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Emerging trends in biopolymer edible coatings for enhancing the shelf life of neglected and underutilized crops

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Neglected and underutilized species (NUS) are nutrient-dense crops, offering high concentrations of essential nutrients relative to their calorie content. These crops are increasingly explored for their potential to meet global consumption demands while promoting ecosystem biodiversity sustainably. However, their commercialization has been limited by short shelf life and significant postharvest losses. One promising solution is the use of biopolymer edible coatings as an alternative to plastic packaging, which could extend the shelf life of these crops. This review examines research conducted over the past decade on preserving underutilized crops with biopolymer coatings and suggests potential directions for future studies. It covers the sources of biopolymer coatings, their benefits and drawbacks, application methods, and strategies to overcome challenges associated with different biopolymers. While various coating formulations have shown promising results, the commercialization of these coatings for underutilized crops remains limited. The review also identifies key research gaps that must be addressed to bridge this gap.

KEYWORDS

edible coating, neglected and underutilized species, postharvest, biopolymer, fruits and vegetables

1 Introduction

A key challenge for global food systems is producing food sustainably while satisfying the increasing nutritional needs of a growing population. Today's agricultural scene is mostly made up of large-scale industrial systems focused on a few main crops, mainly wheat, rice, and maize, which make up about 60% of the world's caloric intake (Sood et al., 2023). This heavy dependence has caused significant problems, including malnutrition, especially in low- and middle-income countries, along with land degradation, loss of biodiversity, and environmental pollution (Hunter et al., 2019).

One promising approach to tackling these issues is integrating neglected and underutilized species (NUS) of nutrient-rich fruits and vegetables traditionally grown in specific regions but ignored mainly by agricultural research, policy, and markets (Hunter et al., 2019; Sood et al., 2023; Onawo and Egboduku, 2025). These species are often well-suited to harsh environments and provide significant nutritional and ecological advantages. Although they are minimally present in mainstream agriculture, NUS can boost dietary diversity, enhance climate-resilient farming systems, and support smallholder farmers'

TABLE 1 Classification of underutilized and traditional crop species based on taxonomy, cultivation status, and geographical distribution.

Species	Scientific name	Taxonomic classification	Cultivation status	Geographical distribution
Jackfruit	*Artocarpus heterophyllus*	Fruit	Semi-domesticated	Tropical and subtropical
Starfruit	*Averrhoa carambola*	Fruit	Underutilized horticultural crop	Tropical and subtropical
Indian jujube	*Ziziphus mauritiana*	Fruit	N/A	Tropical and subtropical
Malay apple	*Syzygium malaccense*	Fruit	Underutilized horticultural crop	Tropical and subtropical
Ivy gourd	*Coccinia grandis*	Vegetable	N/A	Tropical and subtropical
African nightshade	*Solanum scabrum*	Vegetable	N/A	Tropical and subtropical
Fonio	*Digitaria exilis*	Cereal/Pseudocereal	Traditional staple crop	Tropical and subtropical
Amaranth	*Amaranthus* spp.	Cereal/Pseudocereal	Traditional staple crop	Tropical and subtropical
Quinoa	*Chenopodium quinoa*	Cereal/Pseudocereal	Traditional staple crop	Temperate underutilized
Bambara groundnut	*Vigna subterranea*	Legume	N/A	Tropical and subtropical
Winged bean	*Psophocarpus tetragonolobus*	Legume	N/A	Tropical and subtropical
Cassava	*Manihot esculenta*	Root/Tuber	N/A	Tropical and subtropical
Taro	*Colocasia esculenta*	Root/Tuber	N/A	Tropical and subtropical
African oil palm	*Elaeis guineensis*	Oilseed/Nut	Wild-harvested	Tropical and subtropical
Shea	*Vitellaria paradoxa*	Oilseed/Nut	Wild-harvested	Tropical and subtropical

livelihoods. Their potential also reaches emerging sectors, such as functional foods and sustainable technologies, including biopolymer-based edible coatings that extend shelf life and reduce postharvest losses (Mawoneke et al., 2025).

NUS have long been consumed in regions where they are locally grown for their nutritive and medicinal value and their contribution to local biodiversity. However, researchers, policymakers, and breeders have typically overlooked these species (Hunter et al., 2019). Despite their numerous dietary benefits, their market potential is often hindered by their perishable nature, leading to significant postharvest losses. Traditional methods of reducing postharvest decay, such as modified atmospheric packaging, hypobaric storage, and controlled atmosphere, are often costly and challenging to implement in developing countries (Gol et al., 2015). Moreover, the need for refrigerated storage throughout the supply chain results in further economic strain and increased waste, especially for underutilized fruits prone to rapid spoilage and chilling injury.

A more cost-effective and sustainable alternative to conventional plastic packaging for extending such crops' shelf life is using edible biopolymer coatings (Krishnan et al., 2025). These coatings, formulated with specific additives to address the unique characteristics of each fruit or vegetable, offer a practical solution to reduce spoilage and enable storage at room temperature. Research into edible coatings from various natural sources is essential, as each biopolymer offers distinct benefits and limitations. Identifying the most suitable coating for different fruits and vegetables is necessary, as no single coating works universally (Vargas-Torres et al., 2017; Krishnan et al., 2025). This is particularly important in light of the growing concerns about the environmental and health impacts of non-biodegradable synthetic coatings (Dey et al., 2023).

Tropical fruits are generally divided into three groups: (1) underutilized species that are not grown commercially but are consumed locally; (2) locally marketed fruits with limited worldwide distribution, such as pitahaya (*Selenicereus* spp.); and (3) fruits that are widely cultivated for both local and global markets. The third group can be further subdivided into major fruits that lead in global production and minor fruits with limited international trade (Md Nor and Ding, 2020). While earlier reviews mainly focused on major tropical and climacteric fruits (Olunusi et al., 2024), this review addresses edible biopolymer coatings used on NUS. This section examines the sources, application methods, functional benefits, and regulatory aspects of biopolymer-based edible coatings, highlighting their role in extending shelf life and preserving the postharvest quality of NUS. It also discusses recent patented formulations and assesses emerging trends in designing and commercializing coatings specifically for underutilized fruits and vegetables.

2 Classification and benefits of NUS

NUS represent a diverse group of locally important plants globally marginalized in research, policy development, and commercial markets. These species (see Table 1) can be classified based on their taxonomy, cultivation status, and ecological roles (Sood et al., 2023; Hunter et al., 2019).

Despite their significant nutritional and ecological value, NUS occupy only a small fraction of global agricultural land. According to the Food and Agriculture Organization (FAO), although more than 30,000 plant species are considered edible, only 150 crops are widely cultivated, and a mere 30 crops account for 95% of human caloric intake (Hunter et al., 2019). Most NUS are grown for subsistence, catering to local consumption rather than global markets.

Production and usage trends are well documented in three central regions, Sub-Saharan Africa, South Asia, and Latin America, where NUS play a vital role in traditional food systems.

- Africa: Ethiopia is a major producer of teff, while Nigeria leads in bambara groundnut production (Hunter et al., 2019).
- Asia: India, Thailand, and Indonesia are primary cultivators of jackfruit, starfruit, and moringa (Sood et al., 2023).
- Latin America: Brazil, Peru, and Mexico focus on quinoa, amaranth, and cassava production (Sood et al., 2023).

NUS offer several significant benefits, making it essential for advancing sustainable agriculture and improving global food security (Hunter et al., 2019; Habib et al., 2025; Mawoneke et al., 2025). Besides being conservation targets, certain NUS can also serve as valuable raw materials for biopolymer-based coatings. For example, plantain peels, amaranth starch, cassava tubers, and mucilage from okra and cactus have been studied as sources of polysaccharides, gums, and pectins with film-forming potential (Liyanapathiranage et al., 2023; Yadav et al., 2023). There has been increasing interest in obtaining pectin from NUS for use as edible coatings (Surolia and Singh, 2022). Starches from underutilized tuberous crops, such as taro (*Colocasia esculenta*), jackfruit (*Artocarpus heterophyllus*) and Indian yam (*Dioscorea hispida)* have also been explored to create biopolymer edible coatings (Biswal et al., 2024; Rahmawati et al., 2023; Hazrati et al., 2021). These natural polymers can be extracted from agro-industrial waste streams or minimally processed plant biomass, supporting circular economy principles. Valuing NUS in this way creates a closed-loop system where underused crops support both food preservation and material production innovation.

- Nutritional Benefits: Many NUS are richer in vitamins, minerals, and antioxidants than staple crops. For example, bambara groundnuts contain more protein than peanuts, and amaranth leaves provide more iron than spinach.

- Climate Resilience: NUS are often drought-tolerant, pest-resistant, and capable of thriving in poor soils. Fonio and teff, for example, are well-adapted to arid regions.

