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Review

# Application of plant mucilage polysaccharides and their techno-functional properties' modification for fresh produce preservation

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ABSTRACT

The use of edible coating/film to improve fresh produce's quality and shelf life is an old but reliable and popular method of preservation. Recently, plant-derived mucilages have been extensively used to prepare edible packages (MEPs). This review focuses on recent studies that characterize mucilages from different plants, and examine their specific applications as edible packages in preserving fruits and vegetables. Structure–function relations and corresponding influence on film-forming properties are discussed. This review also surveys the additive-modifications of MEPs techno-functional properties. MEPs from a range of plant sources are effective in preventing quality loss and improving the storability of various fruits and vegetables. The preservative mechanisms and essential techno-functional properties of MEPs required for fruit and vegetable packaging were summarized. The key findings summarized in this study will help promote the utilization of mucilages and draw attention to other novel applications of this valuable polymer.

## 1. Introduction

Fruits and vegetables, rich in health-benefiting nutrients, are produced and consumed in abundance worldwide. However, their storability has been of significant concern (Yousuf et al., 2018). Additionally, unlike other crops, they are often consumed without any cooking or further processing. Therefore, their safety and conditions (wholesomeness and freshness) at the point of purchase often determine their acceptance by consumers (Slavin & Lloyd, 2012). Various preservative strategies, such as cold-distribution chain, modified atmosphere packaging, controlled atmosphere storage, active packaging, and using edible packages, have been implemented to improve the storage quality and food safety of fruits and vegetables (Olawuyi et al., 2019;Olawuyi & Lee, 2019;Park et al., 2020;Werner et al., 2017). Notably, the use of edible packages, in the form of coating or film, has gained more interest than other methods because it is sustainable, cheap, convenient, and easy to apply. It is also in line with the consumers' increasing preference for food with guaranteed safety and fewer synthetic additives (Gheribi & Khwaldia, 2019;Misir et al., 2014).

Edible packages, in form of coatings or stand-alone films, are developed from polymeric materials, such as proteins, lipids, and polysaccharides; polysaccharides are especially relevant in the fruit and vegetable industry (Kumar, 2019). Polysaccharide-based materials, such as chitosan, sodium alginate, gums, and mucilages, have been developed into edible packages for food preservation (Guerreiro et al., 2015;Muñoz et al., 2012;Treviño-Garza et al., 2019).

An edible package provides a semipermeable barrier that mitigates moisture transfer and gaseous exchange and impedes the metabolic processes associated with food spoilage and deterioration, consequently extending food's shelf life (Martínez-Romero et al., 2013;Saha et al., 2017). Moreover, edible packages provide some level of mechanical protection (Banasaz et al., 2013;Tabaestani et al., 2013), reduce microbial contamination and proliferation, and act as active components carriers (Adetunui et al., 2012;Valencia-Chamorro et al., 2011). In addition, edible packages can be consumed along with the food, reducing the need for waste disposal (Wang et al., 2011). While there is much literature on utilizing edible coatings from a wide range of polysaccharides (such as chitosan, alginates, carrageenan, starches, etc.) to preserve fruits and vegetables (Basumatary et al., 2020;Kumar, 2019; Valencia-Chamorro et al., 2011;Yousuf et al., 2018), only a few review articles specific to mucilage polysaccharides' application in the preservation of produce are yet available.

Mucilages are generally extracted from certain plants and microorganisms (Albuquerque et al., 2016). They are hydrophilic polymers, mainly composed of water-soluble polysaccharides and proteins, which interact with water to form a viscous mass. They have been used in foods

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as thickeners, gelling agents, texture enhancers, and emulsifiers (Kamel et al., 2020;Zeng & Lai, 2016). Recently, mucilages obtained from various plants and plants parts (i.e. seeds, fruits, leaf) have been used to develop novel edible packages (Beikzadeh et al., 2020;Soukoulis et al., 2018). The use of mucilages in edible packages is increasingly preferred to synthetic materials due to their intrinsic properties, such as non-toxicity, biocompatibility, biodegradability, and adaptability (Alpizar-Reyes et al., 2017).

Mucilage-based edible packages (MEPs) achieve preservative effects by acting as a barrier against gas exchange, preventing quality loss, and in some cases, inhibiting microbial growth. However, some techno-functional limitations, such as poor water vapor barrier and brittleness, have been noted in MEPs (Beigomi et al., 2018;Jouki, Mortazavi, et al., 2014;Razavi et al., 2015). Hence, components such as plasticizers and other materials, such as oils, proteins, starch, and nanoparticles, have been incorporated in the polymer matrices of mucilages to stabilize and improve their techno-functional properties (Capitani et al., 2016; Khazaei et al., 2014;Mujtaba, Koc, et al., 2019;Vieira et al., 2011).

Recent research studies have demonstrated the effectiveness of MEPs in improving the storage quality and extending the shelf life of fruits and vegetables (Allegra et al., 2017;los Santos-Santos et al., 2020;Noshad et al., 2019;Nourozi & Sayyari, 2020;Wu, 2019). Many studies have also been conducted to improve the techno-functional properties of mucilage-based films (de Paiva et al., 2020;Gheribi et al., 2019). However, recent reviews either focused on selected plant mucilage, such as *Cactus* (Gheribi & Khwaldia, 2019) and *Aloe vera* (Misir et al., 2014), while other related reviews studied selected plant-part, such as seeds, (Beikzadeh et al., 2020;Soukoulis et al., 2018), without an in-depth consideration of the mucilage's use in the preservation of produce, as critically examined in this study. For instance,Beikzadeh et al. (2020) presented an overview of the application of seed-based mucilages in the packaging of various food products, including cheese, fruits and vegetables, meat and meat products, and fried products.Soukoulis et al. (2018), described the potentials of plant seed mucilage as alternative hydrocolloids for food and nutraceutical industry applications such as texturizing agents, fat replacers, stabilizing agents, especially in bakery and dairy products, and superficially discussed their food packaging applications, with no mention of their contribution to fresh-produce preservation. Another review only examined the pharmaceutical and environmental applications of selected plant mucilages, specifically Arabinoxylan and Rhamnogalacturonan seed-mucilages (Kamel et al., 2020). However, in this study we described various mucilages derived from different plant sources (and different parts i.e. fruit, leave, seed, tubers, stems etc.), and structure-function relationship and relevant techno-functional properties to predict packaging performance.

To the best of our knowledge, there has been no review that comprehensively examined the application of plant MEPs for the preservation of produce (specifically fruits and vegetables) or the various improvements of their techno-functional properties. This study surveys the research from the last decade on plant mucilage polysaccharides, the modifications of their properties, and their application as an edible package for the preservation of fruits and vegetables.

## 2. Mucilage polysaccharides as edible packages

Mucilages are physiological products obtained from the cell wall of different plant parts, including seeds, leaves, stems, barks, and roots (Kamel et al., 2020). The obtention process of mucilage polysaccharides is summarized inFig. 1A. Mucilage can be extracted using water, dilute acid, or alkali solutions, owing to their hydrophilic properties. In most cases, the solvent pH (4–8), solid-to-liquid ration (1: 10–75 g/mL), and temperature (25–90 °C) have been considered as main extraction parameters ((Alpizar-Reyes et al., 2017;Kaewmanee et al., 2014;Marvdashti et al., 2017;Rodríguez-González et al., 2014;Seyedi et al., 2014)). In addition, various extraction methods ranging from simple water extraction with mild agitation, vigorous vortexing or homogenizing, mechanical stirring, and the use of advanced extraction techniques such as ultrasound, microwave, enzymatic have been reported (Olawuyi et al., 2020;Soukoulis et al., 2018;Zeng & Lai, 2016). After extraction, mucilage can be obtained as a solution after filtration/centrifugation, or dried to obtain a powder. In some cases, ethanol precipitation with one or more purification processes (dialysis, resin, column purification) may be employed before lyophilization to obtain a more purified mucilage.

The mucilages obtained from various plant parts have diverse characteristics and applications, based on their respective structural and functional characteristics. In this section, the preservative properties of edible packages, and specific properties of mucilage required for its successful application as an edible package are discussed.

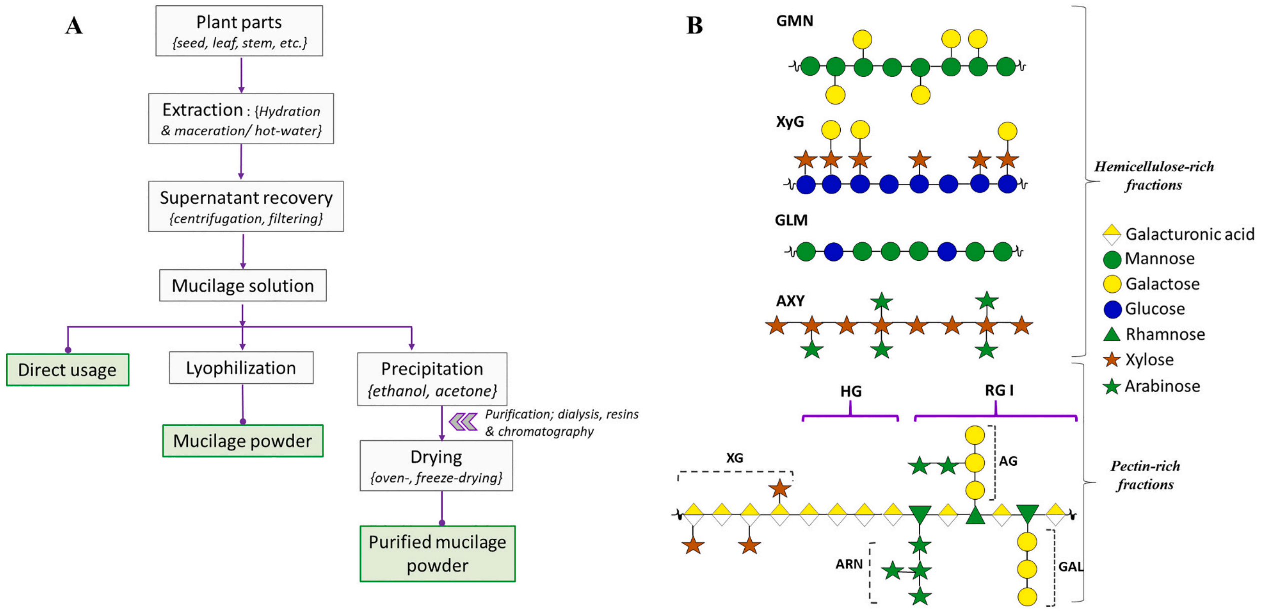

**Fig. 1.** A) Systematic diagram for the preparation of mucilage; B) Illustration of primary cell wall polysaccharides present in various plant-derived mucilages. Abbreviations for GMN:- Galactomannan; XyG:- Xyloglucan; GLM:- Glucomannan; AXY:- Arabinoxylan; HG:- Homogalacturonan; RG-I:- Rhamnogalacturonan-I; XG:- Xylogalacturonan; AG:- Arabinogalactan; ARN:- Arabinan; and GAL:- Galactan.

