Acta Agrícola y Pecuaria 12: e0121032. | e-ISSN: 2395-874X.
https://doi.org/10.30973/aap/2026.12.0121032 (September 6th, 2026)

REVIEW ARTICLE

Edible bio-coatings for postharvest preservation of fruits and vegetables: advances in biopolymer-based materials and emerging sources

Biorrecubrimientos comestibles para la conservación poscosecha de frutas y hortalizas: avances materiales basados en biopolímeros y fuentes emergentes

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Reception date:
March 17th, 2026

Acceptation date:
May 8th, 2026

Published on line:
September 6th, 2026

How to cite:
Ocampo-Góngora, M. J., León-García, E., Evangelista-Martínez, Z., Ramírez-Sucre, M. O., Uc-Varguez, A., & Gastélum-Martínez, É. (2026). Edible bio-coatings for postharvest preservation of fruits and vegetables: advances in biopolymer-based materials and emerging sources. *Acta Agrícola y Pecuaria, 12*, e0121032. https://doi.org/10.30973/aap/2026.12.0121032

ABSTRACT

Edible coatings are a sustainable strategy for postharvest preservation of fruits and vegetables, reducing losses and replacing synthetic packaging. This review synthesizes recent advances in materials, mechanisms of action, and applications, with particular emphasis on the valorization of agro-industrial byproducts within circular bioeconomy models. Conventional starches are compared with *Brosimum alicastrum* Sw. (Moraceae), an underutilized Mesoamerican species that exhibits film-forming capacity, high phenolic content, and antioxidant activity in hybrid systems. The analysis addresses regulatory aspects, sensory limitations, and industrial scalability challenges, while proposing pathways for active and biodegradable formulations adapted to commercial storage conditions. Findings highlight *B. alicastrum* as an emerging resource with potential to strengthen tropical agri-food chains and reduce postharvest waste through sustainable coating technologies. Its use as an edible coating could encourage cultivation in backyard orchards in Mexico and provide added value to this underutilized tropical fruit.

KEYWORDS

Brosimum alicastrum, agricultural byproducts, biopolymers, sustainable packaging, postharvest technology.

RESUMEN

Los recubrimientos comestibles representan una alternativa sostenible para la conservación poscosecha de frutas y hortalizas, al reducir pérdidas y sustituir empaques sintéticos. Esta revisión analiza avances recientes en materiales, mecanismos de acción y aplicaciones, con especial énfasis en la valorización de subproductos agroindustriales dentro de modelos de economía circular. Se comparan las propiedades de almidones convencionales con las de *Brosimum alicastrum* Sw. (Moraceae), especie mesoamericana subutilizada que destaca por su capacidad formadora de películas, elevado contenido fenólico y actividad antioxidante en sistemas híbridos. El análisis incluye aspectos regulatorios, limitaciones sensoriales y retos de escalado industrial, proponiendo rutas para formulaciones activas y biodegradables adaptadas a condiciones comerciales. Se concluye que *B. alicastrum* constituye un recurso emergente con potencial para fortalecer cadenas agroalimentarias tropicales y contribuir a la reducción del desperdicio poscosecha mediante tecnologías de recubrimiento sostenibles. Su aprovechamiento como recubrimiento comestible podría incentivar su cultivo en huertos tropicales de México y otorgar valor agregado a esta especie subutilizada.

PALABRAS CLAVE

Brosimum alicastrum, subproductos agroindustriales, biopolímeros, empaques sostenibles, tecnología poscosecha.

Introduction

The increasing demand for fresh and minimally processed fruits and vegetables has intensified the need for effective postharvest preservation strategies. However, these products are highly perishable due to physiological deterioration, microbial growth, and moisture loss, leading to significant economic losses worldwide (Dhall, 2013).

In this context, edible coatings have emerged as a promising alternative to extending shelf life while maintaining product quality and safety. These coatings act as semi-permeable barriers that regulate gas exchange, reduce water loss, and delay ripening processes (Galus & Kadzińska, 2015; Perez-Vazquez et al., 2023). In recent years, there has been growing interest in the development of bio-based coatings, particularly those derived from natural biopolymers, due to their biodegradability, safety, and potential to replace synthetic packaging materials (Wu et al., 2022; Zhao et al., 2021).

Despite these advances, the available literature remains fragmented regarding the integration of material composition, processing techniques, functional performance, and safety considerations with edible coatings. Additionally, the exploration of underutilized plant sources for coating development remains limited, representing an opportunity for innovation in sustainable food systems.

