $50,000 per unit), low production throughput (typically <1 kg/hour versus conventional lines at >100 kg/hour), and regulatory hurdles including FDA approval for printed edible films, allergen control in multi-nozzle systems, and validation of bioactive stability under Good Manufacturing Practices **[71]**.

Alongside advances in coating technology, polylactic acid (PLA) has emerged as a leading material for 3D-printed packaging. PLA is a biodegradable thermoplastic derived from renewable sources such as bagasse and maize starch, making it a key material for sustainable packaging. Its compatibility with 3D printing enables the fabrication of customized, structurally optimized packaging tailored to specific produce needs, supporting improved freshness retention and reduced waste **[72]**.

4. Innovative Packaging Techniques

Food waste occurs at various stages, from harvesting to packaging, with significant losses during handling and supply chain operations. Packaging maintains the advantages of food processing while enabling safe transport over long distances until it reaches the consumer. Protection of food from air, water vapor, UV light, and chemical and microbial contamination is the primary responsibility of food packaging **[73]**. Plastics, metal, and glass have conventionally been used for packaging, but due to their detrimental environmental impact, alternative, sustainable materials such as biodegradable polymers and microbial polyesters (PHA) have been employed. Active and intelligent packaging are gaining prominence due to technological advances. Active packaging interacts with the product and environment to extend shelf life and maintain food quality attributes like flavor and aroma **[11]**. Intelligent packaging not only senses but also signals the quality status of food, relaying information from the manufacturer's and consumer's perspectives **[74]**.

4.1 Active Packaging (AP)

Active packaging (AP) is the incorporation of chemicals into packaging systems to increase storage life and help preserve or improve food quality. It also encompasses Modified Atmosphere Packaging (MAP), which makes use of the gas composition surrounding and contained within the product to increase shelf life.

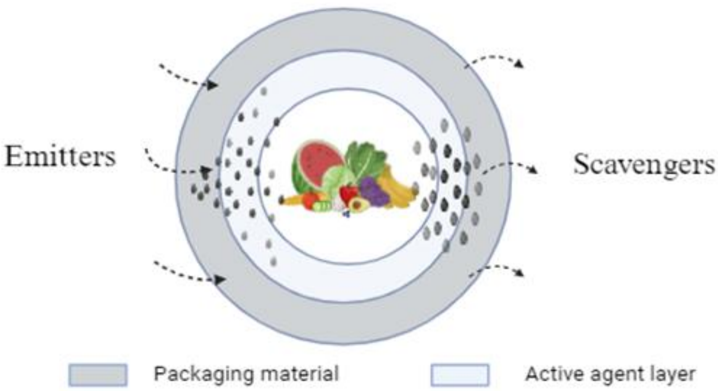

Figure 3 Active Packaging System involves the active agent, which improves the quality of fresh produce.

Figure 3 outlines scavengers in the active packaging system that remove unwanted components from the packaging environment. Emitters release desired compounds that improve food quality. Such compounds will diffuse through the packaging and escape unwanted processes, giving stable conditions while being stored and increasing shelf life **[75]**. Active packaging comprises Oxygen scavengers, ethylene scavengers, Carbon dioxide emitters and absorbers, Odor Absorbers and Emitters, Humidity regulators, Antimicrobials, and antioxidants.

4.1.1 Oxygen Scavenger

Oxygen enhances microbial growth in the form of mold, aerobic bacteria, and yeasts that result in product spoilage and oxidation of lipids and vitamins in food. These can be sensed as off-odors, unpleasant tastes, color changes, and nutrient degradation. To offset this problem, oxygen scavengers reduce oxygen levels to below 0.1% v/v, a common target in high-barrier sealed packages of fruits and vegetables under refrigerated storage, as shown in studies maintaining near-zero O_2 levels**[76]**. Iron, Platinum, and Palladium metals, hydrocarbons, vitamin C, vitamin E, biocatalysts, and microorganism-scavengers are the most widely used oxygen-scavenging systems. One of the innovative solutions is based on the use of linseed oil in the nanocapsule synthesis of oxygen scavengers for the improvement of packaging performance through oxygen content reduction and prolongation of food quality **[77]**.

4.1.2 Ethylene Scavengers

Ethylene, a natural phytohormone, influences ripening and physiological properties of produce. Too much ethylene, especially in sealed fruits and vegetables, will enhance senescence and spoilage. Ethylene scavengers are included in packaging systems to monitor the amount of ethylene gas. Upon exposure to ethylene oxidation, potassium permanganate gel in silica, will turn from purple to brown and is usually packed in sealed sachets for convenient shipping. Zeolite and activated charcoal can also adsorb ethylene **[78]**. For instance, incorporating ethylene absorbers into zeolite clay charges packaging films with it to diminish gaseous emissions, though it does decrease the clarity of films. Otherwise, activated charcoal softens bananas and kiwis and inhibits the breakdown of chlorophyll in spinach.