- Biodiversity Conservation: Promoting the cultivation of NUS help prevent genetic erosion, contributing to a more diverse and resilient food system.

- Economic Opportunities for Smallholder Farmers: As low-input crops, NUS support rural and indigenous communities, especially in developing countries, by reducing dependency on costly inputs.

- Cultural and Culinary Significance: NUS are deeply embedded in local cuisines, traditional medicine, and cultural practices. Moringa, for example, is widely used in South Asian and African dishes for its medicinal properties.

- Postharvest Preservation and Market Expansion: Many NUS are highly perishable, resulting in significant postharvest losses. Innovations like biopolymer edible coatings can extend shelf life, reduce spoilage, and enhance marketability. Alternatively, NUS can be a source of biopolymers that can be valorized to create novel edible coatings.

3 Biopolymer edible coatings for NUS: sources, applications, and functional properties

Edible coatings made from natural biopolymers are a promising approach to enhance postharvest quality, especially in tropical and underused crops (Figure 1). These coatings are created using materials from plants, animals, algae, and microbial fermentation products (Hoque et al., 2021; Santhosh et al., 2021; Pillai et al., 2024; Kocira et al., 2024; Yousuf et al., 2022; Liyanapathiranage et al., 2023; Usman et al., 2025).

3.1 Polysaccharide-based coatings

Polysaccharides are among the most common biopolymers used because of their ability to form films, biodegradability, and compatibility with antimicrobial agents (Nunes et al., 2023). These compounds come from various sources such as seeds (gums), tubers (starches), seaweed (alginate), and agro-industrial residues.

Cellulose, hemicellulose, and pectin are essential parts of plant cell walls, and can be sustainably extracted from food waste like peels and stems. For example, pectin from citrus peels and apple pomace has been used in packaging films (Frosi et al., 2023), while pectin from *Phyllanthus acidus* pomace shows high antioxidant activity (John and Maharaj, 2024; Pillai et al., 2024). Nanocellulose obtained from lignocellulosic waste is also gaining popularity as a packaging material (Ahmad Khorairi et al., 2023; Yadav et al., 2023). Table 2 highlights key biopolymers, their sources, properties, and uses related to NUS.

3.1.1 Chemically modified cellulose

The limited water solubility of native cellulose restricts its direct use in edible coatings. Chemical modifications enhance its functionality and processability. Common derivatives include methylcellulose (MC), carboxymethylcellulose (CMC), hydroxypropylcellulose (HPC), and hydroxypropylmethylcellulose (HPMC) (Nunes et al., 2023). CMC, in particular, is water-soluble, structurally stable, and effective in coatings for tropical fruits (Panahirad et al., 2021; Perez-Vazquez et al., 2023; Xu et al., 2024; Bahmid et al., 2024).

3.1.2 Starch

Starch can be thermoplastically processed with plasticizers, allowing its use in flexible films (Pillai et al., 2024). It is commonly sourced from cassava, potato, sweet potato, corn, wheat, and rice (Ortega et al., 2022; Oyom et al., 2022; Luciano et al., 2022; Wang et al., 2025). The performance of starch-based coatings is often improved with additives that enhance mechanical, barrier, or sensory properties (Majeed et al., 2023; Rashwan et al., 2024; Rob et al., 2024).

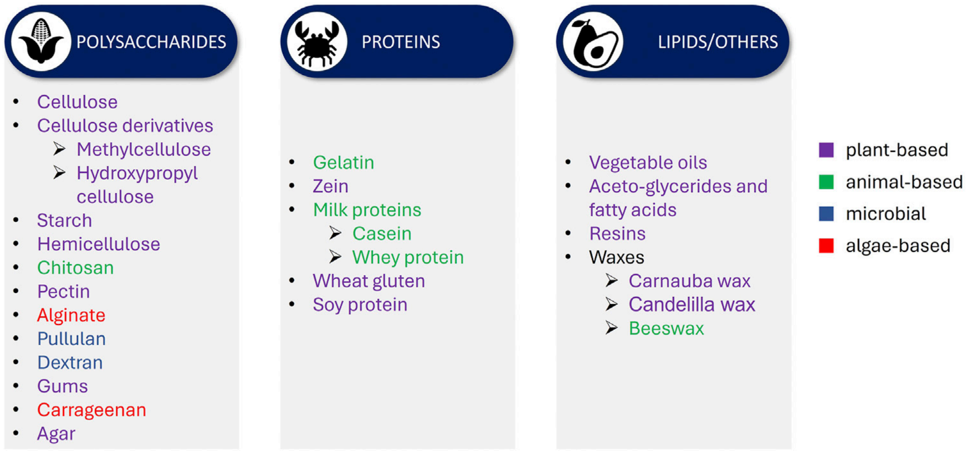

FIGURE 1
Summary of the different types of biopolymers and their origins.

TABLE 2 Selected biopolymers applied to NUS or similar tropical crops.

Biopolymer	Source	Key properties	Relevant NUS applications	References
Chitosan	Chitin (crustaceans, fungi)	Antimicrobial; moderate O_2 barrier; biodegradable	Jamun, guava, rose apple	Adiletta et al., 2021; Gull et al., 2024
Cassava starch	Cassava tubers	High transparency, good mechanical strength, and low moisture resistance	Cassava, yam	Ferreira et al., 2020
Glucomannan and beeswax	Konjac corm	Hydrophobic; ripening delay	Guava	Sothornvit, 2013
Zein	Corn protein	Hydrophobic, antioxidant compatible, low WVP	Phalsa, jamun	Baraiya et al. 2015
Sodium alginate	Brown seaweed	Gelling, water retention, semi-permeable barrier	Indian jujube, sweet cherry	Duong et al., 2023; Gutiérrez-Jara et al., 2021
Carboxymethyl cellulose	Plant cellulose	Water-soluble; adhesive; biodegradable	Papaya, carambola	Panahirad et al., 2021
Aloe vera gel	Aloe vera sap	Hydrating; antimicrobial; ripening delay	Ber fruit, hog plum	Pawar and Singh, 2021; Shakil et al., 2023

3.1.3 Chitosan

Chitosan, obtained from the deacetylation of chitin in crustacean shells and fungal cell walls, shows broad-spectrum antimicrobial activity and maintains good structural integrity (Adiletta et al., 2021). Its use is limited by low water solubility and high vapor permeability, but functional improvements have been made by adding plant extracts (Muñoz-Tebar et al., 2023; Nxumalo et al., 2024; Lafeuillee and Maharaj, 2025).

3.1.4 Algal polysaccharides

Edible coatings made from seaweed-derived polysaccharides, alginate, agar, and carrageenan, are GRAS-classified, abundant, and have excellent gelling and barrier properties (Jayakody et al., 2022). Alginate from brown algae and carrageenan from red algae are particularly prominent.

3.1.5 Microbial exopolysaccharides

Microbial exopolysaccharides (EPSs) such as pullulan, xanthan, gellan, dextran, and bacterial cellulose provide biodegradable, mechanically stable coating matrices (Zikmanis et al., 2021; Singh et al., 2008; Ganduri, 2020). Pullulan, produced by *Aureobasidium pullulans*, offers high tensile strength and excellent adhesion without negatively interacting with the food matrix.

3.1.6 Natural gums

Natural plant gums, including guar, Arabic, locust bean, tara, and tragacanth, are extensively used in edible coatings because of their biocompatibility and non-toxicity (Nehra et al., 2023; Khezerlou et al., 2021; Salehi, 2020; Liyanapathiranage et al., 2023). Gum-based coatings with 1% gum and 20% glycerol (w/w) have proven effective in extending shelf life. For example, 4.5% *Albizia* gum helped maintain guava quality during storage (Gull et al., 2024).

3.2 Protein-based coatings

Proteins offer strong mechanical strength and gas barrier properties. They come from sources like animal proteins (e.g., casein, whey, gelatin) and plant proteins (e.g., soy, zein, wheat gluten). Their physicochemical properties, such as moisture retention, tensile strength, and vapor permeability, impact their effectiveness in edible films (Mihalca et al., 2021; Kandasamy et al., 2021; Thakur et al., 2024).

3.3 Lipid-based coatings

Lipid-based coatings use waxes (e.g., beeswax, carnauba), vegetable oils (e.g., sunflower, safflower), fatty acids, and aceto-glycerides to create hydrophobic barriers (Yousuf et al., 2022; Milani and Nemati, 2022; Pashova, 2023). They offer excellent water resistance and gloss, but are usually thicker and more brittle. Lipids can also act as plasticizers or emulsifiers in multilayer systems.

3.4 Composite coatings

Composite biopolymer coatings combine different types of polymers, usually polysaccharides, proteins, and/or lipids, to harness synergistic interactions and surpass individual limitations. These coatings are applied as bilayers or emulsions, with their effectiveness depending on interpolymer compatibility and the type of product (Dhall, 2016; Yaashikaa et al., 2023).