Brosimum alicastrum Sw. (Moraceae), commonly known as Ramón or maya nut, is a tropical species native to Mesoamerica and cultivated in backyard orchards in Mexican states such as Yucatan, Campeche, Quintana Roo, Chiapas, and Oaxaca. Traditionally, it has been used as food, forage, a medicinal resource, an ornamental plant, and a shade tree, reflecting its cultural and agroforestry importance (Losoya-Sifuentes et al., 2023; Subiria-Cueto et al., 2019). Its incorporation into edible coating technologies not only provides functional properties but may also encourage its cultivation and add value to this underutilized species (Olguin-Maciel et al., 2017; Pech-Cohuo et al., 2022).

In this regard, *B. alicastrum* has gained attention as a potential alternative source due to its promising starch properties and functional potential (Losoya-Sifuentes et al., 2023; Pech-Cohuo et al., 2022). The aim of this review is to provide a comprehensive and critical overview of recent advances in edible bio-based coatings for the postharvest preservation of fruits and vegetables, with a focus on biopolymer-based materials, processing techniques, functional properties, and safety aspects. Furthermore, this review explores the potential of *B. alicastrum* as a sustainable raw material for the development of novel coating systems.

Methodology of the review

This review was conducted through a structured literature search in Scopus, Web of Science, and ScienceDirect. Searches covered the period 2010-2025 using combinations of the terms "edible coatings," "bio-based films," "agricultural byproducts," "fruit preservation," and "*Brosimum alicastrum*" peer-reviewed research articles, review papers, and technological reports focused on fruits and vegetables were prioritized. Studies dealing exclusively with synthetic polymers or non-edible applications were excluded. Emphasis was placed on recent contributions with experimental validation, postharvest relevance, and information useful for agricultural and food applications.

Coating materials, application methods, and mechanisms of action

Polysaccharides such as starch, pectin, alginate, carrageenan, and gums are widely used because they are abundant, inexpensive, and efficient in forming continuous films. Table 1 summarizes the main classes of edible coatings used for fruits and vegetables, including their composition and key functional characteristics. Their main limitation is high water sensitivity, which often requires blending with lipids, proteins, or reinforcing agents to improve moisture resistance (Pillai et al., 2024; Versino et al., 2016; Wu et al., 2022; Zhao et al., 2021). Reinforced starch systems, including starch-chitosan combinations and other bio-based barrier materials, illustrate how polysaccharide matrices can be improved through blending and structuring strategies (Mujtaba et al., 2022).

Protein-based coatings, including gelatin, casein, whey proteins, soy proteins, and zein, generally provide good oxygen barrier properties and acceptable mechanical strength. However, they are also sensitive to ambient humidity and, in some cases, require plasticizers or blending to avoid brittleness and improve

Table 1. Main classes of edible coatings used for fruits and vegetables.

Type of coating	Main characteristics	Application examples	Application method	Advantages	Limitations	Key references
Polysaccharide-based coatings	Abundant biopolymers such as starches (corn, cassava, banana), pectins, gums, and alginates. They offer good barrier properties against gases (O_2, CO_2), but poor resistance to water vapor.	Apple, strawberry, papaya, mango, plum, tomato.	Dipping, spraying, brushing.	Biodegradable, cost-effective, good adhesion, and high transparency. Allow incorporation of active compounds. Some modified starches improve moisture resistance.	Hydrophilic, moisture-sensitive, and fragile without plasticizers. May require structural reinforcement such as gums or proteins. Limited resistance under high relative humidity (>70 % RH).	Md Nor & Ding (2020), Mohamed et al. (2020), Pillai et al., (2024), Wu et al. (2022), Zhao et al. (2021).
Protein-based coatings	Films made from animal or plant proteins (such as gelatin, casein, zein, or soy) that provide good adhesion, high oxygen barrier, transparency, and outstanding mechanical properties, while also facilitating the incorporation of bioactive compounds.	Pear, grape, tomato.	Dipping, brushing.	Excellent gas barrier (O_2), ideal for climacteric fruits. Good mechanical strength and flexibility. High compatibility with functional compounds (antioxidants, antimicrobials, enzymes). Ability to form glossy, transparent, and adhesive films. Compatible with emerging technologies such as nanoemulsions or active coatings.	Sensitive to ambient humidity and extreme pH conditions. Prone to microbial degradation if not modified or combined with other polymers. Require plasticizers (glycerol, sorbitol) to prevent brittleness. Some plant proteins (such as gluten or soy) may pose allergenic risks. Lower water vapor resistance compared to lipid-based or composite films.	Fabra et al. (2009), Galus & Kadzińska (2015), Md Nor & Ding (2020), Mihalca et al. (2021).