Plant mucilages have been used as a polymeric material to develop edible coating and films for food preservation, especially for fruits and vegetables (Basumatary et al., 2020;Kumar, 2019;Yousuf et al., 2018). They can form a film layer on the food's surface directly by dipping or spraying and then drying or fabricated into stand-alone thin-layer films to be used as wraps (Valencia-Chamorro et al., 2011). The stand-alone films are mainly employed to test the techno-functional properties of a coating or film-forming solution. Further, film-forming solutions can be used for direct coating of foods; however, it is necessary to adjust the polymeric concentration according to the intended application. In food coating applications, the thin-layer film formed on the outer surface serves as a protective barrier between the food and its environment, and the film's protective performance depends on the techno-functional properties of the mucilage matrix. The barrier properties of a mucilage may offer discriminate permeability of gases ($O_2$ and $CO_2$), delaying metabolic reactions such as oxidation and ripening associated with quality loss and food spoilage (Dhall, 2013). On the other hand, the film's control of water vapor permeability prevents surface dehydration, reducing quality loss in terms of weight and firmness. Furthermore, mucilage films provide mechanical protection during product distribution and storage and restrict UV light penetration, ensuring the integrity of the product and limiting the loss of light-sensitive compounds through light-catalyzed oxidation, respectively (Aguirre-Joya et al., 2018;Kumar, 2019).

Mucilage intended for developing edible coating or film is expected to have suitable properties, including functional (e.g., viscosity and solubility) and film-forming properties (e.g., wettability and spreadability), to form a uniform and thick film on the surface of the food (Kumar, 2019;Moncayo et al., 2013). The rheological characteristics of a mucilage solution impact important film-forming parameters such as spreadability (Ekrami & Emam-Djomeh, 2014) and are crucial in determining the form of application, i.e., dipping, spraying, or spread-coating (Olawuyi et al., 2020). For instance, a less viscous coating solution is preferred for a spray-coating process, whereas a more viscous solution is suitable for dipping and spread-coating (Zhong et al., 2014). In addition, as they are often used as aqueous solutions, the solubility of mucilage in water is important for the preparation of coating and film-forming solutions. Most plant mucilages are hydrophilic and dissolve readily in cold water to form colloidal solutions, which are often more soluble at elevated (∼60 °C) temperatures, and in some cases less soluble in other solvents (Kalegowda et al., 2017). The solubility of mucilage polysaccharide in water or other aqueous medium is governed by the strength of interaction between their hydrophilic groups and that of the solvent, via hydrogen bonding. Thus, the determination of the optimum solubility of each mucilage helps to achieve maximum functionality (Kamel et al., 2020).

Other crucial functional properties of mucilages include their ability to stabilize emulsifying and encapsulating properties. Mucilage can encapsulate and stabilize oil/water emulsions owing to their surface activity and interfacial absorption properties, thereby preventing coalescence in oils by forming strong multi-molecular anchors around oil droplets (Prajapati et al., 2013). Some studies have produced emulsified films of mucilage and various oils (Capitani et al., 2016;Jouki, Mortazavi, et al., 2014;Niknam et al., 2019;Rodrigues et al., 2016). Moreover, when mucilages are used as active carriers for compounds, such as antimicrobial agents, they may result in the gradual release of active components on the surface of the food, thereby prolonging preservative effects (Bill et al., 2014;Hashemi et al., 2017). Furthermore, MEPs can be consumed along with food when used as edible coatings and may also contain acceptable food additives, such as antimicrobials, primarily incorporated to extend shelf life, as outlined in the U.S. FDA's safety requirement for edible coating and food contact materials (Aguirre-Joya et al., 2018;Werner et al., 2017). Moreover, studies on sensory effects and toxicity (in vivo animal assay) have indicated insignificant sensory defects (Yousuf & Srivastava, 2017) and nontoxicity associated with the application of mucilage as edible packages (Araújo et al., 2018).

In summary, the properties of mucilages in aqueous solution are determined by various factors, such as macromolecular and structural characteristics, which include extraction conditions used to obtain the mucilage and are not only limited to the sources (Adeli & Samavati, 2015;Martin et al., 2017;Sims et al., 2018).

## 3. Mucilage structure–function properties and relationships

Considering that the functionalities of polysaccharides are affected by their respective structural and macromolecular properties, a better understanding of these properties helps predict their subsequent applications (Olawuyi & Lee, 2021). However, owing to the structural diversity and complexity of mucilage polysaccharides, a clear understanding of the relationships between their chemical structures and functional properties is yet to be well established (Ji et al., 2017). Mucilages are heteropolysaccharides comprising two or more repeating units of sugars, such as arabinose, galactose, mannose, xylose, glucose, rhamnose, and galacturonic acid, together with glycosidic linkages that form highly diversified structural-chain configurations (Fig. 1B). Mucilages obtained from various plants have been reported to contain one or more structural units of galactomannan, rhamnogalacturonans, arabinogalactan, arabinan, glucomannan, xylan, galactan, arabinoxylan, glucoxylan, glucan, and xylogalacturonan (Table 1). Most studies on the application of mucilage for coating and film development employed their crude form (unpurified), without elucidating their detailed structure, making it difficult to draw clear conclusions on the structure–function relationships and impeding appropriate comparisons with other works. Nonetheless, this section summarizes some basic structural–function relationships with regards to polysaccharide functionalities applicable to the development of edible packages.

The functional properties of polysaccharides are substantially affected by a variety of factors, including molecular size and distribution; structural linkages; extent and degree of branching; monomeric composition; and the presence of hydrophobic groups (e.g., *O*-acetyl, *O*-methyl, proteins, and phenolic acids), which can be tailored by tuning the extraction protocols (Hung & Lai, 2019;Kontogiorgos et al., 2012;Yu et al., 2017). With regards to coating and film development, the solubility and rheological and film-forming properties of a polymer are important functional parameters to be considered.

The molecular weight of polysaccharides is related to the rheological behavior in aqueous solutions, which is an important functional factor for edible coating/film-forming solutions (Dhall, 2013;Naji-Tabasi & Razavi, 2017). For example, high molecular weight polysaccharides possess larger polymeric moieties which form higher intermolecular associations and create more cohesive strength that increases the thickening effects and viscosity of the solution (Janjarasskul & Krochta, 2010). However, a high intermolecular association often results in poor solubility of a polysaccharide (Guo et al., 2017). Polysaccharides contain hydrophilic moieties and other polar groups uniformly distributed in their polymer chains, which form intermolecular associations and determine their characteristics in aqueous solutions (Guo et al., 2017). Similarly, the rheology of polysaccharides is affected by their side-chain length (Bai et al., 2020). Okra polysaccharides with longer side-chains showed higher viscosity due to a better intermolecular interaction, which led to more molecular entanglement. While inter chain entanglements are greatly disrupted in short side-chained polysaccharides (Nie et al., 2019).

Furthermore, the structural-chain configurations of polysaccharides (i.e., compositional ratio, side-chain substituents, and the degree of branching) need to be taken into consideration to understand the contributions of chain entanglements and intermolecular interactions, which alter their functionalities (Patova et al., 2014;Yu et al., 2017). A previous study on galactomannan-based films produced from five plant sources reported substantial variations in film properties depending on the compositional ratio of mannose to galactose (M/G) and galactose side-chain distribution in galactomannan (Dos Santos et al., 2015). In