3.5 Environmental sustainability and circular bioeconomy potential of biopolymer sources

An estimated 5 billion metric tons of agricultural waste are produced each year, much of which remains underutilized (Ahmad Khorairi et al., 2023). Valorizing this waste through biorefineries into functional biopolymers supports circular economy principles. Agroindustrial residues such as banana peels, pomegranate rinds, and apple cores have been successfully used in coating formulations, contributing to waste reduction, longer shelf life, and environmental sustainability (Yadav et al., 2023).

3.6 Application to NUS

Certain biopolymers display functional traits particularly suited for use with NUS, especially those with high respiration rates or prone to postharvest losses. Chitosan, for example, provides antimicrobial protection for tropical fruits like jamun and guava (Adiletta et al., 2021; Gull et al., 2024). Cassava starch has been applied to root crops, while zein has been effective in decreasing browning in phalsa and jamun due to its hydrophobicity and compatibility with antioxidants (Ferreira et al., 2020; Baraiya et al., 2015).

4 Methods of application of edible coatings

The effectiveness of edible coatings in preserving perishable produce depends not only on the material composition but also on how they are applied (Ali et al., 2025). This is especially important for NUS, which often have high respiration rates, thin or uneven skins, high surface moisture, and a tendency to degrade after harvest. Therefore, choosing the correct application method must be based on the morphological and physiological traits of each crop. Recent studies highlight a variety of application methods, each with specific advantages and limitations when used on NUS and other tropical fruits. Table 3 summarizes these methods about typical NUS examples, outlining their operational benefits, drawbacks, and relevant information from the literature.

4.1 Dipping

Dipping involves immersing the produce in a coating solution for a specific time (usually 30 s to 5 min), then draining and drying (Gurdal and Cetinkaya, 2023). This method provides even coverage, especially on uneven or textured surfaces, and is commonly used for fruits such as jamun, guava, and phalsa (Gol et al., 2015; Perez-Vazquez et al., 2023). Its simplicity and low cost make it suitable for small-scale operations. However, dipping can result in coatings that are too thick, which can block gas exchange and increase contamination risk when the dip bath is reused (Suhag et al., 2020).

4.2 Spraying

Spray coating is the most commonly used method at the commercial level, especially for fruits that are sensitive to mechanical damage. It allows for the application of controlled, thin, and uniform layers through air spray atomization, pressure systems, or air-assisted nozzles (Das et al., 2024; Suhag et al., 2020). Spraying is particularly suitable for ber fruit and Indian jujube because of their delicate skins. However, the method is less effective on fruits with highly curved or hairy surfaces and works best with low-viscosity coating solutions (Pham et al., 2023; Ju et al., 2019).

4.3 Vacuum impregnation (VI)

VI enhances coating penetration into porous tissues by immersing fruit in a coating solution under reduced pressure. The vacuum displaces gases in the intercellular spaces, allowing the coating to permeate the matrix once atmospheric pressure is restored (Escobedo-Avellaneda et al., 2018). This method has proven effective for jackfruit and starfruit, improving internal barrier properties without affecting external appearance (Minh et al., 2019; Soares et al., 2018). However, VI requires specialized equipment and may alter texture and firmness (Senturk Parreidt et al., 2018).

TABLE 3 Application methods for edible coatings used in NUS and tropical fruits.

Application method	Typical NUS examples	Advantages	Limitations	References
Dipping	Jamun, guava, phalsa, papaya	Uniform coating, suitable for irregular surfaces, and low cost	Thick coatings, dip bath contamination	Gol et al., 2015; Perez-Vazquez et al., 2023
Spraying	Ber fruit, Indian jujube, carambola	Thin layers, minimal handling damage, scalable	Limited for hairy or highly curved surfaces	Suhag et al., 2020; Pham et al., 2023
Vacuum Impregnation (VI)	Jackfruit, pumpkin, starfruit	Deep penetration into porous tissue; enhances barrier functions	Alters texture; equipment-intensive	Minh et al., 2019; Soares et al., 2018
Spreading	Cassava slices, yam chips	Simple manual or automated application	Inconsistent coverage; dependent on operator skill	Díaz-Montes and Castro-Muñoz, 2021
Electrospraying	Strawberries, starfruit	Ultra-thin films, low material usage, enhanced adhesion	Lab-scale only; high-voltage requirements	Cakmak et al., 2019; Khan et al., 2017
Layer-by-Layer (LbL)	Pear, mango, sweet cherry	Multilayer control of gas/moisture exchange; superior microbial barrier	Technically complex, material, and time-intensive	Hira et al., 2022; Adhikari et al., 2023
Cross-linking	Rose apple, pear, sweet cherry	Improved structural integrity; moisture resistance	Requires additional reagents and steps	Deng et al., 2024; Duong et al., 2023

4.4 Spreading

In the spreading method, coatings are manually or mechanically applied to the surface of sliced or processed products, such as cassava chips or yam slices. While spreading provides flexibility and is easy to implement, it can lead to uneven application due to manual variation and irregularities on the fruit surface (Díaz-Montes and Castro-Muñoz, 2021; Pham et al., 2023). Optimizing viscosity, applicator design, and drying conditions is essential for achieving consistent results and performance.

4.5 Electrospraying

Electrospraying uses a high-voltage electric field to produce fine, charged droplets that coat surfaces, creating ultra-thin, uniform films (Pham et al., 2023; Khan et al., 2017). This process needs minimal coating material and works well on delicate fruits like strawberries (Cakmak et al., 2019) and starfruit (Khan et al., 2017; Peretto et al., 2017). Electrospraying allows precise control over droplet size and film thickness, but its use is still mainly limited to laboratory settings because of scalability challenges.

4.6 Layer-by-layer (LbL) deposition

The LbL method deposits layers of oppositely charged biopolymers onto the fruit surface in a sequence, allowing for customized control of gas exchange and microbial growth (Arnon-Rips and Poverenov, 2018; Gupta et al., 2024). This technique has been used on mango, pear, and sweet cherry, with combinations such as chitosan and alginate (Yan et al., 2019; Hira et al., 2022; Adhikari et al., 2023). Although LbL systems extend shelf life and improve coating durability, they are technically challenging and require careful formulation of polyelectrolytes and pH conditions (Aloui and Khwaldia, 2016; Treviño-Garza et al., 2017).

4.7 Cross-linked coatings

Cross-linking is performed after deposition using agents that strengthen the internal structure of protein- or polysaccharide-based coatings through covalent and non-covalent interactions. For example, gluconolactone has been used to cross-link whey protein isolate and sodium alginate, resulting in self-healing and water-resistant films (Deng et al., 2024). Cross-linked coatings have been effectively applied to pears, sweet cherries, and rose apples, enhancing their mechanical strength and barrier properties (Dai et al., 2020; Duong et al., 2023; Gutiérrez-Jara et al., 2021).

Therefore, selecting the proper coating application method is essential for maintaining postharvest quality in NUS. These species often have unique surface textures, high perishability, and physiological variability. As a result, application strategies must be tailored to each crop's specific morphological and compositional traits. Pilot-scale validation and crop-specific optimization are crucial for ensuring consistent performance and scalability in real-world conditions.

5 Mechanisms of action of edible coatings in NUS: species-specific challenges and gaps

Edible biopolymer coatings play a crucial role in reducing postharvest losses by functioning as semi-permeable barriers that regulate mass and gas exchange, enzymatic activity, and oxidative stress. These coatings help extend shelf life and preserve quality attributes of fresh produce through various interconnected mechanisms, especially important for perishable fruits with sensitive anatomical and physiological characteristics. The multiple physiological and biochemical effects of edible biopolymer coatings are summarized in Table 4, illustrating their mechanisms of action, postharvest advantages, and specific relevance for NUS.

TABLE 4 Mechanisms of action of edible biopolymer coatings for postharvest preservation, with relevance to NUS.