Type of coating	Main characteristics	Application examples	Application method	Advantages	Limitations	Key references
Lipid-based coatings	Formulated with waxes, fatty acids, and monoacylglycerols, these hydrophobic coatings provide excellent water vapor barrier, reduce moisture loss, and enhance the visual appearance of fruits. They are applied as an external layer or in emulsions with hydrocolloids to improve functionality and control transpiration.	Mango, apple, orange.	Spraying, brushing.	Highly effective against dehydration, enhance visual appearance, compatible with bioactive emulsions.	Mechanically fragile when used alone, low gas permeability, less transparency, potential allergenicity or solvent residues.	Babarabie et al. (2024), Günal-Köroğlu & Capanoglu (2024), Md Nor & Ding (2020), Milani & Nemati (2022), Pashova (2023), Yousuf et al. (2022).
Composite & nanostructured films	These coatings combine biopolymers with functional nanoparticles to enhance their strength, barrier properties, and active functionality. The use of advanced techniques such as 3D printing or layer-by-layer assembly enables precise control over their structure and the release of bioactive compounds.	Strawberry, plum, guava.	Layer-by-layer, spraying, 3D printing.	High mechanical and tensile strength. Enhanced antioxidant and antimicrobial properties. Potential to design intelligent films (responsive to pH, humidity, temperature). Greater control over structure and controlled release of bioactive compounds. Potential to function as food sensors or active packaging.	High production and raw material costs. Limited industrial scalability due to specialized equipment. Need to comply with stricter regulations on nanomaterials in contact with food. Toxicological evaluation required for human consumption use.	Mujtaba et al., (2022), Odetayo et al. (2022), Sun et al. (2024), Xu et al. (2024).

stability (Fabra et al., 2009; Han et al., 2023; Mihalca et al., 2021).

Lipid-based systems, such as waxes, fatty acids, and monoacylglycerols, are effective moisture barriers but tend to be brittle and less permeable to gases. For this reason, they are commonly used in emulsified or composite formulations (Milani & Nemati, 2022; Yousuf et al., 2022). Plant waxes and wax-containing systems remain particularly relevant for reducing dehydration and preserving fruit appearance under commercial storage (Babarabie et al., 2024; Günal-Köroğlu & Capanoglu, 2024; Pashova, 2023).

Composite and nanostructured coatings combine two or more biopolymers or incorporate nanofillers to improve barrier properties, mechanical performance, and the controlled release of active compounds. Current developments include nanocellulose-based reinforcements, nano-enabled films, and multifunctional matrices with active properties (Ghosh & Singh, 2022; Odetayo et al., 2022; Pirozzi et al., 2021; Sun et al., 2024; Xu et al., 2024).

Dipping and spraying remain the most common methods for coating fresh produce because they are adaptable to both laboratory and industrial conditions (Amin et al., 2022; Bourtoom, 2008). Brushing is less common but useful for selective applications, while layer-by-layer deposition and electrostatic spraying provide more controlled deposition and can improve surface coverage or active compound delivery (Peretto et al., 2017).

After application, coatings act by reducing transpiration and gas exchange, creating a modified microenvironment on the fruit surface, and delivering antioxidant or antimicrobial compounds incorporated into the matrix. These mechanisms work together to delay ripening, maintain firmness, preserve color, and reduce microbial growth (Rosero et al., 2020; Pavlath & Orts, 2009; Ungureanu et al., 2023).

Agricultural byproducts as raw materials and functional additives

The use of agro-industrial residues in edible coatings supports circular bioeconomy strategies by transforming low-value waste into preservation materials. Byproducts such as citrus peels, grape pomace, banana peels, avocado pits, and potato peels are sources of starch, pectin, cellulose, lipids, and phenolic compounds that can contribute both structural and functional properties (Carnaval et al., 2024; Castillo-Patiño et al., 2024; Gaspar & Braga, 2023; Ligarda-Samanez et al., 2025).

Beyond their role as polymer sources, agricultural residues also provide antioxidant and antimicrobial molecules that can be incorporated into active coatings. Polyphenol-rich extracts and residue-derived fractions have been associated with delayed browning, lower fungal incidence, and improved retention of firmness and color in coated produce (Carnaval et al., 2024; Kumar et al., 2021; Yadav et al., 2022).