**Table 1**
Characteristics and application of mucilages obtained from various plant parts.

| Plant part | Plant name | Structural component | Molecular weight (kDa) | Forms of application | Reference |
|---|---|---|---|---|---|
| Seeds | Sage (*Salvia macrosiphon*) | Galactomannan | 400 | Film | (Razavi et al., 2015) |
| | Pepperweed (*Lepidium perfoliatum*) | | | Film | (Seyedi, Koocheki, Mohebbi, & Zahedi, 2014, 2015) |
| | Quince (*Cydonia oblonga*) | | $9.61 \times 10^3$ | Film | (Jouki, Mortazavi, et al., 2014;Jouki, Yazdi, et al., 2013; Rezagholi et al., 2019) |
| | Flax (*Linum usitatissimum*) | Rhamnogalacturonans | $1.47–1.51 \times 10^3$ | Film and coating | (Kaewmanee et al., 2014; Qian, Cui, Wu, & Goff, 2012) |
| | Balangu (*Lallemantia iberica*) | Arabinogalactan | $1.19–1.55 \times 10^3$ | Film | (Sadeghi-Varkani et al., 2018;Behbahani & Fooladi, 2018) |
| | Moldavian dragonhead (*Dracocephalum moldavica*) | | | Film | (Beigomi et al., 2018) |
| | Basil (*Ocimum basilicum* L.) | Glucomannan, Xylan | $1.05–5.98 \times 10^3$ | Film and coating | (Khazaei et al., 2014;Hashemi et al., 2017; Naji-Tabasi & Razavi, 2017) |
| | Cress (*Lepidium sativum*) | Galactomannan | 540 | Film | (Karazhiyan et al., 2011) |
| | Chia (*Salvia hispanica* L.) | | $0.8–2.0 \times 10^3$ | Film | (Muñoz et al., 2012) (Dick et al., 2015) |
| | Qodume Shirazi (*Alyssum homolocarpum*) | Galactan | $0.37–122.5 \times 10^3$ | Film | (Marvdashti et al., 2017;Nafchi et al., 2017) |
| | Psyllium (*Plantago ovata*) | Arabinoxylan | $1.5 \times 10^3$ | Film and coating | (Tóth & Halász, 2019;ur Rehman et al., 2015) |
| | Shameplant (*Mimosa pudica*) | Glucoxylan | | | (Ahuja, Kumar, Yadav, & Singh, 2013) |
| | Tamarind (*Tamarindus indica* L.) | Glucan | 720–880 | | (Alpizar-Reyes et al., 2017) |
| | Cereus (*Cereus triangularis*) | Arabinogalactan | $8.43 \times 10^3$ | | (Petera et al., 2015) |
| | Fenugreek (*Trigonella foenum-graecum* L.) | Galactomannan | ~30 | Film | (Memiş et al., 2017;Saha et al., 2017) |
| | Mesquite (*Prosopis flexuosa*) | Galactomannan | $1.2 \times 10^3$ | Film | (D. C.Rodrigues et al., 2016; López-Franco, Cervantes-Montaño, Martínez-Robinson, Lizardi-Mendoza, & Robles-Ozuna, 2013) |
| | Cassia (*C. obtusifolia* and *C. tora*) | Galactomannan | 514 | Film | (Huang, Chow, & Tsai, 2012) |
| | Barhang (*Plantago major*) | Galactomannan | $1.2 \times 10^3$ | | (Behbahani et al., 2017) |
| | Linseed (*Linum usitatissimum*) | | | | (Treviño-Garza et al., 2017) |
| | Mutamba (*Guazuma ulmifolia*) | Gal:Rha:GalA:GlcA:Glc (33:21:19:19:8) | | | (Pereira et al., 2019) |
| Fruits | Okra (*Abelmoschus esculentus*) | Rhamnogalacturonan-I, Homogalacturonan | 193 | Film | (Araújo et al., 2018;Olawuyi et al., 2020) |
| | Cordia (*C. myxa and C. obliqua*) | | 22.3 | Film | (Haq et al., 2014; Keshani-Dokht, Emam-Djomeh, Yarmand, & Fathi, 2018) |
| | Jujube (*Ziziphus lotus*) | Rhamnogalacturonan-I | 86–160 | | (Adeli & Samavati, 2015) |
| | Baobab (*Adansonia digitata* L.) | Xylogalacturonan | 19–42 | | (Alba, Offiah, Laws, Falade, & Kontogiorgos, 2020;Ji et al., 2017) |
| | Barbados gooseberry (*Pereskia aculeata*) | Arabinogalactan | | | (Silva et al., 2019) |
| Root, Tuber, & Rhizome | Taro (*Colocasia esculenta*) | Arabinogalactan | | | (Andrade, de Oliveira Silva, Nunes, & Pereira, 2020) |
| | Palmate-tuber salep (*Orchis*) | Glucomannan | | Film | (Ekrami et al., 2019) |
| | Yam (*Dioscorea opposita*) | Glc:Man:Gal:Xyl (50:33:11:5) | 143.7 | Film | (Ma et al., 2017;Wang et al., 2020) |
| Stem | Spinach (*Basella alba*) | Gal:Glc:Ara:Rha:GalA (39:16:28:4:12) | $2.39 \times 10^3$ | | (Hung & Lai, 2019) |
| Cladodes (leaflike stem) | Cactus (*Opuntia dillenii, Opuntia robusta, Opuntia monacantha, Opuntia spinulifera, Opuntia ficus-indica*) | Arabinogalactan; Rhamnogalacturonan | $3.67 \times 10^3$ | Film and coating | (Bernardino-Nicanor et al., 2018;Gheribi & Khwaldia, 2019;Madera-Santana et al., 2018;Rodríguez-González et al., 2014) |
| Leaves | *Aloe vera* (*A. barbadensis* and *A. arborescens*) | Galactan, Glucomannan, Arabinan, Rhamnogalacturonan | 202 | Coating | (Sogvar et al., 2016;Hassanpour, 2015; Guillén et al., 2013;Shi et al., 2018) |
| | Spinach (*Basella alba*) | Gal:Glc:Ara:Rha:GalA (39:15:36:6:4) | $1.91 \times 10^3$ | | (Hung & Lai, 2019) |
| | Lacebark (*Hoheria populnea*) | Rhamnogalacturonan | $1.8–3.0 \times 10^3$ | | (Sims et al., 2018) |
| | Barbados gooseberry (*Pereskia aculeata*) | Arabinogalactan | 790 | Films | (Martin et al., 2017; Oliveira et al., 2019) |
| | Baobab (*Adansonia digitata* L.) | Homogalacturonan; Rhamnogalacturonans | 74–205 | | (Alba et al., 2020) |
| | *Asplenium australasicum* fronds | Gal:Man:Glc:Ara:Xyl:Fuc:Rha:GlcA:GalA (24:8:7:12:13:23:2:10:3) | $0.13–7.68 \times 10^3$ | | (Zeng & Lai, 2016) |
| | Okra (*Abelmoschus esculentus*) | Rhamnogalacturonan-I | $0.26–1.6 \times 10^3$ | | (Li et al., 2017;Olawuyi & Lee, 2021) |

particular, highly-branched galactomannan films with larger contents of galactose units along the mannan backbone chain (M/G values of 1.7–2.9) presented high water vapor permeability (WVP) due to the formation of interchain space, which promoted the diffusion of water molecules (Cerqueira et al., 2012;Dos Santos et al., 2015). However, at M/G values above 3 (low galactose substituents and high number of unlinked mannan units), low WVP was observed owing to increased intermolecular forces between the mannan backbone and a densely-packed structure restricting the diffusion of water molecules (Albuquerque et al., 2016;Dos Santos et al., 2015). Another study revealed that the arabinose to xylose ratio (A/X) and side-chain distribution of arabinose substituents in arabinoxylans (AXY) from *Plantago ovata* are key factors responsible for their distinct rheological properties (Yu et al., 2017). The authors further explained that in aqueous solution, the arabinose side-chain hydrogen-bond interactions are directly involved in the gel-forming capacity of *P.ovata* AXYs. Thus, highly branched mucilage extracts with high A/X ratio (0.30 & 0.33) showed gel-like behaviors, in contrast to that of low A/X ratio of 0.20, which exhibited viscoelastic fluid properties in aqueous solution (Yu et al., 2017).

Furthermore, branching along a polymer backbone weakens intramolecular interactions due to steric effects and affects solubility and flow behavior of polysaccharides by preventing intermolecular associations and chain entanglements, thereby resulting in chain flexibility and easy penetration of water molecules through intermolecular spaces (Guo et al., 2017;Patova et al., 2014). In contrast, most linear polysaccharides exhibit highly regular chain conformations, a higher radius of gyration, and entanglement, thereby resulting in higher viscosity and better film-forming properties compared with those of branched polysaccharides of similar molecular weights (Patova et al., 2014).

In basil seed mucilage consisting of both hydrophobic glucomannan (~43%) and hydrophilic xylan (~24%) fractions, a higher proportion of glucomannan tends to increase the hydrophilicity of the mucilage solution, which is consequently favorable to hydrophobicity-dependent properties of films, such as low water solubility, water permeability, and oxygen permeability (Khazaei et al., 2014;Razavi et al., 2015). The structural hydrophobic–hydrophilic proportion of galactomannan has been reported to determine important functional properties and the possible food-related applications of galactomannan (Prajapati et al., 2013).Dos Santos et al. (2015) reported that films with more water resistance can be produced from galactomannan polysaccharides containing higher proportions of hydrophobic mannans in the galactomannan structure due to changes in the crystalline arrangement of films. Moreover, the presence of hydrophobic groups such as proteins, phenolic acids, acetyl and methyl esters, and charged carboxyl groups in the structural units of mucilage containing pectic polysaccharides have been associated with various functional properties, such as emulsifying property, solubility, and viscosity, owing to intermolecular associations of hydrophobic portions in solution (Kontogiorgos et al., 2012;Olawuyi & Lee, 2021;Shi et al., 2018). A proportional increase in charged carboxyl groups of uronic acid was found to increase coil dimensions, which favors pseudoplastic behavior of polysaccharide solutions (Kontogiorgos et al., 2012;Olawuyi et al., 2020). Overall, the knowledge of structural and functional relationships of mucilage polysaccharides is important to predict their techno-functional properties when used as edible packages.

## 4. Additive modification of techno-functional properties of MEPs

Compared to other synthetic polymers, the use of plant mucilage to develop edible packages is often limited in terms of their mechanical and barrier properties (Jouki, Yazdi, et al., 2013;Khazaei et al., 2014). Moreover, some mucilage solutions may be used by themselves to fabricate films with acceptable properties (Mohite, 2020), whereas