Mechanism	Target process or enzyme	Biochemical/ Physiological effect	Postharvest outcome	Relevance to NUS	References
Water vapor barrier	Transpiration	Reduces water loss driven by vapor pressure gradients	Maintains fruit weight, reduces shriveling	Critical for high-moisture NUS like ber, guava, and phalsa	Gol et al., 2015; Kader and Yahia, 2011
Gas exchange control	Aerobic respiration	Modulates O_2 and CO_2 diffusion; slows metabolic rate	Delays in ripening and senescence	Important for climacteric NUS with high respiration rates	Kader and Yahia, 2011
Antioxidant preservation	Ascorbic acid, phenols, flavonols, anthocyanins	Limits oxidation and scavenging of radicals	Preserves nutritional value and visual quality	Crucial for colored NUS (e.g., jamun, phalsa) with labile antioxidants	Baraiya et al., 2015; Gol et al., 2015
Enzymatic browning inhibition	Polyphenol oxidase (PPO)	Reduces oxygen availability and PPO activity	Delays in browning and visual deterioration	Beneficial for pigmented NUS prone to enzymatic browning	Baraiya et al., 2015
Cell wall enzyme suppression	Pectinesterase, polygalacturonase, cellulase, β-galactosidase	Limits the degradation of pectin and cellulose	Retains firmness; delays softening	Suitable for soft-skinned NUS with rapid texture loss	Baraiya et al., 2015
Sugar accumulation delay	Starch-degrading enzymes	Slows the conversion of starch to soluble sugars	Delays sweetness increase; prolongs ripening	Relevant for starchy tropical NUS (e.g., breadfruit, yam)	Baraiya et al., 2015
Acidity preservation	Organic acid metabolism	Retards the consumption of organic acids during respiration	Maintains lower pH; slows flavor change	Enhances flavor stability in acidic NUS (e.g., acerola, hog plum)	Gol et al., 2015
Enzymatic antioxidant support	CAT, SOD, APX	Detoxifies ROS and preserves cellular integrity	Enhances oxidative stress tolerance	Especially useful in high-ROS-generating tropical storage environments	Hu et al., 2022; Huan et al., 2016
Antimicrobial protection	Pathogenic fungi and bacteria	Inhibits microbial growth on the fruit surface	Reduces spoilage and extends shelf life	Critical for thin-skinned NUS with poor microbial resistance	Aloui and Khwaldia, 2016

5.1 Regulation of water loss and respiration

One of the leading causes of postharvest deterioration is water loss, which occurs due to vapor pressure gradients across the fruit's outer layer. This moisture loss speeds up metabolic activity, leading to ripening, softening, and aging (Gol et al., 2015). Edible coatings reduce the diffusion of water vapor and oxygen, lowering transpiration and slowing down respiration processes. By keeping internal oxygen levels above the critical threshold, these coatings help prevent anaerobic respiration, which can harm flavor, texture, and nutritional value (Kader and Yahia, 2011). Edible coatings reduced weight loss in several NUS such as mangaba (Ferreira et al., 2020), hog plum (Shakil et al., 2023), ber (Ramana Rao et al., 2016), and jamun (Gol et al., 2015).

5.2 Preservation of antioxidants and phytochemicals

Biopolymer coatings also preserve endogenous antioxidant compounds such as ascorbic acid, anthocyanins, phenols, flavonols, and pigments by limiting oxygen exposure and subsequent oxidative reactions (Baraiya et al., 2015). Phenolic compounds, in particular, enhance overall antioxidant capacity and have antimicrobial properties that help control microbial growth after harvest (Gol et al., 2015). Ascorbic acid, a key dietary antioxidant, is stabilized by reducing oxidative degradation and decreasing metabolic consumption during ripening. Similarly, anthocyanins, responsible for the visual appeal of many pigmented fruits, are protected from oxidative breakdown, which maintains color integrity (Gol et al., 2015). In jamun, composite coatings made from chitosan, alginate and CMC kept the antioxidant capacity maintained (Gol et al., 2015).

5.3 Inhibition of enzymatic browning and color degradation

Color changes, especially enzymatic browning, are mainly driven by the oxidation of phenolic substrates catalyzed by polyphenol oxidase (PPO). Coating-induced oxygen restriction decreases PPO activity, thereby limiting the formation of brown pigments and maintaining the fruit's sensory quality (Baraiya et al., 2015). Edible coatings helped to reduce browning in fruits such as starfruit, which prolonged its shelf life (Shapawi et al., 2023).

5.4 Modulation of texture and cell wall integrity

Fruit softening is closely linked to the enzymatic breakdown of the cell wall, involving pectinolytic and cellulolytic enzymes like pectinesterase, polygalacturonase, cellulase, β-galactosidase, and pectate lyase. Edible coatings create a microenvironment with reduced oxygen and increased carbon dioxide levels, which inhibit these enzymes' activity and slow the conversion of pectins and starches into water-soluble forms (Baraiya et al., 2015). This helps maintain firmness and slows the rise of soluble sugar content. Edible coatings decreased the activity of cell-wall degrading enzyme, which extended the shelf life of jamun fruit (Gol et al., 2015).

5.5 Maintenance of organic acid content and pH

During ripening, organic acids are metabolized as respiratory substrates, which decreases acidity and raises pH. Edible coatings slow this process by reducing organic acid breakdown, helping to maintain sourness longer and delaying aging (Gol et al., 2015). Edible coatings delayed the ripening process in mangaba fruits which helped preserve them longer (Felicio et al., 2021; Ferreira et al., 2020).

5.6 Enhancement of antioxidant enzyme activity

In addition to preserving non-enzymatic antioxidants, edible coatings enhance the activity of enzymatic antioxidants involved in detoxifying reactive oxygen species (ROS). These include catalase (CAT), which breaks down hydrogen peroxide; superoxide dismutase (SOD), which neutralizes superoxide radicals; and ascorbate peroxidase (APX), which is central to the ascorbate–glutathione cycle (Hu et al., 2022; Huan et al., 2016). The stabilization of ascorbic acid by edible coatings further supports the sustained activity of APX and other antioxidant enzymes, strengthening the fruit's inherent defense against oxidative stress.

5.7 Antimicrobial and antifungal protection

Many biopolymer coatings also act as carriers for antifungal and antimicrobial agents, boosting their effectiveness against spoilage organisms. This dual function, physical protection and biochemical inhibition, has been extensively reviewed and highlights the versatility of edible coatings in postharvest disease management (Aloui and Khwaldia, 2016). For example, starch-chitosan composite coatings reduced the growth of both naturally occurring and artificially introduced microbes on the surface of mangaba fruits, which prolonged its shelf life (Vargas-Torres et al., 2017).

5.8 Considerations for NUS

Although the mechanisms described above are well-established in conventional fruits, applying them to NUS requires crop-specific adjustments. NUS often have high water activity, rapid ethylene-driven ripening, thin cuticles, and irregular surface textures, making them highly vulnerable to postharvest quality loss. For example, jamun and phalsa are susceptible to quick enzymatic browning and anthocyanin breakdown, while the ber fruit often suffers from epidermal shriveling and microbial growth. These traits demand coating systems that offer both moisture retention and antioxidative protection. Despite this need, there is limited data on enzyme modulation, such as PPO or pectinase inhibition, in NUS treated with edible coatings. Additionally, few studies have systematically measured how coatings impact phytochemical stability (e.g., anthocyanins, carotenoids, phenolic acids) in these fruits. Improving postharvest preservation strategies for NUS will require research focused on customizing coating formulas to match the physiological characteristics of each species. Studying the biochemical and structural responses of NUS to different coating systems could help develop tailored biopolymer matrices that reduce oxidative stress, enzymatic breakdown, and nutrient loss. These efforts are vital for enhancing the value and market presence of NUS with high nutraceutical potential.

6 Application of edible coatings on underutilized fruits and vegetables

Non-typically consumed NUS fruits and vegetables are often highly perishable due to their thin skins, high water content, and susceptibility to microbial spoilage. Edible biopolymer coatings have emerged as a sustainable postharvest solution to extend the shelf life of these crops by reducing moisture loss, preventing microbial contamination, and delaying ripening. Many of these coatings are derived from plant-based polysaccharides and proteins, making them both vegan-friendly and environmentally sustainable.

Table 5 summarizes recent research from the past decade on extending the shelf life of selected underutilized crops in tropical regions. These crops usually have thin skins and mesocarps with high water activity, making them susceptible to rotting caused by fungal and bacterial infections. Hydrophobic biopolymer composite coatings help prevent water loss and, as a result, weight loss. It lists various plant-based carbohydrate and protein polymers used at concentrations ranging from 1% to 6% (w/v), ensuring that the coatings are vegan-friendly.

To further enhance preservation, preservatives such as potassium sorbate, salicylic acid, lactic acid, basil oil, and other plant extract essential oils can be incorporated into the coatings for their antimicrobial properties, ensuring microbes do not proliferate beneath the coating. Polyols like glycerol, sorbitol, and mannitol serve as plasticizers to strengthen the coating, while stabilizers improve adhesion to the fruit surface.

Although the coatings act as practical barriers, refrigeration in some experiments further contributed to the longevity of the fruits. On average, these coatings extended the shelf life of the fruits by about 1 week. This additional shelf life could provide more time for shipping, increasing the potential for exporting these highly perishable, underutilized fruits and, in turn, boosting revenue.

It is essential to recognize that the effectiveness of biopolymer coatings in extending the shelf life of underutilized crops depends on various external factors, including cold chain availability, ambient storage conditions, and the intended market destination (local versus export). Coating performance is therefore not absolute, and shelf life data should be interpreted within the specific context of the postharvest system and its infrastructure.

TABLE 5 Summary of recent studies on edible biopolymer coatings applied to underutilized fruits and vegetables.