4.1.3 Carbon Dioxide Emitters and Absorbers

Modification of CO_2 in a food package can improve the longevity of foods through various mechanisms, such as altering the bacterial cell membrane, inhibiting certain enzymes, and altering cytoplasmic hydrogen ion concentration, which contribute to extending the lag phase and reducing wilting. CO_2 releasers or absorbers, which are placed in sachets or tags, make use of products such as ferrous carbonate, metal halides, iron powder, or calcium hydroxide **[79]**. These commercial systems maintain packaging atmosphere by controlling the respiration rates, limiting oxygen levels, reducing bacterial proliferation, and sensory attributes, and the life span of the food products. In addition, these systems, along with oxygen scavengers, promise to offer optimum conditions and product freshness **[80]**.

4.1.4 Odor Emitters and Absorbers

Fragrances and odors can be incorporated into food packs to enhance the shopping experience, for example, by improving the smell or odor upon opening (Figure 4). Additives release slowly over the product's shelf life, contributing to preservation and restoration of sensory traits that fade in the lapse of time, particularly in products with long storage life **[81]**.

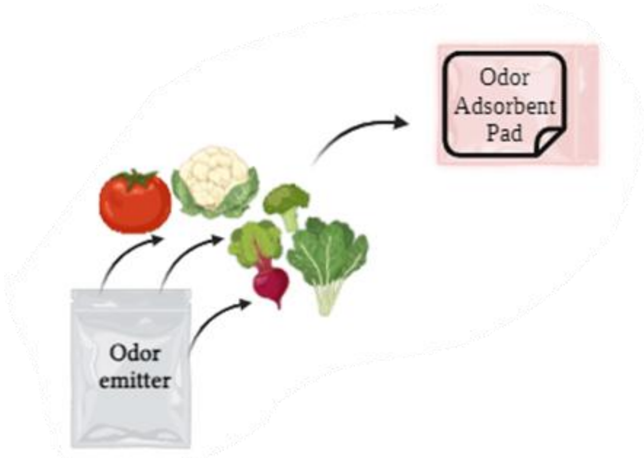

Figure 4 Odor-emitting Sachets and absorbent pads.

4.1.5 Humidity Regulators

Humidity is a major issue in the food industry, often causing spoilage during storage and transit. High relative humidity (RH) inside packaged food headspace, such as fresh fruits and vegetables, encourages the growth of mold and bacteria, which results in product quality degradation as well as its nutrient content **[80]**. RH may be controlled by physical adsorption, humectant/moisture absorbers in the form of sachets, pads, trays, and films. Sorbitol and fructose in a polymer matrix are the most common natural moisture absorbers because of their hygroscopic nature; these sugar alcohols and sugars can absorb and hold water to counteract the impact of excess humidity **[78]**.

4.1.6 Antimicrobial Packaging

The primary concept behind this packaging is the migration of molecules to prevent microbial growth on the product layer, thereby extending the lag phase and reducing microbial life.

Subramaniyan et al. (2023) similarly explored the application of probiotics in food packaging that not only enhanced food's microbial resistance but also provided it with nutritional content **[82]**. Subramaniyan et al. (2024) similarly explored postbiotic-enriched coatings, i.e., guar gum and flaxseed mucilage, to maintain figs' freshness. The work contained promising fruit storage preservation prospects **[83]**. Furthermore, Soares Silva et al. (2023) **[84]** proved that bacterial nanocellulose-zinc oxide composites possess effective antibacterial behavior by creating a sheltering barrier against microbial contamination. These works assessed biopolymer-derived antimicrobial packaging in preventing freshness loss and restricting foodborne pathogens.

4.1.7 Anti-Oxidants

Oxidation adversely affects the flavour, texture, nutrient quality, and shelf life of produce. Antioxidants counteract these effects by neutralising free radicals and slowing spoilage. Although synthetic antioxidants such as BHT and BHA are still widely used, safety concerns have increased interest in natural alternatives **[85]**. Cellulose acetate films, known for their flexibility and controlled-release properties, can be combined with natural antioxidants such as tyrosine and ascorbic acid for packaging applications.

However, natural antioxidants often face challenges such as light sensitivity, heat instability, and strong odours. Mishra et al. (2024) addressed these issues by developing biopolymer films incorporating quercetin and catechins, which showed improved antioxidant activity and better stability under heat and light **[86]**.

Wei Zhang et al. (2023) further demonstrated that natural antioxidants such as cinnamaldehyde and nonanal vapours enhance oxidative resistance by donating hydrogen or electrons to stabilise radicals and by chelating metal ions. Phenolic antioxidants like catechins stabilise radicals through hydrogen donation **[87]**.