Representative studies show that residue-derived coatings can improve the postharvest performance of strawberries, tomatoes, guavas, mangoes, and other horticultural products. Their practical value lies in reducing dependence on virgin inputs while providing formulations tailored to the preservation needs of specific fruits and vegetables (Carnaval et al., 2024; Castillo-Patiño et al., 2024; Kumar et al., 2021; Yadav et al., 2022).

Brosimum alicastrum as an emerging source for edible coatings

Brosimum alicastrum, commonly known as Maya nut or Ramón, is a native Mesoamerican species traditionally used as food and forage. Its seeds contain substantial amounts of starch, dietary fiber, and minerals, making the species attractive both nutritional and technological perspectives (Losoya-Sifuentes et al., 2023; Subiria-Cueto et al., 2019). Starch isolated from *B. alicastrum* has shown film-forming behavior comparable to that of conventional starches, with favorable gelatinization and thermal characteristics for coating preparation. Reported properties, such as water absorption, viscosity, and thermal stability, indicate that it can be processed using conventional film-forming methods (Martínez Ruiz, 2023; Olguin-Maciel et al., 2017; Pech-Cohuo et al., 2022).

In addition to its starch content, *B. alicastrum* contains phenolic compounds, including chlorogenic acid and caffeoylquinic derivatives. This profile gives the material particular relevance for the development of active coatings intended to control oxidation or serve as carriers of additional bioactive compounds

(Losoya-Sifuentes et al., 2023). Hybrid systems based on Ramón starch, chitosan, and quercetin have already demonstrated favorable physicochemical, structural, and antioxidant properties in film formulations (Pech-Cohuo et al., 2022).

Although *B. alicastrum* starch alone does not exhibit intrinsic antimicrobial activity comparable to chitosan, studies on hybrid systems have shown that combining it with chitosan, quercetin, or other phenolics can improve antioxidant performance without compromising the structural integrity of the films (Han et al., 2023; Pech-Cohuo et al., 2022).

From a sustainability perspective, *B. alicastrum* offers advantages linked to the valorization of underutilized native resources. Its use may promote agroforestry systems, biodiversity conservation, and local value chains in tropical regions. These characteristics make it a particularly relevant candidate for future coating development in Latin American agricultural contexts (Ligarda-Samanez et al., 2025; Subiria-Cueto et al., 2019). In addition, the potential integration of starches and other plant fractions into hybrid biodegradable matrices is consistent with broader trends in starch-based films and sustainable biopolymer development (Versino et al., 2016).

In this context, *B. alicastrum* has attracted attention as a promising alternative source of starch due to its availability and functional potential. Its properties make it a suitable candidate for the development of edible films with improved performance. Table 2 compares the physicochemical and functional properties of *B. alicastrum* starch with those of conventional starches used in coating formulations.

Safety considerations and regulatory aspects

Materials intended for edible coatings must be food-grade, non-toxic, and compatible with the intended use of the coated product. In practice, regulatory evaluation concerns not only the main polymer but also plasticizers, cross-linkers, colorants, solvents, and bioactive additives that may migrate into food (Gammage & Marangoni, 2025; Md Nor & Ding, 2020).

Beyond compliance with additive lists, safety evaluation requires toxicological studies to confirm the absence of adverse effects, particularly when bioactive compounds such as antimicrobials, antioxidants, or natural pigments are incorporated (Jahangiri et al., 2024). Consumer acceptance is another critical factor, as sensory attributes including flavor, aroma, and texture can influence market viability. Studies highlight that coatings must balance functional performance with minimal sensory interference to gain consumer trust (Gammage & Marangoni, 2025).

Labeling and commercialization also represent challenges. Transparent communication regarding the composition, biodegradability, and functional claims of coatings is essential to meet regulatory standards and build consumer confidence. Furthermore, the harmonization of international regulations remains a pending issue, as differences among countries can limit the scalability of edible coating technologies in global markets (Gammage & Marangoni, 2025; Md Nor & Ding, 2020).

Functional properties relevant to postharvest performance

Key performance indicators for edible coatings include water vapor permeability, mechanical resistance, solubility, opacity, adhesion, and antioxidant or antimicrobial activity. In practical terms, effective coatings should limit moisture loss without causing anaerobic conditions, remain attached during handling, and preserve the visual and sensory quality of the produce (Pillai et al., 2024; Rosero et al., 2020).