Species name (common name)	Coating origin	Coating composition	Storage conditions	Efficiency summary	References
Artocarpus heterophyllus L. (jackfruit)	Whey + pectin + transglutaminase; Aloe vera; polysaccharide gums	80:20 whey:pectin + sorbitol + transglutaminase; CaCl2 + Aloe vera; xanthan/alginate/gellan gum + glycerol	4°C	Reduced weight loss and microbes; improved sensory score	Minh et al., 2019; Prathiba et al., 2019; Vargas-Torres et al., 2017
Averrhoa carambola (starfruit)	Pectin/maltodextrin; sodium alginate + olive oil; spirulina/chitosan-gelatin	NaCl dip +6% pectin +4% maltodextrin; 2% alginate +0.2% olive oil; 4% starch + spirulina + gelatin	25°C–28°C or 26°C ± 1°C	Shelf life extended to 12–16 days; reduced browning and decay	Mohd Suhaimi et al., 2021; Baraiya et al., 2014; Shapawi et al., 2023
Coccinia grandis (ivy gourd)	Polyols (plant-based)	Mannitol/sorbitol (100–400 µM); 1:1 mixtures	4°C ± 1°C	300 µM mannitol doubled the shelf life to 10 days	Trivedi et al., 2023
Grewia asiatica (phalsa)	Soy protein; composite (LbL)	SPI 3.45% + HPMC + olive oil + sorbate; SPI/CMC bilayer system	4°C or RH 40% ± 10%	Shelf life extended to 8–10 days; better firmness and microbial control	Dave et al., 2016; Chinnaswamy et al., 2023
Hancornia speciosa (mangaba)	Cassava starch; whey; chitosan	Cassava + chitosan + EO; whey protein; babassu flour blend	10°C; 25°C	Reduced microbial load and delayed ripening	Frazão et al., 2017; Felicio et al., 2021; Ferreira et al., 2020
Spondias mangifera (hog plum)	Aloe vera	Aloe vera 1:1 with citric acid (pH 4)	25°C ± 3°C and 80%–85% RH	Reduced skin discoloration, weight, and water loss	Shakil et al., 2023
Syzygium cumini (jamun)	Zein, chitosan, guggul gum, Aloe vera	Zein 2% + additives; chitosan + SA; GG 10%–15% + basil oil; Aloe vera; biosurfactants	10°C–20°C; room temperature	Shelf life extended to 6–16 days; improved firmness and antioxidants	Baraiya et al., 2015; Saurabh et al., 2019; Khaliq et al., 2020; Gol et al., 2015; Vandana et al., 2019; Jodhani and Nataraj, 2025
Syzygium malaccense (Malay apple)	Gum arabic + essential oil	Eucalyptus oil nanoencapsulated in gum arabic	Room temperature	Reduced severity of fungal rot (Colletotrichum spp.)	Matche and Adeogun, 2022
Ziziphus mauritiana (ber)	Sodium alginate, Aloe vera, beeswax	Alginate + olive oil + ascorbic acid; 75% Aloe vera + ascorbic acid; beeswax + karonda extract	25°C; 7.5°C	Shelf life extended to 6–28 days; reduced decay and enzyme activity	Ramana Rao et al., 2016; Pawar and Singh, 2021; Kaur et al., 2023

6.1 Key insights for commercialization

The selection of suitable coatings for each fruit was based on physicochemical compatibility, target shelf-life extension, microbial sensitivity, and film performance metrics (e.g., barrier properties, antioxidant retention). These criteria were derived from the literature summarized in Table 5. Examples below are supported by recent studies that tested coatings under comparable storage conditions.

- Zein, chitosan, and soy-based coatings have significantly improved the shelf life of jamun and phalsa.
- Guggul gum-based coatings offer a novel, natural alternative with no adverse sensory effects.
- Antioxidant-infused coatings (e.g., ascorbic acid, salicylic acid) effectively prevent enzymatic browning, improving the fruit's appearance and shelf life.
- Cassava starch-based coatings have proven highly effective in preserving root and tuber crops.
- Essential oil-infused coatings show promising commercial potential due to their antimicrobial properties and enhanced preservative effects.
- Sodium alginate and Aloe vera-based coatings have effectively preserved Indian jujube (*Ziziphus mauritiana*), maintaining freshness and quality.
- Ascorbic acid-infused coatings can significantly extend the storage potential of various crops by reducing oxidation.

7 Challenges and future perspectives of biopolymer edible coatings

Although biopolymer edible coatings show potential to reduce postharvest losses, their use on NUS remains limited in practice. This is mainly due to technical, infrastructural, and socioeconomic challenges specific to local and regional contexts. Table 6 outlines common limitations of different biopolymer types, while Table 7 provides examples of performance-enhancing additives used to address these limitations (Matloob et al., 2023; Díaz-Montes and Castro-Muñoz, 2021).

While much of the current research highlights export-focused systems, this section examines the challenges and opportunities for locally adopting biopolymer coatings in areas where NUS are grown and consumed, especially in Latin America, Sub-Saharan Africa, and South Asia.

TABLE 6 Advantages and disadvantages of the major types of biopolymers used to create edible films.

Biopolymer	Advantages	Disadvantages	Possible applications in NUS preservation
Polysaccharides	• Good solubility, stability, availability, and flexibility • Good gaseous barrier since the polymer is arranged in a well-ordered network • Visually appealing, as it is colorless, not oily, and has a minor caloric content • Safe, non-toxic, and not an allergen • Low price	• Poor barrier to moisture due to their hydrophilic properties	• Can be used in NUS that are susceptible to browning due to oxidation and in cut fruit products, as it does not affect taste, e.g., jackfruit bulbs, jamun, pommerac
Proteins	• Better mechanical properties than lipids and polysaccharides • Good gaseous barrier – effectively blocks oxygen, even at low relative humidity, since its structure is a tightly packed hydrogen-bonded network (Hassan et al., 2018)	• Poor barrier to moisture due to their hydrophilic properties • Some proteins may have allergenicity	• Can be used in NUS that are susceptible to browning due to oxidation and in cut fruit products, as it does not affect taste, e.g., jackfruit bulbs
Lipids	• Exceptional barrier against moisture due to their hydrophobic nature • Provides a glossy appearance on food surfaces	• Poor mechanical properties - brittle and denser than other biopolymers • Can affect the overall appearance and perception of the coated product (can affect aroma, taste, film color) (Yousuf et al., 2022)	• Can be used for underutilized fruits that typically have a glossy appearance, e.g., Indian jujube
Other/composites (emulsions, suspensions, bilayers)	• Improved mechanical and barrier properties compared to pure biopolymer	• The preparation of bilayers is more labor-intensive, with more coating and drying stages	• Versatility of composite coatings allows them to be used in most cases

TABLE 7 Functions of different additives to edible biopolymer film formulations.

Additive	Function	Applications in NUS preservation
Plasticizer (e.g., glycerol, sorbitol, sucrose, fatty acids, monoglycerides, propylene glycol, polyethylene glycol)	Improved film flexibility, toughness, elongation, and permeability by reducing the intermolecular forces between polymer chains (Dhall, 2016)	Increases the strength of the coating
Antioxidants	Prevent oxidation and browning	Ideal for fruits that are prone to oxidation and browning, e.g., starfruit
Colorants	Makes the color visually appealing	Not reported
Flavoring agents	Prevents off tastes that may decrease the sensory value	
Antimicrobial agents (e.g., essential oils)	Prevent microbial degradation	Can provide added protection against fungal and bacterial pathogens
Additional biopolymers	Reinforcement and increased mechanical strength to prevent bruising	Most edible coatings for NUS have been a combination of two or more different types of biopolymers (Table 5)
Cross-linking agents (e.g., transglutaminase)	Improved physical properties	Used when combining two biopolymers
Emulsifiers/surfactants (e.g., polysorbates such as Tween 80, fatty acids, fatty acid esters, sucrose ester, lecithin, glycerol monostearate, glycol monostearate, sorbitan monostearate)	Reduces the surface tension of the coating, which increases wettability, spreadability, and the ability to adhere to the fruit's surface uniformly; increases the stability of the emulsion (Md Nor and Ding, 2020; Dhall, 2016)	Improves the ease of application of the coating
Inorganic nanoparticles	Improved physical and thermo-mechanical properties	Not reported
Spacing agents	Forms discontinuities in the coating that allow gaseous exchange for respiratory reactions, thus preventing damage from respiratory distress	Not reported

7.1 Technical challenges

In tropical and subtropical regions, high ambient humidity significantly diminishes the effectiveness of hydrophilic coatings made from polysaccharides and proteins. These coatings tend to absorb moisture, which damages film integrity, increases microbial risks, and shortens shelf life. Although lipid-based coatings provide better moisture resistance, they are susceptible to cracking and are often more costly to produce. Additionally, low-tech preparation and application methods are essential for local use. Many regions producing non-urban supplies lack access to atomization equipment, vacuum drying, or continuous coating lines. Instead, practical methods include manual dipping, brushing, or spraying, which require coatings with stable viscosities, quick drying times, and strong adhesion to a variety of skin types and surfaces.