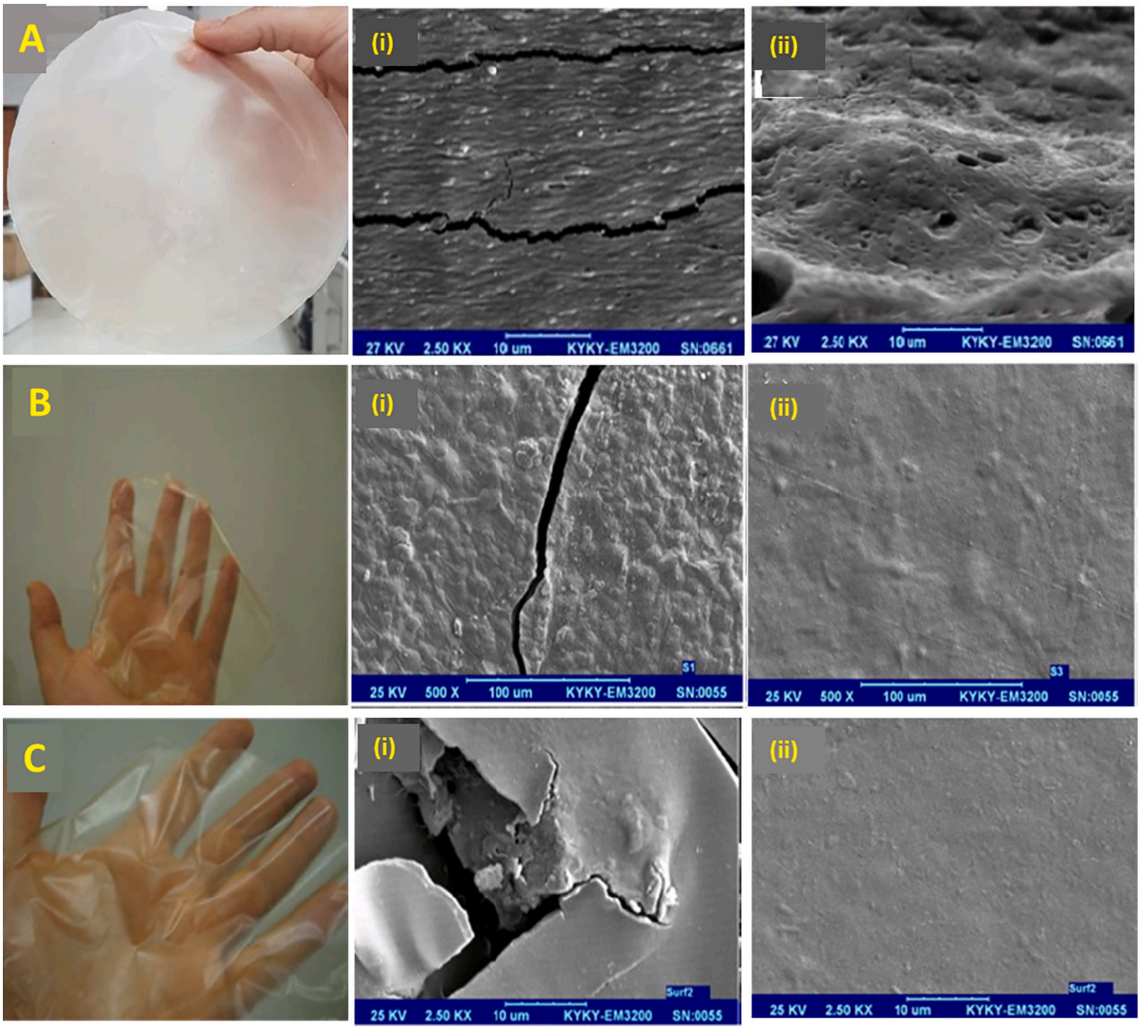

**Fig. 2.** Mucilage-based films fabricated from A) Moldavian dragonhead (Beigomi et al., 2018), B) Basil (Khazaei et al., 2014), C) Quince seeds (Jouki, Yazdi, et al., 2013). Alphabets in parentheses represent corresponding scanning electron microscopic images of the outer surfaces of films (i) without plasticizers/additives and (ii) with plasticizers/additives. Permission for images obtained from Elsevier.

others may require the addition of plasticizers and other components (Gheribi et al., 2018).Fig. 2A shows the microstructure observation of thin-layer films fabricated from mucilages with or without the addition of plasticizers. To reduce rigidity and produce ductile film wraps with smooth and uniform surface morphology, additives are usually incorporated into the mucilage matrix. However, this is not mandatory for their direct food coating application. Generally, mucilages intended for MEP development are fabricated into thin-layer films to assess certain techno-functional properties, which predict their preservative performance. Over the years, the modification of MEPs' techno-functional properties has been extensively studied (Table 2) and will be discussed in detail in this section.

### *4.1. Oxygen and water vapor barrier properties*

Gaseous permeability of an edible package influences its preservative performance as $O_2$ consumption and $CO_2$ accumulation are critical factors in the spoilage of fresh produce (Park et al., 2020). Furthermore, the effectiveness of a preservative package is measured by its ability to selectively control internal gas exchange (Olawuyi & Lee, 2019). A lower $O_2$ level and a higher $CO_2$ level inside a fruit helps control enzyme and microbial activities, contributing to quality retention in the coated product during storage (Sapper & Chiralt, 2018). Mucilage possesses good oxygen barrier property due to its compact hydrogen-bond network, and further modifications have been investigated (Jouki, Yazdi, et al., 2013). The addition of glycerol to mucilage solutions obtained from flaxseed, Qodume Shirazi seed, and *Cordia myxa* fruit was reported to increase oxygen permeability of the corresponding mucilage films (Haq et al., 2014;Nafchi et al., 2017;Tee et al., 2017;Wang et al., 2011). Similar results were observed in films containing sorbitol, polyethylene glycols, and lipids; however, the increases in oxygen permeability were relatively low compared to glycerol (Ekrami & Emam-Djomeh, 2014;Gheribi et al., 2018;Jouki, Yazdi, et al., 2014;Razavi et al., 2015).

The addition of polyvinyl alcohol (PVA) polymer was observed to decrease the oxygen permeability of Qodume Shirazi seed films (Marvdashti et al., 2017). This is due to an increased association between the polymer chains, and the modification of the polymer structure by PVA, which affected the polymer-free volume and resulted in the reduction of the film's oxygen permeability (Jouki, Yazdi, et al., 2013;Marvdashti et al., 2017). In addition, surface morphology revealed high compatibility of both polymer blends to form a homogeneous, dense, and thick film structure, which provided much better oxygen barrier properties (Marvdashti et al., 2017). Similar effects have been observed for polymer/PVA composite films (Cano et al., 2015;Wang et al., 2015). Increasing the amount of nanoclay was also reported to decrease oxygen permeability of fenugreek seed films, as measured by its ability to reduce the level of peroxidation in stored sunflower oil (Memiş et al., 2017).

Generally, the structure of polymer chains and the plasticizer distribution within the matrix play a significant role in the gas permeability of plasticized films. Also, the physical state and molecular weight of the plasticizer, the chemical interaction of the plasticizer with oxygen, and the type of film structure (i.e. crystallinity, density, orientation, and the molecular weight of polymer), affects the oxygen permeability of plasticized films (Jouki, Yazdi, et al., 2013). The increase in oxygen permeability by the addition of these materials results from their molecular dispersion, which increases free volumes within the mucilage networks (Seyedi et al., 2014;Tee et al., 2017). On the contrary, a reduction in gas permeability results from the formation of aggregates within the mucilage network that results in a denser and more compact structure (Lira-Vargas et al., 2014;Memiş et al., 2017).

WVP of an edible package is important for food storage because it directly affects transpiration rate and deteriorative reactions (Beigomi et al., 2018). Mucilages are hydrophilic by nature; therefore, MEPs generally have a low water vapor barrier. Alterations in WVP using different plasticizers and other materials have been reported (Table 3). Plasticizers, such as glycerol, PEG, and sorbitol, are consistently observed to increase WVP due to their hydrophilic properties, which increase intermolecular spacing and readily allow water diffusion across the film (Sadeghi-Varkani et al., 2018). No significant changes were observed in WVP of flaxseed mucilage films when polyvinyl alcohol (PVA) was added (de Paiva et al., 2020). However, WVP was found to increase in films made of cactus or Qodume Shirazi mucilages (Gheribi et al., 2019;Marvdashti et al., 2017). Lipids, such as olive, maize, and canola oils (Niknam et al., 2019); beeswax (Lira-Vargas et al., 2014); fatty acids (Amini & Razavi, 2020;Seyedi et al., 2015); and some essential oils (Ekrami et al., 2019;Hashemi et al., 2017), have been shown to decrease WVP of mucilage films. However, the data on the effects of essential oils on WVP is inconsistent. WVP of quince seed mucilage films was observed to increase with increasing concentrations of thyme and oregano essential oils (Jouki, Mortazavi, et al., 2014;Jouki, Yazdi, et al., 2014), likely due to the hygroscopic properties of the oils. In addition, corn and taro starches (Araújo et al., 2018;Mohite, 2020), gelatin, whey proteins (Lira-Vargas et al., 2014;Muñoz et al., 2012), and nanomaterials (Memiş et al., 2017;Shekarabi et al., 2014) have been used to produce mucilage films with low WVP. Generally, changes in WVP mostly depend on the hydrophilic and hydrophobic portions of a film-forming solution. Attenuation of the hydrophilic portion by addition of hydrophobic materials is expected to decrease WVP of fabricated films and vice versa. While hydrophilic materials increase film porosity (Sadeghi-Varkani et al., 2018), the incorporation of hydrophobic materials tends to close microvoids and reduce water vapor passage (Vieira et al., 2011).

Generally, a suitable package for preservation of fruits and vegetables requires less permeation of water vapor and oxygen; therefore, modifying MEPs to achieve adequate oxygen and water barrier properties would help in preventing respiration-induced spoilage and the loss of food mass and water-soluble nutrients by transpiration.

### *4.2. Physical properties*

The physical properties of an edible package, such as transparency and water solubility, affect the consumers' experience with the food. The transparency of a package may influence the consumers' perception of the food (Gheribi et al., 2019). Transparent packages are often preferred because they do not alter the food's visual appearance but still enable monitoring of quality changes, especially in fresh-cuts, during storage. Thus, an opaque film or package may not be suitable for fruit and vegetable storage (Amini & Razavi, 2020). However, a less transparent or translucent package may provide a light barrier, restricting the oxidation of light-sensitive compounds and discoloration in some foods (Gheribi et al., 2019;Mohite, 2020). Generally, the inclusion of common plasticizers, such as glycerol, PVA, and sorbitol, has been reported to increase the transparency of mucilage-based films (Jouki, Yazdi, et al., 2013;Nafchi et al., 2017). On the other hand, the addition of lipids, proteins, and starch produces films with increased translucency (Araújo et al., 2018;Lira-Vargas et al., 2014).

Modification of water solubility and hygroscopic properties (moisture uptake) of mucilage-based films is based on their hydrophilic and hydrophobic properties. For example, addition of hydrophilic polyol plasticizers, such as glycerol, sorbitol, PEG, and PVA, increases the film's hydrophilicity and consequently enhances its water solubility (Ahmadi et al., 2012;Beigomi et al., 2018;Razavi et al., 2015). Conversely, the incorporation of hydrophobic materials, including lipids (Niknam et al., 2019;Seyedi et al., 2015), proteins (Capitani et al., 2016;Muñoz et al., 2012), and nanofibers (Mujtaba, Akyuz, et al., 2019), decreased water solubility and moisture uptake of mucilage-based films.