5. Intelligent Packaging

Intelligent Packaging (IP) monitors environmental variables inside and outside packaged food, enabling tracking of product location, shelf life, and quality. It includes indicators such as biosensors, time-temperature indicators, gas sensing, ripeness indicators, toxin indicators, and radio frequency identification (RFID) **[78]**. These sense, quantify, and communicate changes in food package headspace, providing details on conservation practices through the supply chain. Bhowmik et al. (2024) researched the application of chitosan films as smart packaging for food, with emphasis on freshness assessment and biomarker detection **[88]**.

5.1 Data Carriers

These carriers support supply chain information exchange through transparency, automation, theft protection, and anti-counterfeiting, tracking product quality during processing, production, and distribution. This involves storing and broadcasting data on shipping, storage, and other attributes, typically on tertiary packaging. Barcode labels and RFID tags are common data carriers **[89]**.

5.1.1 BARCODES

Barcodes are optical data storage devices that use scanners to read encoded information in alphanumeric form. They support inventory and stock management due to their low cost, ease of use, and availability in 1D and 2D formats. 1D barcodes consist of parallel bars and spaces, while 2D barcodes store more data using matrix-like patterns, offering higher capacity and improved functionality **[90]**.

The first commercial Universal Product Code (UPC) was represented as a series of spaces and lines, even though it is used currently. A colour-based sensor was developed using silica beads to detect the spoilage in chicken, which was later changed into a barcode using three dyes, such as Nile red, Zinc Tetraphenylporphyrin, and Methyl red **[91]**. The Food Sentinel System was developed with two barcodes: one for product information and the other for contamination information. A microbial TTI, especially Lactic acid bacteria bound with a barcode, called TRACEO, modifies the colour of the barcode during the exposure of the package to a high temperature **[92]**.

5.1.2 Rfid Tags

RFID (Radio Frequency Identification) tags can store information such as nutritional values, cooking instructions, temperature, and humidity. There are three basic components of the system: the reader, the tag, and the software **[93]**. In essence, it is a wireless sensing technology with a chip that stores data and identifies products using specific tags.

It is categorised as active and passive, where active uses batteries, whereas passive derives power from the signals received. It is most commonly used in the meat, dairy, bakery, fisheries, and beverage industries. These tags help identify rotted fish by measuring vapor and humidity levels. On the contrary, these are also known as advanced data carriers, with storage of up to 1 MB, but they are expensive and require a robust electronic information network than barcodes.

In combination with temperature-sensing technology, they can improve the supply chain management and lower costs. For instance, Inkjet Printing Technology has chipless RFID tags that can be printed on traditional packaging. It was fabricated in such a way as to reduce the manufacturing cost of RFID tags **[92]**.

5.2 Indicators

Indicators assess food quality from production to sale, providing information on freshness and authenticity. They detect compounds, quantify concentrations, and signal reactions via changes such as color shifts, whether inside or outside containers. Natural compounds enhance environmental sustainability and sensitivity to spoilage **[78]**.

5.2.1 Time-Temperature Indicators (TZIs)

Temperature critically affects cold chain integrity and food safety. TTIs record the temperature history of food products, verifying product reliability. Limitations of TTIs include radiation protection needs, low-temperature operation, cost, and reliability validation. Some new TTIs include Fresh-Check®, VarioSens®, Log-ic®, OnVuTM, OnVu Ice, and Monitor MarkTM **[94]**.

5.2.2 Leak and Seal Indicator

These use numerous factors, such as packaging type, environmental conditions, leaks, the activity of food products, and the impact of the package headspace on the gas composition of packaged foods. Whereas CO_2 indicators change color when the environmental CO_2 level in the package goes down, O_2 indicators make use of redox dyes like methylene blue and 2,6-dichloroindophenol **[91]**. Ageless Eye® and Wondersensor have been developed to color change when exposed to oxygen. Another alternative is smart inks or light-induced indicators, which are helpful for oxygen indication **[78]**.

5.2.3 Freshness Indicator

For assessing the deterioration of packaged goods, freshness indicators are crucial. They show how volatile metabolites such as diacetyl, hydrogen sulfide, amines, ammonia, and carbon dioxide accumulate as food ages. Furthermore, ripeness and the presence of microbial metabolites can also be identified using these indicators by color changes caused by pH variations. Metabolites that indicate quality include sugar components, acids, alkalis, volatile gases, and byproducts of adenosine triphosphate breakdown. Biogenic amines use Food Quality Services International (FQSI) approved labels/sensors (Figure 5) **[95]**.