Polysaccharide-based films generally provide suitable gas barrier properties but require modification to improve moisture resistance. Protein-based systems contribute mechanical strength and oxygen barrier properties, whereas lipid-containing coatings are especially valuable when dehydration is the primary concern. Composite systems often provide the best balance by combining barrier, structural, and active functionalities (Md Nor & Ding, 2020; Mihalca et al., 2021; Milani & Nemati, 2022; Yousuf et al., 2022).

Published examples show that properly designed coatings can reduce weight loss, delay softening, maintain color, and extend the shelf life of products such as plums, tomatoes, papayas, mangoes, guavas, and citrus fruits. This has been demonstrated in starch-based plum coatings, chitosan-based tomato systems, chitosan-oxidized starch coatings for papaya, chitosan-pullulan coatings for mango, active starch coatings for guava, and nanocellulose-reinforced systems with improved mechanical performance (Escamilla-García et al., 2018; Kumar et al., 2021; Paul et al., 2018; Pirozzi et al., 2021; Yadav et al., 2022). These results confirm that formulation design must be guided by the physiology of the commodity and storage conditions.

Beyond these general indicators, edible coatings also exhibit functional properties that are critical for postharvest performance. Physical barriers functions include moisture and gas control; mechanical properties encompass flexibility, resistance, and transparency; whereas bioactivity involves the incorporation of antimicrobials, antioxidants, and natural dyes. Emerging smart films add an innovative dimension, as they can act as sensors that change color in response to deterioration or contamination (Versino et al., 2016; Zhao et al., 2021; Odetayo et al., 2022; Xu et al., 2024). In fruits, the mechanisms of action include the regulation of respiration and ripening, reduction of weight loss and firmness loss, protection against microorganisms and UV radiation, and improvement of visual attributes as shine, color, and freshness (Rosero et al., 2020; Ungureanu et al., 2023).

Table 2. Comparative properties of *Brosimum alicastrum* and conventional starches relevant to edible films.

Property	*Brosimum alicastrum*	Corn Starch	Potato Starch	Cassava Starch	References
Starch content (%)	63-65	70-75	65-80	65-70	BeMiller (2011); Hoover (2001); Jane et al. (1999); Losoya-Sifuentes et al. (2023); Olguin-Maciel et al., (2017); Pech-Cohuo et al. (2022); Subiria-Cueto et al. (2019).
Water absorption capacity (g/g)	1.55	0.6-1.2	1.1-1.4	1.0-1.3	BeMiller (2011); Hoover (2001); Jane et al. (1999); Losoya-Sifuentes et al. (2023); Olguin-Maciel et al., (2017); Pech-Cohuo et al. (2022); Subiria-Cueto et al. (2019).
Oil absorption capacity (g/g)	1.3	0.5-1.0	0.9-1.3	0.8-1.2	BeMiller (2011); Hoover (2001); Jane et al. (1999); Losoya-Sifuentes et al. (2023); Olguin-Maciel et al., (2017); Pech-Cohuo et al. (2022); Subiria-Cueto et al. (2019).
Gelatinization temperature (°C)	~68	62-72	59-66	52-65	BeMiller (2011); Hoover (2001); Jane et al. (1999); Losoya-Sifuentes et al. (2023); Olguin-Maciel et al., (2017); Pech-Cohuo et al. (2022); Subiria-Cueto et al. (2019).
Viscosity behavior	Forms viscous, stable solutions with good film adhesion.	High peak viscosity, good for thickening.	Very high viscosity, less stable.	Moderate viscosity, stable at low shear.	BeMiller (2011); Hoover (2001); Jane et al. (1999); Losoya-Sifuentes et al. (2023); Olguin-Maciel et al., (2017); Pech-Cohuo et al. (2022); Subiria-Cueto et al. (2019).
Crystallinity	Semi-amorphous, lower retrogradation.	A-type crystalline.	B-type crystalline.	A-/B-type crystalline.	BeMiller (2011); Hoover (2001); Jane et al. (1999); Losoya-Sifuentes et al. (2023); Olguin-Maciel et al., (2017); Pech-Cohuo et al. (2022); Subiria-Cueto et al. (2019).