Adding hydrophilic or hydrophobic materials to the polymer matrix alters intermolecular chain interactions and affects the dissolubility of polymers in water (Haq et al., 2014). Thus, an increase or decrease in water solubility and hygroscopicity of a polymer film is proportionally influenced by a high or low hydrophilic/hydrophobic ratio of the

**Table 2**
Recent improvements in the properties of mucilage-based films.

| Category | Plasticizer/material type | Mucilage source | Significant/observed effects[a,b] | Reference |
|---|---|---|---|---|
| Common Plasticizers | Glycerol | Balangu (*Lallemantia iberica*) seeds | WVP, OP, WS, EAB, and thickness of films were increased. Increase in EAB and the corresponding decrease in TS. Increased transparency and light color of films | (Sadeghi-Varkani et al., 2018) |
| | | Moldavian dragonhead (*Dracocephalum moldavica*) seeds | | (Beigomi et al., 2018) |
| | | Basil (*Ocimum basilicum* L.) seeds[c] | | (Khazaei et al., 2014) |
| | | Pepperweed (*Lepidium perfoliatum*) seeds | | (Seyedi et al., 2014) |
| | | Quince (*Cydonia oblonga*) seeds | | (Jouki, Yazdi, et al., 2013) |
| | | Flax (*Linum usitatissimum*) seeds[c] | | (Tee et al., 2017; Wang et al., 2011) |
| | | Psyllium (*Plantago ovata* Forsk) seeds | | (Ahmadi et al., 2012) |
| | | Honey locust (*Gleditsia triacanthos*) seeds[c] | | (Cerqueira et al., 2012) |
| | | Cress (*Lepidium sativum*) seeds[c] | | (Jouki, Khazaei, et al., 2013) |
| | | Chia (*S. hispanica* L.) seeds[c] | | (Dick et al., 2015) |
| | | Qodume Shirazi (*Alyssum homolocarpum*) seeds[c] | | (Nafchi et al., 2017) |
| | Glycerol, Sorbitol, and Polyethylene glycol (PEG-400) | Sage (*Salvia macrosiphon*) seeds | All polyol plasticizers showed similar trends in increasing hydrophilicity, WS, WVP, OP EAB, and thickness of films, which was significantly higher and lower in glycerol and PEG, respectively. TS of films were reduced, with PEG-400 having more fragility | Razavi et al. (2015) |
| | | *Cordia myxa* fruit | | (Haq et al., 2014) |
| | | Cactus cladodes (*Opuntia ficus-indica*)[c] | | (Gheribi et al., 2018) |
| | | Psyllium (*Plantago ovata*) seeds | | (Tóth & Halász, 2019) |
| | Polyvinyl alcohol | Cactus (*Opuntia ficus-indica*) cladodes[c] | Increased WVP and thickness, WS decreased. Increased EAB without a significant decrease in TS | (Gheribi et al., 2019) |
| | | Qodume Shirazi (Alyssum homolocarpum) seeds[c] | Increased thickness, moisture resistance (WVP), WS, and decreased OP of films | (Marvdashti et al., 2017) |
| | | Flax (*Linum usitatissimum* L.) seed[c] | No effects on WVP, TS decreased, EAB and opacity increased | (de Paiva et al., 2020) |
| Lipids | Palmitic, Stearic, and Oleic acids | Sage (*Salvia macrosiphon*) seeds | Fatty acids increased hydrophobicity, opacity, and TS, whereas WVP and EAB decreased | (Amini & Razavi, 2020) |
| | Stearic and Palmitic acids | Pepperweed (*Lepidium perfoliatum*) seeds | Lowered WS, WVP, TS, and EAB, and increased hydrophobicity of films | (Seyedi et al., 2015) |
| | Corn oil | Honey locust (*Gleditsia triacanthos*) seeds[c] | WS, WVP, and EAB increased, whereas TS decreased | (Cerqueira et al., 2012) |
| | Palm fruit oil | Mesquite (*Prosopis juliflora*) seeds[c] | Increased opacity and hydrophobicity and EAB. Reduced TS, WS, and WVP | (D. C.Rodrigues et al., 2016) |
| | Olive oil, Maize oil, Canola oil | Barhang (*Plantago major*) seeds | Plant oils showed similar effects in increasing the thickness and EAB and reduced TS, moisture content, and WVP | (Niknam et al., 2019) |
| | Pennyroyal (*Mentha pulegium*) essential oil | Palmate-tuber salep (*Orchis*)[c] | Higher hydrophobicity, thickness, EAB, and OP. WVP, TS, WS, and transparency decreased. Showed substantial biological activities | (Ekrami et al., 2019) |
| | Thyme essential oil | Quince (*Cydonia oblonga*) seeds | Reduced WS, TS, and lightness. WVP, OP, EAB, thickness, and biological activities increased | (Jouki, Mortazavi, et al., 2014) |
| | *Origanum vulgare* essential oil | Basil (*Ocimum basilicum L*) seeds[c] | Reduced WVP and enhanced biological activities | (Hashemi et al., 2017) |
| | Oregano essential oil | Quince (*Cydonia oblonga*) seeds | Thickness, WVP, OP, and EAB increased, whereas TS decreased. Increased biological activities | (Jouki, Yazdi, et al., 2014) |
| | Clove essential oil | Chia (*Salvia. Hispanica* L.) seeds[c] | Reduced transparency and TS and EAB. Bacterial inhibition increased | (Capitani et al., 2016) |
| | Beeswax | Cactus (*Opuntia ficus-indica*) cladodes | Beeswax films increased TS and decreased OP and WVP | (Lira-Vargas et al., 2014) |
| Starch | Corn starch | Okra (*Abelmoschus esculentus*) pods | Increased thickness and WVP. Lowered WS and TS, no effect on EAB | (Araújo et al., 2018) |
| | Taro starch | Fenugreek (*Trigonella foenum-graecum* L.) seeds[c] | Opacity, TS, EAB, and WVP reduced | (Mohite, 2020) |
| | Modified starch (wheat acylation starch) | Psyllium (*Plantago ovata*) seeds | EAB and thickness increased, WS, WVP, and TS decreased | (Sadeghi-Varkani et al., 2018) |
| Protein | Whey protein concentrate (WPC) | Chia (*Salvia. Hispanica* L.) seeds[c] | WVP, WS were reduced, while lightness, TS, and EAB were increased | (Muñoz et al., 2012) |
| | Chia seed Protein | Chia (*Salvia. Hispanica* L.) seeds[c] | Lowered transparency and WS. TS increased, decrease in water content, and improved thickness of films as protein increased | (Capitani et al., 2016) |
| | Gelatin | Cactus (*Opuntia ficus-indica*) cladodes[c] | Increased TS and decreased WVP, $O_2$, and $CO_2$ permeability | (Lira-Vargas et al., 2014) |

(*continued on next page*)

Table 2 (*continued*)

| Category | Plasticizer/material type | Mucilage source | Significant/observed effects[a,b] | Reference |
|---|---|---|---|---|
| Nanomaterial | Nanoclays; Na + montmorillonite (MMT); Halloysite, (HNT); Nanomer® I.44 P (NM) | Fenugreek (*Trigonella foenum-graecum* L.) seeds[c] | Nanoclay decreased OP. No significant effect on thickness and lightness. TS increased, and EAB decreased | (Memiş et al., 2017) |
| | Starch nanocrystals | Chia (*Salvia. Hispanica* L.) seeds[c] | Reduced transparency, hydrophobicity, TS, and EAB. Increased biological activities | (Mujtaba, Koc, et al., 2019) |
| | Cellulose nanofibers | Chia (*Salvia. Hispanica* L.) seeds[c] | Transparency and WS decreased. Hydrophobicity and thickness, and TS increased without a reduction in EAB. Improved biological activities | (Mujtaba, Akyuz, et al., 2019) |
| | Nanoclay; Cloisite 30B | Quince (*Cydonia oblonga*) seeds | Increase in the TS and EAB. Reduced OP and WVP. WS decreased | (Shekarabi et al., 2014) |

[a] TS, tensile strength; WS, water solubility; EAB, elongation at break; WVP, water vapor permeability; OP, oxygen permeability.

[b] Biological activities include antioxidant and antimicrobial activities.

[c] Mucilage feasible for stand-alone film preparation without additives.

polymer matrix, respectively. Therefore, it is essential to consider the purpose and intended application of a package before deciding on the mucilage for modification. Due to the high moisture content of fruits and vegetables, a low water-soluble package can be used to maintain film integrity. Alternatively, if the package is not intended to be consumed with food, a water-soluble package may be used for easy removal.

### 4.3. Mechanical properties

The ability of films to protect food is crucial in extending the food's shelf life. Various plasticizers, lipids, and other materials have been added to mucilage films to modify their crucial mechanical properties such as flexibility, tensile strength, and thickness (Table 3). The flexibility of films is estimated by measuring their elongation at break (EAB) or their stretchability upon applied stress. In most cases, the addition of plasticizers and other lipids to the mucilage solution increased the thickness and flexibility of the films but reduced the tensile strength (TS) (de Paiva et al., 2020;Jouki, Mortazavi, et al., 2014;Khazaei et al., 2014; Tóth & Halász, 2019). However, the inclusion of whey protein and nanoclay in mucilage solutions was observed to simultaneously improve these mechanical properties of mucilage films (Muñoz et al., 2012; Shekarabi et al., 2014), which are favorable for edible packages intended to preserve the structural integrity of food (Niknam et al., 2019). The structural examination of modified films by SEM microscopy revealed that the addition of plasticizers and other components increased intermolecular spacing and chain mobility between adjacent polymeric chains, thereby expanding the structure and volume of polymers and enhancing the flexibility and thickness of films (Fig. 2A) (Razavi et al., 2015;Sadeghi-Varkani et al., 2018;Tahir et al., 2019).

The thickness of the film formed on the surface of a coated product is influenced by the film's wetting properties, such as the spreading and adhesive coefficients, as well as the film's interaction with the product's surface (Moncayo et al., 2013;Sapper & Chiralt, 2018). It was thought that a mucilage solution with good wetting properties would produce a thicker surface film layer, consequently improving the film's barrier properties and preservative effects (Sapper & Chiralt, 2018). Therefore, understanding the wetting properties of a mucilage solution and the surface properties of a product is crucial before the coating is applied. It is necessary to modify a mucilage solution's wetting properties in terms of polarity, like hydrophobicity and hydrophilicity, to improve the film's compatibility with the product surface and maximize the preservative potential of a mucilage solution. The modification of wetting properties of commonly used coating polymers, such as chitosan, with plasticizers has been studied to improve the polymers' compatibility with fruit surface (Skurtys et al., 2011;Vieira et al., 2016). However, the number of studies on mucilage-based coating solutions is limited.