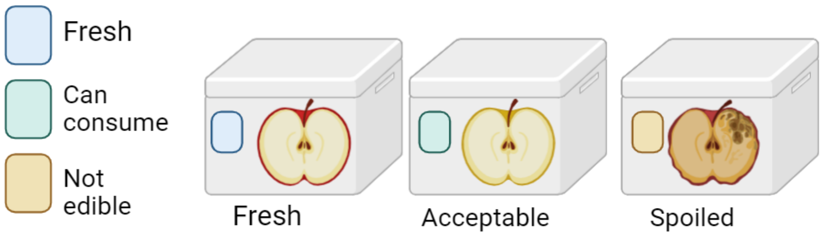

Figure 5 Freshness metric based on the color change.

5.2.4 pH Indicators

pH indicators detect the change in the Hydrogen ion concentration in a packed food with the help of polyphenols like anthocyanins. Pigments like curcumin, alizarin, shikonin, and betalains are reactive to pH modifications and exhibit a quick response. At present, these are fabricated from compounds with high pH sensitivity. For example, this system is made from potato starch, which acts as an immobilizer for anthocyanin, causing a color change from red to green. Similarly, a film has been derived from carrageenan and black fruit wolfberry, which reverses the color from pink to colorless and blue-violet to yellow within the pH range 2 to 10, representing the quality retention **[5]**.

5.3 Sensors

5.3.1 Gas Sensors

Gas sensors have pivotal importance in intelligent packaging systems due to their ability to sense the standard of the product with the help of their digitalised chemical sensor, which detects gases like Hydrogen Sulphide (H_2S), or Carbon dioxide in the spoiled meats and fish indicated by metabolites such as ammonia, biogenic amines, and H_2S **[96]**. They are of various types, like Electrochemical, optical, nanostructured metal-oxide semiconductor, and Surface Acoustic Wave (SAW) sensors **[97]**. Yet, these sensors face some difficulties in the case of their cost, selectivity, and integration, but the recent findings are working on improving their efficiency, biodegradability, and also the incorporation of wireless or smartphone-based readouts **[98]**.

5.3.2 Bio-Sensors

Biosensors are compact, convenient, and easy-to-use devices for assessing food quality, currently focusing only on freshness but expanding. However, there are still issues, such as checking for signs of degradation in sealed packaging without pretreatment and handling the variety of food structures.

Apart from monitoring applications, biosensors detect poison, toxins, and spoilage via an analyte-specific receptor that translates physiological pulses into an electrical response **[99]**. Building on this potentiality, Sobhan et al. (2025) developed printable biosensors in edible films for low-cost bulk production **[100]**.

5.3.3 Nano Sensors

Nano sensors are an emerging intelligent packaging system that detects biochemical/physicochemical food spoilage using nanomaterials. These are ideal sensors due to their ability to detect low-concentration gases, microbial compounds, and spoilage markers, as well as their fast response time. The most common materials used in fabrication are metal oxide nanoparticles, quantum dots, graphene, and carbon nanotubes. In dairy packaging, these sensors are vital in verifying organic compounds, pH, and contamination. On the contrary, these face some difficulties due to material safety, sensor stability, and approval of regulatory compliance **[96]**.

CONCLUSION

Advanced post-harvest technologies are fundamentally transforming the methods for fresh produce storage, significantly extending their inherent shelf life while ensuring safety and nutritional integrity. Traditional preservation techniques often proved insufficient in mitigating critical issues such as mechanical injury, subtle physiological deterioration, and the detrimental impact of pest and pathogen attacks. In marked contrast, contemporary developments, notably sophisticated edible coatings and intelligent packaging systems, are specifically engineered to comprehensively address these multifaceted challenges.

Current scholarly investigations consistently underscore the critical importance of employing optimal packaging and coating materials to consistently deliver post-harvest produce with superior freshness and sustained quality. Edible coatings, for instance, function as dynamic, multi-functional protective barriers directly applied to the produce surface. These thin, often imperceptible layers effectively safeguard against detrimental moisture loss, inhibit microbial proliferation by creating an unfavorable microenvironment for growth, and counteract oxidative deterioration. This comprehensive protection ensures that the produce retains its desired texture, color, and flavor profiles for extended durations.

Complementing these coating technologies are highly advanced smart packaging systems, which ingeniously integrate various digital identifiers, including barcodes, sophisticated RFID chips, embedded chemical and environmental sensors, and interactive QR codes. Such integration provides consumers with immediate access to comprehensive product information.

While it is acknowledged that a majority of these groundbreaking innovations are currently in various stages of research, development, or pilot implementation and have yet to achieve widespread commercialization and mass adoption, their collective potential to fundamentally transform the entire food industry is demonstrably immense. Dedicated scientists, pioneering researchers, and influential stakeholders within the food industry continue to tirelessly develop and refine these remarkable innovations.

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