7.2 Regulatory alignment and food-grade approval at the national scale

Most countries producing NUS depend on their national food safety agencies rather than international regulatory frameworks. Still, even local use requires that coatings be made with GRAS-certified, food-grade ingredients, mainly when they include antimicrobial agents, essential oils, or nanoparticles. The absence of standardized national guidelines for biopolymer coatings can reduce confidence among smallholders and microenterprises. Additionally, fragmented approval processes may discourage the adoption of formulations developed in academic settings. Efforts to harmonize food-grade additive registries at the regional level (e.g., Comunidad Andina, ECOWAS) could boost scalability.

7.3 Consumer perception and sociocultural acceptance

Consumer trust is vital for expanding into local markets. Many small-scale producers and vendors avoid coated produce because they fear consumer rejection or have misconceptions about "artificial" coatings. Sometimes, coatings that change the appearance, such as glossiness or opacity, or that affect the perceived naturalness of fruits, may lower purchase intentions. Religious or cultural dietary preferences must also be considered. Coatings made from animal-based ingredients like gelatin or casein may be unacceptable in specific communities. Therefore, plant-based, culturally appropriate formulations should be prioritized. Clear labeling and affordable educational campaigns aimed at traditional markets can help increase familiarity and acceptance.

7.4 Commercial barriers and distribution limitations

Even when coatings are technically effective, their commercial adoption is limited by cost, infrastructure, and access to inputs. Functional additives, such as essential oils and cross-linkers, may be too expensive or unavailable in rural areas. Additionally, the lack of cold storage infrastructure, especially in tropical climates, reduces the overall shelf-life benefits of coatings. Unlike global fruit markets, most NUS are sold through short-distance, informal supply chains. In these systems, the motivation to extend shelf life beyond 5–7 days may be minimal. However, reducing postharvest losses during transit or display at ambient temperature remains a significant opportunity for coatings. Finally, the absence of open-access technologies and the dominance of patented formulations limit innovation at the local level. Support for open-source, low-cost coating protocols, ideally based on locally available materials such as cassava starch and plant mucilage, is crucial.

7.5 Context-specific future directions

To promote the integration of biopolymer edible coatings in the value chains of NUS, the following strategies are recommended:

- Develop simple, modular coating kits adapted for smallholders, based on natural and locally sourced ingredients.
- Promote the use of plant mucilage, agro-wastes, and by-products (e.g., banana peels, tamarind seed gum) to reduce costs and valorize existing biomass.
- Encourage open-label transparency and nutritional co-benefits to appeal to local consumers (e.g., antioxidant retention).
- Support national regulatory bodies in defining streamlined food-grade approval lists for biopolymer-based coatings.
- Foster regional cooperation and knowledge sharing, including between agricultural extension services, cooperatives, and food science laboratories.

Therefore, the future of edible coatings for NUS lies in their local adaptation, affordability, and social acceptability rather than in technological complexity alone.

8 Commercialization and patents on edible coatings: trends and implications for NUS

Over the past decade, the commercialization of edible biopolymer coatings has increased markedly, driven by advances in formulation, functionality, and sustainability. An analysis of patents and commercially available products shows that most innovations focus on high-value, globally traded fruits such as apples, bananas, avocados, berries, and citrus (Md Nor and Ding, 2020). These coatings are generally tailored to specific physiological traits, including moisture content, cuticle thickness, and surface microstructure, allowing for longer shelf life and improved marketability (Table 8).

Recent patents show a rising trend toward bio-based and multifunctional coatings that include natural antioxidants, antimicrobial agents, and cross-linking components. Common additives such as essential oils, sucrose esters, and emulsifiers improve water resistance, adhesion, and microbial protection, matching consumer demands for clean-label and plant-based products (Perez et al., 2017). For example, Apeel™, a commercial lipid-based coating made from depolymerized plant cutin, provides moisture retention and oxidative stability, and is vegan- and allergen-friendly. These innovations respond to global trends in veganism and organic produce consumption, highlighting the market's movement toward sustainable and inclusive food preservation technologies.

By contrast, many academic and research-stage coatings remain in the exploratory phase, focusing on new bioactive ingredients like pomegranate seed oil, algal polysaccharides, or bacterial biosurfactants. These formulations often show improved

TABLE 8 Patented and or commercially available edible coating formulations for fruits and vegetables.

Patent no.	Filing date	Assignee	Product	Formulation	Application method	Benefits
CA3220053A1	27 May 2022	Agrosustain Sa	Edible coating for fruits and vegetables	Emulsion of 0.3%–2.5% w/w natural vegetable oil(s) + sucrose fatty acid ester emulsifier (30%–70% mixture of sucrose monoester and sucrose polyester) + water (+ optional natural fungicide)	Spraying or immersion	Prolonged shelf life and reduced weight loss of fruits and vegetables
US20240008501A1	6 July 2023	Apeel Technology Inc.	Apeel - currently commercially used on avocados, limes, English cucumbers, oranges, mandarins, lemons, mangoes, apples, and grapefruit	coating (75–98 wt% monoglycerides + 1–5 wt% fatty acid salts + 1–20 wt% lecithin, ammonium phosphatide, and lysolecithin) + base + solvent (+ optional pH modifier, e.g., citric acid) (+ optional food-safe antimicrobial, antifungal, antioxidant, enzyme, catalyst, pigment, salt, fragrance, stabilizer, buffer, vitamin or mineral)	Spraying or immersion	Increased shelf life of fruits and vegetables by reducing oxidation and water loss; provides mechanical stability to the fruit surface, which reduces spoilage due to bruising
US20230200404A1	7 March 2023	Decco Worldwide Post Harvest Holdings BV	Edible coating for pome fruits, tropical fruits, and stone fruits	0.05 wt% sucrose esters of fatty acids +0.02 wt% cellulose derivative +0.05 wt% glycol +0.05 wt% alcohol +0.03 wt% glucose polymer +0.01 wt% potassium sorbate +0.02 wt% defoamer + water	Spraying or immersion	Delays senescence; prevents dehydration and chilling injuries in fruits and vegetables; maintains nutritional value and appearance
CN116114754A	15 December 2022	Jimei University	Edible coating for cucumber	Aqueous sodium alginate (0.8–1.2 wt% %) solution	Spraying	Improved post-harvest storage of cucumber up to 12 days
US20230134284A1	10 November 2022	Startchy Inc.	Edible coating for apples	Starch slurry (polymerized starch and unmodified starch granules) + plasticizer (e.g., glycerin, aloe vera gel 0–30 wt% %) + cross-linking agent (e.g., citric acid 0–25 wt% %) + surfactants/emulsifiers/stabilizers/anti-oxidants	Spraying	Improved post-harvest storage of apples at ambient temperature for up to 28 days when compared to the standard wax coating control
US20230048027A1	9 September 2022	Yissum Research Development Co. of the Hebrew University of Jerusalem	Edible wax coating for peppers, eggplants, cherries, berries, plums, and persimmons	Wax (e.g., beeswax 10–25 wt%) + non-gelling hydrocolloid polymer (e.g., locust bean gum/guar gum/gum tragacanth/xanthan gum up to 1 wt%) + fatty acid (e.g., oleic acid 0.2–10 wt% + emulsifier (e.g., morpholine 0.1–15 wt%) + water _ resin/antifoaming agent/preservative/adhesive agent/cross-linker/plasticizer/surfactant	Immersion/pouring, spraying, brushing	Adds glossiness to the fruit surface and reduces water loss without compromising the fruit's sensory properties; shelf life is extended
CN115444031A	1 September 2022	Shaanxi Normal University	Protein-based antibacterial edible coating for fruit, e.g., winter jujube	Lysozyme + L-cysteine + solvent (water) in a 0.2–0.6 wt%: 0.2–0.6 wt%:10–100 wt% ratio	Immersion	Increased activity of the antioxidant enzymes: catalase (CAT) and superoxide dismutase (SOD), which extended the shelf life by reducing oxidative damage and preserving the fruit's antioxidant levels
WO2022217089A1	8 August 2022	Apeel Technology Inc.	Antimicrobial edible coating for fruits and vegetables, e.g., avocados, lemons	Monoglycerides/diglycerides + surfactant + antimicrobial (e.g., sodium benzoate) + pH adjuster (e.g., citric acid) + water + stabilizer/buffer/essential oil/	Spraying or immersion	Prevents spoilage due to microbial pathogens, water loss, or oxidation

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TABLE 8 (*Continued*) Patented and or commercially available edible coating formulations for fruits and vegetables.