In summary, this section has reviewed the modification of different techno-functional properties of mucilage-based films, which helps improve desired properties. The variation in the results from the studies can be attributed to specific structural characteristics of different mucilages in addition to the types and concentrations of materials added to mucilage matrices. Therefore, it is advisable to undertake an initial study to characterize and optimize individual mucilage matrices before applying them for fruit and vegetable packaging.

## 5. Recent application of mucilage in fresh produce preservation

Fruits and vegetables are highly perishable and prone to rapid quality deterioration during storage. Additionally, mechanical injury or bruising during harvest and transportation contributes to their poor storability. Hence, postharvest practices that retain quality and delay spoilage are necessary for extended storage (Qadri et al., 2016). The application of an edible coating has been a reliable method to preserve produce (Olawuyi et al., 2019;Yousuf et al., 2018). The preservative properties of mucilage-based packaging, such as antimicrobial activity and barrier properties, have been evaluated in vitro using fabricated films and in vivo by applying a coating onto products (Fig. 3). This section focuses on the MEPs derived from aloe, linseed, Plantago, cactus, basil, and other mucilages that have been successfully employed as edible coatings on fruits and vegetables (Table 2).

### 5.1. Aloe mucilage

The utilization of *Aloe vera* mucilage (AVM) by itself or with other components to preserve various fresh-cut or whole fruits has been extensively reported (Misir et al., 2014). At various concentrations, AVM coating can reduce metabolic activities such as respiration and ethylene synthesis. Furthermore, AVM can help maintain texture and color qualities, minimize weight loss, and suppress bacterial and fungal growth in a wide range of produce during storage (Ali et al., 2019; Benítez et al., 2013;Ergun & Satici, 2012;Hassanpour, 2015;Sophia et al., 2015). For instance,Guillén et al. (2013) compared the mucilage's effectiveness from two aloe species (*A. vera* and *A. arborescens*) on peach and plum during 7 days of storage at 20 °C. Both aloe coatings substantially improved the storage properties of both fruits. However, *A. arborescens* was more effective than the commonly used *A. vera*. The difference in the observed effects was attributed to the different physicochemical properties of the mucilages, such as hydrophobicity, which favored adhesion and barrier properties and improved the preservative performance of the mucilage coating (Guillén et al., 2013;Zapata et al., 2013).

The incorporation of additives, such as ascorbic and citric acid, has been used to improve the preservative efficiency of AVM coatings. The coating containing 5% (w/v) ascorbic acid effectively maintains the postharvest quality of strawberries and suppresses aerobic mesophilic bacterial and fungal growth (Sogvar et al., 2016). Some researchers have equally considered the use of both ascorbic and citric acid (0.5%–1% w/v) incorporated in AVM and observed an extended shelf life for pomegranate arils and fig fruits due to delayed tissue degradation, ripening, and microbial spoilage. They also found the coated fruits to retain better

**Table 3**
Preservative effects of mucilage-based coatings on stored fruits and vegetables.

| Mucilage source | Active component/ material | Form of coating | Food matrix | Preservative effects | Effective amount (w/v or v/v) | Storage condition | Reference |
|---|---|---|---|---|---|---|---|
| Aloe (*A. vera and A. arborescens*) | None | Immersion | Fresh-cut apples | Reduced bacteria growth and fungal decay incidence | 1.2% | 30 days, 6 °C | (Chauhan et al., 2011) |
| | | | Raspberry fruits | Delayed respiration and ripening | 50% | 8 days, 4 °C | (Hassanpour, 2015) |
| | | | Kiwifruit slices | Inhibited polyphenol oxidase and enhanced key antioxidant enzyme activities | 5% | 12 days, 4 °C | (Benítez et al., 2015) |
| | | | Mangoes | Delayed weight losses and tissue softening | 50% | 20 days, 13 °C | (Sophia et al., 2015) |
| | | | Table grapes | Retained color and alleviated surface browning | 25% | 35 days, 2 °C | (Castillo et al., 2010) |
| | | | Cherry laurel fruits | | 33% | 60 days, 0 °C | (Ozturk et al., 2019) |
| | | | Lotus fruit slices | | 50% | 8 days, 5 °C | (Ali et al., 2019) |
| | | | Green apples | | 5% | 6 months, 2 °C | (Ergun & Satici, 2012) |
| | | | Peach and plum fruits | | Fresh solution | 6 days, 20 °C | (Guillén et al., 2013) |
| | | | Tomatoes | | 2% | 35 days, 4 °C | (Khatri et al., 2020) |
| Aloe (*Aloe vera*) | 5% Ascorbic acid | Immersion | Strawberry fruits | Delayed weight loss, reduced total aerobic mesophilic, and suppressed fungi growth | Fresh solution | 18 days, 1 °C | (Sogvar et al., 2016) |
| | 1% Ascorbic and 1% Citric acid | Immersion | Pomegranate arils | Reduced respiration, retained firmness, inhibited bacterial and fungal growth, and improved sensory acceptability | Fresh solution | 12 days, 3 °C | (Martínez-Romero et al., 2013) |
| | 0.2% Ascorbic and 0.5% Citric acid | Immersion | Fig fruits | Reduced ripening, reduced decay and weight loss, and changed physical qualities | Fresh solution | 8 days, 29 °C | (Marpudi et al., 2013) |
| | 0.1% Thymol | Immersion | Nectarines fruits | Alleviated fungal infection with *Rhizopus stolonifer, Botrytis cinerea and Penicillium digitatum* | Fresh solution | 6 days, 25 °C | (Navarro et al., 2011) |
| | 1% Thyme oil | Immersion | Avocado fruits | Alleviated anthracnose and showed in vitro and in vivo fungicidal effects against *Colletotrichum gloeosporioides* | 2% | 5 days, 20 °C | (Bill et al., 2014) |
| | Papaya leaf extract (1:1) | Immersion | Papaya fruits | Delayed ripening, fruit softening, and decay, maintained fruit size, and reduced weight loss | 50% | 15 days, 30 °C | (Marpudi et al., 2011) |
| | 0.5% Cysteine | Immersion | Apple slices | Delayed browning, weight loss, and fruit softening and suppressed aerobic bacterial and fungal growth | 50% | 16 days, 4 °C | (Song et al., 2013) |
| | 1% *Fagonia indica* extract | Immersion | Sapodilla fruits | Improved resistance to decay, reduced weight and firmness loss | Fresh solution | 12 days, 20 °C | (Khaliq et al., 2019) |
| Flax/Linseed (*Linum usitatissimum*) | Probiotics (*Lactobacillus casei*, 10 g/L) | Immersion | Fresh-Cut yacon vegetables | Reduced weight loss, browning, and color change | 0.3% | 15 days, 5 °C | (Rodrigues et al., 2018) |
| | None | Immersion | Fresh-cut cantaloupes | Reduced juice leakage, decreased decay rates by inhibiting fungal growth | 2% | 18 days, 4 °C | (Treviño-Garza et al., 2019) |
| | Lemongrass oil (800 ppm) | Immersion | Pomegranate arils | Decrease bacterial and fungal growth, reduced weight loss, and delayed ripening | 0.6% | 12 days, 5 °C | (Yousuf & Srivastava, 2017) |
| Plantago Seed (*P. major, P. psyllium,* and *P. ovata*) | None | Immersion | Fresh-cut apples | Reduced enzymatic browning activity, loss of firmness, and total bacterial count | Fresh solution | 10 days, 4 °C | (Noshad et al., 2019) |
| | None | Immersion | Strawberry Fruit | Improved water retention and delayed fungal growth | 1.25% | 12 days, 4 °C | (Yarahmadi et al., 2014) |
| | None | Immersion | Fresh-cut apples | Delayed enzymatic browning, prevented color changes, maintained firmness | 0.2% | 8 days, 4 °C | (Banasaz et al., 2013) |
| | None | NA | Fresh-cut papayas | Minimized weight loss and reduced bacterial and fungal growth | 1% | 6 days, 4 °C | (Yousuf & Srivastava, 2015) |
| | 6%–8% Garlic extract | NA | Mandarins | Reduced weight loss and inhibited fungal growth | 1.29% | 28 days, RT | (ur Rehman et al., 2015) |
| Cactus (*Opuntia ficus-indica, Opuntia dillenii, Opuntia robusta)* | None | Immersion | Mangoes | Exhibited bactericidal and fungicidal effects, decreased microbial population | 20% | 42 days, 27 °C | (Adetunui et al., 2012) |
| | None | Immersion | Fig fruits | Maintained weight and firmness | Fresh solution | 7 days, 4 °C | (Allegra et al., 2018) |
| | None | Immersion | Hayward' kiwifruit slices | Retained firmness and weight, enhanced visual appearance and flavor scores | 6% | 12 days, 5 °C | (Allegra et al., 2016) |
| | None | Immersion | Fresh-cut potatoes | | 1% | 5 days, 5 °C | (Wu, 2019) |

(*continued on next page*)