Property	*Brosimum alicastrum*	Corn Starch	Potato Starch	Cassava Starch	References
Phenolic content	High (chlorogenic acid, caffeoylquinic acids, resveratrol traces; up to 120 mg GAE/g).	Low	Low	Low	BeMiller (2011); Hoover (2001); Jane et al. (1999); Losoya-Sifuentes et al. (2023); Olguin-Maciel et al., (2017); Pech-Cohuo et al. (2022); Subiria-Cueto et al. (2019).
Antioxidant activity	High, especially when combined with chitosan or flavonoids.	Absent	Absent	Absent	BeMiller (2011); Hoover (2001); Jane et al. (1999); Losoya-Sifuentes et al. (2023); Olguin-Maciel et al., (2017); Pech-Cohuo et al. (2022); Subiria-Cueto et al. (2019).
Thermal stability (TGA)	Degradation between 280-310 °C.	260-300 °C	250-280 °C	260-300 °C	BeMiller (2011); Hoover (2001); Jane et al. (1999); Losoya-Sifuentes et al. (2023); Olguin-Maciel et al., (2017); Pech-Cohuo et al. (2022); Subiria-Cueto et al. (2019).
Environmental advantage	Grows without agrochemicals; promotes agroforestry; low-input crop.	Requires irrigation, agrochemicals.	Requires cool climate, pesticides.	Often industrially processed with chemical inputs.	BeMiller (2011); Hoover (2001); Jane et al. (1999); Losoya-Sifuentes et al. (2023); Olguin-Maciel et al., (2017); Pech-Cohuo et al. (2022); Subiria-Cueto et al. (2019)
Bioeconomy/ circular potential	Allows valorization of wild resources; byproducts usable in hybrid films or compostable blends.	Commonly used but with limited residue valorization.	Limited use of byproducts.	Peels are sometimes used for biofuel or feed.	BeMiller (2011); Hoover (2001); Jane et al. (1999); Losoya-Sifuentes et al. (2023); Olguin-Maciel et al., (2017); Pech-Cohuo et al. (2022); Subiria-Cueto et al. (2019).

Challenges and future perspectives

Despite encouraging progress, several limitations still constrain large-scale applications. Sensory effects remain important because some polymers or active compounds can alter flavor, aroma, gloss, or mouthfeel, and postharvest treatments that preserve quality must also maintain consumer acceptability (Nain et al., 2021; Radziejewska-Kubzdela et al., 2014). In addition, the development of advanced nanostructured systems must balance innovation with safety and regulatory feasibility (Ghosh & Singh, 2022; Odetayo et al., 2022).

Industrial adoption is also limited by processing costs, raw material availability, and the need for continuous systems compatible with irregular fruit surfaces. Scaling bio-based packaging and coating technologies from laboratory studies to commercial application remains a major challenge (Bremenkamp & Sousa Gallagher, 2025).

Future research should prioritize scalable formulations based on locally available materials, robust validation under commercial storage conditions, and clearer regulatory pathways for active systems. Specifically for *B. alicastrum*, further research is needed on fruit-level validation, storage stability, interactions with active agents, and consumer acceptance, although its starch and antioxidant potential have already been documented (Losoya- Sifuentes et al. 2023; Martínez Ruiz, 2023; Pech-Cohuo et al., 2022).

Conclusions

Edible bio-coatings represent a promising component for sustainable postharvest management because they can extend shelf life while reducing the environmental burden associated with synthetic packaging. Their effectiveness depends on the rational selection of film-forming materials, additives, and application methods according to the physiological characteristics of the produce.

Agricultural byproducts offer an important pathway toward circular bioeconomy models by providing structural biopolymers and bioactive compounds that can be transformed into value-added preservation technologies. Within this context, *B. alicastrum* emerges as a particularly attractive raw material for the development of future edible coatings in tropical regions.

Further advances will depend on integrating material innovation with regulatory compliance, industrial scalability, and sensory validation. Addressing these aspects will improve the practical applicability of edible coatings for reducing postharvest losses in fruits and vegetables.

Moreover, the valorization of *B. alicastrum* as a source of edible coating material could encourage its cultivation in backyard orchards of southeastern Mexico, strengthen tropical agri-food chains, and increase the cultural and economic value of this underutilized species. By integrating functional properties, mechanisms of action, and regulatory considerations, edible coatings derived from this resource have the potential to become a cornerstone of sustainable postharvest technologies.

Acknowledgments

The authors acknowledge the financial support provided from Secretaria de Ciencia, Humanidades, Tecnologia e Innovacion (Scholarship 4019581 and project PND-2016-2900).

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