Patent no.	Filing date	Assignee	Product	Formulation	Application method	Benefits
				preservative/antioxidant/ vitamin/mineral/pigment/ aroma/enzyme/catalyst		
BR102022003079A2	18 February 2022	Federal University of Campina Grande	Edible coating for fruits	Agar (2–3 wt%) dissolved in water + Tween + pomegranate seed oil + *Chlorella* sp	Immersion	Extends the shelf life and preserves its organoleptic and nutritional properties
WO2020226495A1	6 May 2020	Liquid seal Holding B	Edible coating for fruits and vegetables (e.g., avocados, limes, lemons, oranges, tangerines, melon, papaya, mango, cucumber)	Monoglyceride/diglyceride (0.1–20 wt%) + fatty acids (e.g., oleic acid, palmitic acid 0.1–20 wt%) + alkaline agents + polyol spacing agent + lecithin + ammonium phosphatides + anti-foam agent	Spraying or immersion	Prolonged shelf life by reducing postharvest water loss
CN113678884A	5 July 2021	Qingdao Boting Technology Co., ltd.; Shandong Xianpin Wuyu Fruit Industry Co., Ltd.; Qingdao University	Edible coating for fresh-cut fruits	Ascorbic acid + buffer solution + mannan + cinnamic acid + citric acid + tea polyphenol + vitamin C + vitamin E + citric acid + sodium bicarbonate + chitosan + cellulose	Immersion	Preservation of fresh-cut fruit for longer than with traditional preservatives
ES2926917A1	28 April 2021	Universidad Catolica Santa Teresa de Jesus de Avila	Edible coating for fruits and vegetables	Fruit puree (10–65 wt%) + pectin (2.2–4.5 wt%) + glycerol (3–8 wt%) + citric/ascorbic acid (0.5–1 wt%) + (optional 1.5% chitosan in aqueous acetic acid)	Spraying or immersion	The coating is prepared from food waste raw materials, which promotes the circular economy
BR102021007386A2	17 April 2021	Universidade Federal De Pernambuco	Edible coating for fruits and vegetables	Sodium alginate + brown seaweed (antimicrobial and antioxidant) + crosslinking agent (calcium chloride) + glycerol	Spraying or immersion	Delays fruit ripening and maintains the fruit's nutritional and sensory qualities
CN112616915A	13 January 2021	Individual	Edible coating for fruits and vegetables	Kudzu root starch + carboxymethylcellulose + casein + sodium alginate + chitosan + mint essential oil extract + perilla extract	Not specified	Uses natural preservatives and has antimicrobial properties, which extend fruit shelf life
CN112674163A	23 December 2020	Kunming University of Science and Technology	Edible coating for fresh-cut fruits and vegetables	Natural antibacterial peptide (from oil meal, grain, or nuts) + Penthorum chinense Pursh powder + aronia nigrica fruit powder + rosemary powder + chia seed powder + linseed pectin + passion fruit pectin + purified pectin	Immersion	Prolongs the shelf life of fresh-cut fruits and vegetables by inhibiting microbial proliferation, preserving their nutritional properties, and inhibiting water loss
WO2021107878A1	27 November 2020	Agency for Science, Technology, and Research	Vegan/halal/kosher edible coating for fruits and vegetables	Polysaccharide hydrogel (e.g., agar, pectin, starch, sodium alginate, *etc.*) + phenolic phytochemical + anti-fungal agent (e.g., benzoic acid)	Immersion	Extends fruit shelf life by preventing water loss and inhibiting microbial growth
BR102020022369A2	3 November 2020	Universidade Federal De Campina Grande - Pb	Nutraceutical edible coating for fruits and vegetables	Agar (2–3 wt%) dissolved in water + Tween + pomegranate seed oil + powdered *Spirulina platensis*	Immersion	Extends fruit shelf life and also provides a vehicle for nutraceutical consumption
CN112136544A	4 September 2020	Sichuan Agricultural University	Edible coating for fruits, e.g., blueberries	Konjac glucomannan + low acyl gellan gum + stearoyl calcium lactate + thymol microcapsules + water	Spraying	Prolongs blueberry shelf life by reducing water loss, reducing damage to the blueberry's natural wax, and reducing

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TABLE 8 (*Continued*) Patented and or commercially available edible coating formulations for fruits and vegetables.

Patent no.	Filing date	Assignee	Product	Formulation	Application method	Benefits
						decay due to microbial infection
MX2020004018A	13 July 2020	Universidad Autónoma de Coahuila	Edible coating for fruits	Whey protein + candelilla wax + glycerol + *Flourensia cernua* polyphenolic compounds	—	Prolongs fruit shelf life at room temperature by the presence of natural antimicrobials, which also eliminates the use of fungicides
CN110999953A	29 November 2019	Dalian Minzu University	Edible coating for fresh-cut potatoes	Chitosan + water + calcium chloride + ascorbic acid + citric acid + glycerol + cinnamon essential oil	Immersion	Prevents the enzymatic browning of the fresh-cut potatoes and inhibits microbial growth
MX2019003679A	29 March 2019	Universidad de Guadalajara	Edible coating for fruits and vegetables	Chitosan (0.9–50 wt%) + pentoxifylline (0.5–50 wt%) + metallic nanoparticles (0.001–50 wt%)	—	Extends the shelf life of fruits and vegetables by preventing oxidation
WO2019119168A1	20 December 2018	Pontificia Universidad Católica De Chile, Universidad Veracruzana	Edible coating for fruits and vegetables	Quinoa flour + chitosan + orange essential oil	Spraying or immersion	Extends the shelf life of fruits and vegetables by preventing microbial growth, preserving antioxidant properties, and preserving organoleptic properties
WO2019245482A2	3 October 2018	Petro Yag Ve Kimyasallar San. Ve TicA.S.	Edible coating for fruits and vegetables	Carnauba wax + shellac + morpholine + oleic acid + water + (ammonia/glycerol/NaOH/ ethanol)	Spraying	Prevention of fruit and vegetable spoilage
PH12018000213A1	9 August 2018	Polytechnic University of The Philippines	Edible coating for mangoes	Cassava starch + kappa-carrageenan + glycerol	—	Shelf life extension
KR101954970B1	1 January 2017	Seoul Women's University Industry-University Cooperation Foundation	Antimicrobial edible coating for mandarin	Grapefruit seed extract + carnauba wax + Tween-80	Immersion	Extends shelf life by reducing microbial infection and by maintaining the phenolic and antioxidant capacity of the fruits
CN106578031A	27 December 2016	Hebei Academy of Forestry Sciences	Edible coating for pears	Calcium chloride + starch + Arabic gum + garlicin + water	Immersion	Extension of shelf life and improvement of storage quality
MX2016016016A	5 December 2016	Alianza Para El Desarrollo Tecnologico S A De C V	Edible coating for fruits and vegetables	Lipid (e.g., sunflower oil) + stabilizer (e.g., mixture of monoesters and fatty acid diglycerides) + thickener (carob flour + guar gum + carrageenan) + film former (glycerin) + preservative	—	Extends shelf life while maintaining organoleptic conditions
CA2996348A1	30 August 2016	Production and Innovation on Edible Coatings SL	Edible coating for fresh-cut potatoes	Modified potato starch + sodium ascorbate + calcium ascorbate + citric acid	Immersion	Extension of shelf life and reduced browning
CN106259877A	11 August 2016	Southeast University	Edible coating from fruits and vegetables	Chitosan + calcium chloride + sodium carboxymethylcellulose	Immersion	The coating has self-healing properties and extends shelf life by maintaining fruit and vegetable hardness and preventing microbial degradation and oxidation
BR102016018306A2	9 August 2016	Universidade Federal Do Ceará		Encapsulated bioactive compounds from fruit	Immersion	

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TABLE 8 (*Continued*) Patented and or commercially available edible coating formulations for fruits and vegetables.