**Table 3** (*continued*)

| Mucilage source | Active component/ material | Form of coating | Food matrix | Preservative effects | Effective amount (w/v or v/v) | Storage condition | Reference |
|---|---|---|---|---|---|---|---|
| | | | | Reduced weight loss by five times, maintained color, inhibited browning, and exhibited bacteriostatic effects | | | |
| | None | Immersion | Guava fruits | Delayed skin color and firmness deterioration and reduced weight loss | 5% | 6 days, 28 °C | (Zegbe et al., 2013) |
| | None | Spreading | Tomatoes | Significantly reduced weight loss and improved firmness | 12% | 21 days, 20 °C | (Bernardino-Nicanor et al., 2018) |
| Basil seed (*Ocimum basilicum L*) | 20% Cumin essential Oil | Immersion | Whole cherry tomatoes | Lowered weight loss and improved color and acceptability ratings | 10% | 9 days, 20 °C | (Tabaestani et al., 2013) |
| | 3% *Echinacea* extract | Immersion | Strawberry fruits | Reduced tissue softening and showed antibacterial and antifungal activities | 3% | 20 days, 1 °C | (Moradi et al., 2019) |
| | 6% *Origanum vulgare* essential oil | Immersion | Fresh-cut apricots | Decreased bacterial and fungal populations | 5% | 8 days, 4 °C | (Hashemi et al., 2017) |
| Quince seed (*Cydonia oblonga*) | None | | Mandarin slices | Delayed softening, reduced weight loss and color change | | 10 days, 4 °C | (Kozlu & Elmacı, 2020) |
| Roselle (*Hibiscus sabdariffa L.*) calyx | None | Immersion | Soursop fruits | Reduced weight loss and loss of firmness | 2% | 8 days, 22 °C and 15 °C | (los Santos-Santos et al., 2020) |
| Composite polymer | Basil seed + *Aloe vera* | Immersion | Apricot fruits | Lowered weight loss, respiration rate, and ripening index and retained or improved physicochemical properties | 0.1:30% | 28 days, 2 °C | (Nourozi & Sayyari, 2020) |
| | *Aloe vera* + Gum Arabic | Immersion | Guava fruits | Suppressed skin browning lightly and improved storability | 100:10% | 15 days, 25 °C | (Anjum et al., 2020) |
| | *Aloe vera* + Chitosan | Immersion | Tomatoes | Reduced weight loss, delayed ripening, and reduced microbial proliferation and fungal decay | 1:1% | 42 days, 4 °C | (Khatri et al., 2020) |
| | | | Blueberry fruits | | 0.5:0.5% | 25 days, 5 °C | (Vieira et al., 2016) |
| | | | Kiwifruit slices | | 5:1% | 12 days, 4 °C | (Benítez et al., 2015) |
| | Linseed + Chitosan | Immersion | Fresh-cut cantaloupes | Reduced juice leakage, decreased decay rates by inhibiting fungal growth | 1:1% | 18 days, 4 °C | (Treviño-Garza et al., 2019) |
| | Linseed + *Aloe vera* + Nopal cactus | Layer-by-Layer immersion | Fresh-cut pineapples | Enhanced shelf life by reducing weight loss and tissue softening and inhibiting color changes; also suppressed decay rate and microbial growth | 1.5, 4.0, and 50%, respectively | 18 days, 4 °C | (Treviño-Garza et al., 2017) |
| | Okra pod + Quince seed | Immersion | Strawberry fruits | Reduction in weight loss, retain skin color and suppressed microbial growth | 5% | 12 days, 4 °C | (Shahbazi et al., 2020) |

physical qualities during the storage period (Marpudi et al., 2013;Martínez-Romero et al., 2013).

Similarly, the incorporation of antibacterial and antifungal extracts from papaya leaves (Baskaran et al., 2012) and *Fagonia indica* leaves (Kouser & Qureshi, 2013) into AVM coatings increased the antimicrobial properties of the coating and improved the decay resistance of papaya (Marpudi et al., 2011) and sapodilla fruits (Khaliq et al., 2019) stored at room temperatures. The addition of an antimicrobial essential oil with 0.1% thymol and 1% thyme oil reduced the incidence of decay caused by various fungal pathogens (*Rhizopus stolonifer, Botrytis cinerea, Penicillium digitatum*, and *Colletotrichum gloeosporioides*) in coated nectarines (Navarro et al., 2011) and avocado fruits (Bill et al., 2014). Further,Song et al. (2013) observed weight-loss reduction, browning, softening, and microbial growth in fresh-cut apples coated together with 0.5% cysteine.

### 5.2. Flaxseed/linseed mucilage

Flax, also known as linseed (*Linum usitatissimum*), is another mucilage-containing seed widely used in edible coatings. Flax's frequent application on fruits and vegetables involves being incorporated as an active ingredient (Yousuf & Srivastava, 2017) or applied in a composite coating with other polymers (Treviño-Garza et al., 2017).Rodrigues et al. (2018) included 0.3% linseed mucilage (LM) in an alginate-based coating containing *Lactobacillus casei* probiotic bacteria. The incorporation of LM in the composite coating solution showed no significance in maintaining the physicochemical parameters of stored fresh-cut yacon vegetables. However, LM improved the encapsulation of probiotics, reduced surface browning, and increased color retention during storage at 5 °C for 15 days (Rodrigues et al., 2018). Further, coating solutions of 2% LM and 1% LM with 0.5% chitosan showed early inhibition (~6 days) of bacterial and fungal growth and slightly improved storage color and sensory perception of appearance and odor of coated fresh-cut cantaloupe during 18 days of cold storage (Treviño-Garza et al., 2019). Thereafter, rapid microbial growth was observed throughout the storage period (Treviño-Garza et al., 2019).Treviño-Garza et al. (2017) applied multilayer coating on fresh-cut pineapples, using 1.5% LM and 1.5% chitosan as first and second coating layers, respectively. The positive effects on microbial growth inhibition and color and firmness maintenance observed during storage were attributed to the presence of chitosan. However, this study did not present data on LM coating alone (i.e., without chitosan), which makes it difficult to highlight the preservative effects of LM (Treviño-Garza et al., 2017). Another study fully attributed the microbial inhibition observed in coated pomegranate arils to 200–800 ppm of lemongrass oil emulsified with LM coating (Yousuf & Srivastava, 2017). The above-discussed studies together demonstrate the application of LM as an edible coating, but do not report pronounced long-term preservative effects of an LM-only coating. Thus, more studies are required to investigate the preservative potential of LM.

### 5.3. Plantago seed mucilage

Plantago is a medicinal plant with mucilage-containing seeds. In recent studies, *Plantago major, P psyllium,* and *P. ovata* have been utilized in coatings and film-forming solutions. Plantago mucilage (PM) has been demonstrated to exert preservative effects by regulating respiration, minimizing weight and tissue loss, and delaying enzymatic browning

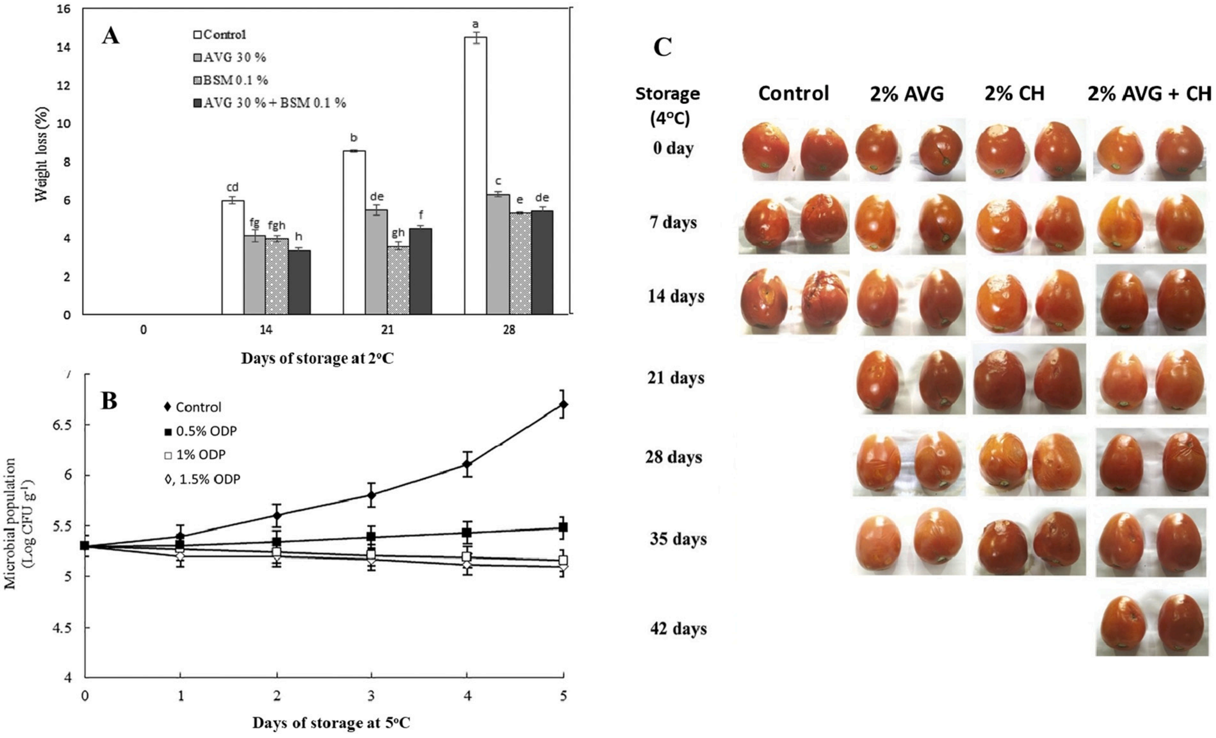

**Fig. 3.** Effects of various mucilage-based coatings on the qualities of stored produce. (A) Weight loss of apricot fruits (Nourozi & Sayyari, 2020), (B) total viable counts of fresh-cut potatoes (Wu, 2019), and (C) shelf-life of tomatoes (Khatri et al., 2020). AVG, BSM, ODP are *Aloe vera*, basil seed and cactus mucilage solutions, while CH is chitosan solution. Permission for images obtained from Elsevier.

and microbial growth in coated fresh-cut apples (Noshad et al., 2019), fresh-cut papaya (Yousuf & Srivastava, 2015), and strawberries (Yarahmadi et al., 2014). Interestingly, PM at a low concentration of 0.2% was reported to effectively maintain the color and firmness of fresh-cut apples during 8 days of storage at 4 °C and demonstrate comparable preservative effects to the coating with 1% chitosan (Banasaz et al., 2013). These results suggest that PM could be an alternative to chitosan as a commercial coating material. PM's antifungal effects were also enhanced by the addition of garlic extracts, preserving coated mandarins stored at room temperature for 4 weeks (ur Rehman et al., 2015).

### 5.4. *Cactus mucilage*

The cactus genus *Opuntia* is another plant that has gained significant attention over the years for its application as an edible coating. The species whose cladodes are frequently used for fruit and vegetable coatings include *Opuntia ficus-indica*, *Opuntia dillenii*, and *Opuntia robusta* (Gheribi & Khwaldia, 2019).Bernardino-Nicanor et al. (2018) applied cactus mucilage (CM) on freshly harvested tomatoes before storage at 20 °C for 21 days and observed a preservative effect on the tomatoes' weight and tissue firmness. CM was also observed to efficiently reduce weight loss, preserve color and firmness in coated figs (*Ficus carica L.*) (Allegra et al., 2018) and guava fruits (Zegbe et al., 2013) under their respective storage conditions.