Patent no.	Filing date	Assignee	Product	Formulation	Application method	Benefits
			Edible coating for minimally processed fruits	processing by-products + chitosan + glacial acetic acid		Maintains the quality and microbiological safety of fruits
WO2016084094A1	29 November 2015	Yissum Research Development Company of The Hebrew University of Jerusalem Ltd	Edible coating for fruits and vegetables	Hydrocolloid polymer (e.g., alginate, agar, chitosan, *etc.*) + edible wax (e.g., beeswax, carnauba wax) + fatty acid (e.g., oleic acid) + water + edible alkaline component that is free of ammonia or morpholine + natural plant sterol + cross-linking agent/gelation inducing agent	Immersion, spraying, brushing, rubbing	Better extension of shelf life compared to morpholine-containing products; reduction in weight loss during postharvest storage
CN105211276A	2 November 2015	Hunan Agricultural University	Edible coating for fruits and vegetables	Pullulan polysaccharide + anthocyanidin + antioxidant (e.g., ascorbic acid) + emulsifying agent (e.g., sucrose fatty ester) + calcium chloride + sodium stearate + ethanol + nano-calcium carbonate	Immersion	Extends the shelf life of fruits and vegetables; preserves the nutritive value and shape
MX2015014317A	9 October 2015	Universidad Autónoma de Nuevo León	Bilayer edible coating for freshly chopped fruit	Prickly pear anionic plant mucilage + cationic chitosan polymer + plasticizer (e.g., glycerol)	Immersion	Extension of shelf life for up to 18 days by preventing weight loss, firmness loss, vitamin C degradation, and microbial growth while maintaining sensory qualities
MX2015014327A	9 October 2015	Universidad Autónoma de Nuevo León	Bilayer edible coating for freshly chopped fruit	Neutral pullulan polymer + cationic chitosan polymer acidified with acetic acid + plasticizer (e.g., glycerol)	Immersion	Extension of shelf life for up to 18 days by preventing weight loss, firmness loss, and microbial growth while maintaining sensory qualities
ES2550219A1	21 September 2015	Tabuenca S A	Edible coating for fruits and vegetables	Polysaccharide (e.g., hydroxymethylcellulose) + citric acid + alum + chitosan + hydrochloric acid	Immersion	Extends the shelf life of fruits and vegetables
MX2015002794A	4 March 2015	Universidad Nacional Autónoma De México	Edible coating for freshly cut fruits and vegetables	Nanocapsules or solid lipid nanoparticles + polymer supporting material + plasticizer + surfactant + preservative	—	
WO2015104440A1	30 December 2014	Production and Innovation on Edible CoatingsS.L.	Edible coating for pieces of fruit	Carboxymethylcellulose polysaccharide + calcium ascorbate + antioxidant (e.g., citric acid) + antimicrobial agent	Immersion	Extension of shelf life by preventing browning, microbial growth, and weight loss
CN104336170A	18 November 2014	Gansu Shengdafangzhou Potato Modified Starch Co., Ltd.	Edible coating for cherry tomato	Starch (modified starch from potato or maize) + plasticizer (stearic acid + lipoprotein + glycerine) + reinforcing agent (agar)	Immersion	Extends shelf life by reducing water loss and maintaining fruit texture and brightness

biodegradability or nutraceutical benefits but need further development to meet regulatory and scalability standards. While commercial coatings target export-focused fruits with high market visibility, academic research is increasingly exploring coatings for underused crops in tropical and subtropical regions.

Despite these scientific advances, the use of edible coatings on NUS remains limited. An analysis of patent databases (e.g., USPTO, EPO, WIPO) conducted in 2024 shows that less than 3% of edible coating patents mention or directly target indigenous fruits such as *Syzygium cumini* (jamun), *Ziziphus mauritiana* (ber), *Grewia asiatica* (phalsa), or *Hancornia speciosa* (mangaba).

Table 8 shows that there are a few commercial patents and many developed from university researchers. While most coatings were not tested on NUS, this dataset is an excellent starting point for future studies, as it helps to understand why commercial coatings have gained more traction than those produced from universities. A key distinction between commercial patents and those filed by university research teams is that commercial coatings are generally more complex, often incorporating a wider variety of additives. This allows the formulation to be adapted to different types of fruits and vegetables depending on their characteristics. Therefore, important considerations for future research include developing scalable, cost effective methods to obtain biopolymers from agro-industrial waste and designing flexible edible coating formulations using bio-based additives such as natural plant antioxidants and antimicrobials. Such innovations should be used across most NUS with minimal modification to the formula, thereby supporting circular bioeconomy principles while expanding preservation strategies to more regionally important crops.

8.1 Barriers to intellectual property development for NUS

Several structural and market-related factors contribute to the limited patent activity involving NUS:

- Low commercial incentive: NUS are typically cultivated on a small scale and consumed within localized markets, limiting their appeal to global food technology firms.
- Lack of standardization: High variabilities in physicochemical properties, such as surface morphology, cuticle permeability, and ripening kinetics, complicate the formulation of universal coatings for these crops.
- Weak patentability: Many coating components derived from agro-industrial waste or traditional knowledge systems may not fulfill novelty or industrial applicability criteria under standard IP frameworks.
- Resource constraints: Public institutions, local research centers, and smallholder cooperatives in the Global South often face legal, financial, and infrastructural limitations in filing, maintaining, or defending patents.

8.2 Toward inclusive and open innovation models

To expand the benefits of edible coatings to include NUS, future commercialization efforts should embrace inclusive innovation frameworks. These may involve:

- Open-access protocols and pre-competitive consortia: Multi-stakeholder partnerships can co-develop and disseminate coating formulations adapted to NUS, using locally abundant resources such as cassava starch, banana peel flour, or tamarind gum.
- Geographical indication (GI)-linked coatings: Coatings developed for culturally significant fruits may be integrated into regional value chains through GI protection, promoting biodiversity and regional branding.
- Alternative IP models: Licensing mechanisms such as Creative Commons, defensive publishing, or utility models offer viable alternatives to conventional patents, particularly for small-scale or non-profit actors.
- Technology transfer units: National research institutions and universities should establish mechanisms for translating laboratory-scale innovations into field-level applications, especially for rural and decentralized supply chains.

9 Regulation of biopolymer edible coatings

The regulation of biopolymer edible coatings varies significantly across different regulatory bodies, with the FDA (United States) and EFSA (European Union) implementing distinct frameworks. The FDA follows a "Generally Recognized as Safe" (GRAS) approach, which allows the use of edible coatings and additives under good manufacturing practices (GMP), provided they meet safety standards. In contrast, the EFSA enforces more stringent guidelines, requiring comprehensive toxicological evaluations and safety assessments before approval. Additionally, countries such as Canada, Australia, and China have specific regulations and permissible limits for food contact materials, creating challenges for global commercialization and regulatory harmonization.

The acceptable limits for additives depend on the type of substance and its intended function. For example, antimicrobial agents like potassium sorbate and sodium benzoate are commonly permitted in edible coatings, with regulatory bodies defining maximum allowable concentrations. Plasticizers such as glycerol and sorbitol, used to enhance coating flexibility, are generally accepted but must adhere to specific limits to prevent migration into food beyond the acceptable daily intake (ADI) levels. Essential oils, widely used as natural antimicrobial and antioxidant agents, often occupy a regulatory gray area, as they are classified as flavoring agents and preservatives. This dual classification leads to inconsistent regulations across different jurisdictions.

Emerging concerns surrounding nanomaterials in edible coatings have prompted increased scrutiny from regulatory authorities. Using nano-sized antimicrobial agents, nano-emulsions, and nano-cellulose composites raises questions about potential toxicity, bioaccumulation, and long-term health effects. The FDA has not yet established specific regulatory guidelines for nanomaterials in edible coatings, while the EFSA requires thorough risk assessments to evaluate the safety of engineered nanoparticles before approval. The lack of global consensus on the safety of nanomaterials remains a critical issue, underscoring the need for further research, standardized testing protocols, and precise labeling requirements to ensure consumer safety and regulatory compliance worldwide (Bizymis and Tzia, 2021; Priya et al., 2023).

10 Conclusion

NUS are important to help combat the growing food crisis and increase biodiversity, but their highly perishable nature impedes their commercial potential. Biopolymer-based edible coatings are a promising way to reduce postharvest losses and extend the shelf life of NUS, many of which are grown in tropical and subtropical regions with limited resources. These coatings, made from polysaccharides, proteins, and lipids, provide biodegradable, non-toxic, and often locally available alternatives to traditional packaging and synthetic materials preservatives.

However, several critical gaps must be addressed to facilitate the integration of edible coatings into NUS value chains:

- Limited specificity of formulations: Most coating technologies are optimized for major global fruits and not tailored to the physicochemical properties of NUS.
- Technical and infrastructural constraints: High humidity, lack of cold storage, and limited access to standardized application methods hinder real-world adoption.
- Regulatory fragmentation: The absence of harmonized food-grade approval processes for natural additives impedes the deployment of coatings in local markets.
- Lack of targeted patenting and commercialization strategies: NUS remain underrepresented in innovation ecosystems, with few dedicated R&D initiatives or intellectual property protections.
- Consumer skepticism and sociocultural variability: Perception issues around coated fruits, mainly when derived from animal sources or synthetic agents, must be addressed through clear labeling and education.

To fully realize the potential of edible coatings for NUS, future efforts must focus on developing solutions that are specific to the context, low-cost, and culturally acceptable. These efforts should include utilizing agro-industrial residues as sources of biopolymers, creating open-access formulations, and encouraging participatory innovation involving smallholders, local markets, and national regulatory bodies.

By aligning coating technologies with the needs of decentralized, short food supply chains, it is possible to enhance the postharvest resilience, marketability, and nutritional quality of NUS, thus contributing to biodiversity conservation, food security, and circular bioeconomy strategies particularly in the Global South.

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