In addition, improvement in visual appearance and flavor attributes was observed in fresh-cut kiwifruits coated with 6% CM and stored at 5 °C for 12 days (Allegra et al., 2016). Moreover, bactericidal and fungicidal activities were observed in 20% CM-coated mangoes stored at 27 °C for 42 days under an evaporative cooling system (Adetunui et al., 2012). The CM-coated mangoes were observed to have a decreasing microbial count. In contrast, the uncoated mangoes had higher total bacteria and fungi counts during 6 weeks of storage (Adetunui et al., 2012).

### 5.5. *Basil mucilage*

Basil (*Ocimum basilicum* L.) seeds contain a substantial amount of mucilage, which has been used to prepare coating solutions and applied for their preservative properties. Improved storage quality and sensory ratings were reported for whole cherry tomatoes coated with basil seed mucilage (BSM) with cumin essential oil (Tabaestani et al., 2013). Moradi et al. (2019) reported a longer shelf life for the strawberries coated with 3% BSM and 3% echinacea extract than the uncoated ones during storage of 20 days at 1 °C. Also, BSM coating without extract significantly exhibited antimicrobial activity, delayed tissue degradation, and improved the acceptability ratings of coated strawberries (Moradi et al., 2019). In another study, BSM coating solution containing *Origanum vulgare* essential oil (EO) maintained the freshness and reduced bacterial and fungal concentrations of fresh-cut apricots (Hashemi et al., 2017). Remarkably, these studies suggest that BSM is applicable in retaining storage quality even without the addition of EO. Moreover, BSM enables the entrapment of the essential oil, thereby improving BSM's preservative effects, as reported by the reviewed studies.

### 5.6. *Other plants' mucilage and composite polymer*

The mucilages extracted from other plants have also been used as edible coatings to preserve fruits and vegetables. For example, hsian-tsao leaf (*Mesona procumbens* Hemsl.) mucilage with 5% green tea extract was reported to reduce the initial concentration and inhibit the growth of bacteria and fungi in spray-coated fruit salads stored at 4.2 °C for 8 days (Chiu & Lai, 2010). A recent study compared the effects of the mucilage from the calyx of roselle (*Hibiscus sabdariffa* L.) on the storage properties of soursop fruits stored for 8 days at 15 °C and 22 °C (los Santos-Santos et al., 2020). The coated samples were found to have lower mass loss and better texture than the uncoated samples at the end of the storage. Besides their preservative properties, these studies confirmed no sensory defects of coatings. Notwithstanding, few studies are available, and a consistent report of their applications and safety profile will be another suggestion for future research.

Furthermore, composite coatings, which are a combination of polymers, are often used to achieve better preservative effects. Composite coatings consisting of plant mucilages and other polymers, such as gum arabic, gum tragacanth, and chitosan, have been used to improve the preservative efficiency and extend the shelf life of various fruits, including guava fruits (Anjum et al., 2020), fresh-cut pineapples (Treviño-Garza et al., 2017), apricots (Nourozi & Sayyari, 2020), tomatoes (Khatri et al., 2020), blueberries (Vieira et al., 2016), strawberries (Shahbazi et al., 2020), and kiwi slices (Benítez et al., 2015). The effectiveness of the composite coatings over the single-polymer coatings could be attributed to the synergistic effect of the individual polymers in the composite matrix, which compensate for the limitations of single-polymer coatings.

## 6. Mechanism of preservative effects of MEP

The data on the specific preservative mechanism of mucilage coatings on fruits and vegetables have been inconsistent. Some mucilages contain compounds like polyphenols, which induce biological activities, including antimicrobial and antioxidant activities (Khaliq et al., 2019; Noshad et al., 2019;Song et al., 2013). For example, mucilages obtained from various species of *Aloe vera* were reported to show in vitro antimicrobial activity against pathogenic bacteria (*Staphylococcus aureus, Escherichia coli, Bacillus cereus,* and *Salmonella typhimurium*) and fungi (*Botrytis cinerea, Penicillium digitatum, Penicillium expansum,* and *Penicillium italicum*) due to the presence of anthraquinones and aloin (Misir et al., 2014;Navarro et al., 2011;Zapata et al., 2013).Castillo et al. (2010) confirmed the antifungal potency of AM, which showed concentration-dependent inhibitory effects of 99% and 87% against *Penicillium digitatum* and *Botrytis cinerea* at a concentration of 100 mL/L. Other compounds such as saponins and acemannan have also been associated with the antimicrobial properties of AM (Song et al., 2013). Furthermore, a study performing an in vitro antimicrobial screening assay revealed the growth inhibitory efficiency of Balangu mucilage (2 mg/mL) on *Bacillus subtilis* and *Streptococcus pyogenes*. However, no significant effects were observed for *Bacillus cereus*, *Escherichia coli*, and *Pseudomonas aeruginosa*. Moreover, this mucilage solution effectively reduced bacterial growth in coated beef throughout 18 days of storage (Behbahani & Fooladi, 2018). The antimicrobial property was attributed to phenolic contents of the mucilage, but the study did not specify the possible compound(s) underlying this effect. Other studies have equally correlated antimicrobial properties of mucilage with their respective total phenolic contents (Allegra et al., 2017;Khaliq et al., 2019;Noshad et al., 2019;Nourozi & Sayyari, 2020). Further, the presence of uronic acids in mucilage has been associated with its antimicrobial properties (Olawuyi et al., 2020;Vignesh & Nair, 2018). Uronic acids and its derivatives, 4, 5-dihydroxy-2-cyclopentan-1-one (DHCP) are considered to possess antimicrobial activities (Vignesh & Nair, 2018). However, as applicable to their use as edible coating, the film-forming properties of a mucilage solution play a crucial role in determining its preservative performance.

To some extent, the preservative effects of mucilage-based coatings, like other polymers, can be attributed to their techno-functional properties, e.g., barrier, physical, and mechanical properties of film layers formed on the outer surface of produce. When a coating is applied to a fruit, it binds to the fruit's surface and alters its porosity, forming a thin-layer film (Nourozi & Sayyari, 2020). The film creates a modified internal atmosphere in fruits and restricts the diffusion of gases like $O_2$ and $CO_2$ through the surface, thereby controlling respiration rate and oxidative degradation. The coating's adhesion on the fruit's surface also creates a barrier against water diffusion, reducing transpiration (Song et al., 2013). Besides, natural mucilages exhibit hygroscopic properties, which favor the inward movement over the external transfer of moisture transfer, thereby achieving a balance in moisture between the fruit and the environment (Misir et al., 2014;Passafiume et al., 2020). As a result, the protective coating or film delays the ripening and reduces dehydration, enzyme-mediated tissue degradation, and microbial proliferation that are associated with the postharvest deterioration of produce (Chauhan et al., 2011;Olawuyi & Lee, 2019). For color retention and browning inhibition in produce, the protective layer formed by mucilage coating prevents oxidation of phenols and contact of phenols with oxidative enzymes such as polyphenol oxidase and peroxidase (Ali et al., 2019;Kumar, 2019).

It should be noted that the preservative effect may vary in different fruits coated with the same mucilage solution owing to different surface properties and interaction between the mucilage matrix and the fruits' epidermis (Guillén et al., 2013). Therefore, a mucilage matrix's preservative potential can be maximized by characterizing and appropriately modifying its critical techno-functional and antimicrobial properties before applying it in a coating solution.

## 7. Conclusions, limitations and potential research areas

This review surveyed recent and relevant studies on plant-derived mucilage polysaccharides, mucilage-based edible packages (MEPs), and their applications in preserving fruits and vegetables. The mucilages' sources, including plant seeds, leaves, and roots, obtention, and structure-function relationships, and their specific properties applicable to the development of edible coatings and films, have been discussed. Essentially, mucilages are being employed as direct coatings on food to form thin-layer protective coverings and fabricated into dried film to access their techno-functional properties. The studies reviewed here confirm the applicability of MEPs in retaining the quality and extending the shelf life of fruits and vegetables. The MEPs' preservative effects are attributed to the techno-functional properties of mucilage matrices, which are influenced by their respective structural-chain configurations. And mucilage matrices can be modified according to different intended applications. The modification of mucilage matrices' techno-functional properties by adding plasticizers and other materials is also highlighted. It is suggested that more studies should focus on improving the preservative performance of MEPs by incorporating novel food additives and active ingredients for the industrial packaging of specific fruits and vegetables. Furthermore, since mucilages have distant functionalities, future studies on MEPs could benefit from the synergistic effects of appropriately combining different mucilage types to produce a more versatile package.

A broad range of mucilages has been characterized for their film-forming properties and preservative effects. However, the commercial application of MEP is very much limited, and some mucilages are yet to be applied for fruit and vegetable packaging. Besides, the practical use of mucilage films as food wraps is yet unconfirmed, since most studies are mainly on the application of MEPs as edible coatings and not as wrapping foils. Therefore, future research should assess the preservative potentials of these unapplied mucilages and likewise extend their applications as food wraps, especially for commercial products. There are still various potential opportunities in the application of plant-derived mucilages; such as in the development of edible protective gel “bandage” for damaged/injured fruit surface to reduce fluid exudation (Sason & Nussinovitch, 2020); as an alternative polymer for the microencapsulation of beneficial probiotics and bio-controls (Bustamante et al., 2017;Rodrigues et al., 2018). However, studies on these topic areas are still lacking. Other gaps include the lack of economic assessment of mucilage-based coating/films/wraps relative to synthetic counterparts. In addition, the characterization of new mucilage polysaccharides is required to fully understand the relationship between the structural properties and film-forming capacity to predict MEPs' preservative performance.

Overall, with the remarkable progress in the modification and application of MEPs for produce preservation, as well as their low cost, non-toxicity, and biodegradability, it is anticipated that the industrial utilization and preference for plant-derived mucilage will increase in years to come.

## CRediT authorship contribution statement

**Olawuyi I.F:** Conceptualization, Investigation, Data Curation, Writing – original, Visualization, Writing - review & editing. **Kim. S.R:** Conceptualization, Supervision, Writing - review & editing. **Lee W.Y:** Conceptualization, Supervision, Resources, Writing - review & editing.

## Declaration of competing interest

None.

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