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Protein and polysaccharide edible coatings: A promising approach for fruits preservation - recent advances

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ABSTRACT

Biodegradable packaging, especially edible coatings (EC) for fruit preservation, is a sustainable and eco-friendly approach. ECs, such as polysaccharides and proteins, are widely used in fruit preservation, with a preference for polysaccharides in coating studies. Fundamental EC properties include barrier properties, tensile strength, elongation at break, and UV blocking. Extra materials such as antimicrobial agents, antioxidants, anti-browning agents, and antagonistic microorganisms enhance EC benefits. ECs impact fruit metabolism by reducing malondialdehyde production and enhancing the activities of key enzymes. However, extra materials at high concentrations affect the bonding network of the EC and weaken its structure. Therefore, selecting an appropriate concentration of extra materials is crucial to ensure adequate preservation and safety without affecting sensory properties. Combining coating materials and extra materials to reduce fruit metabolism, maintain fruit quality, inhibit damage pathogens, prevent browning, and provide antioxidants would be an excellent way to promote the green potential of fruit preservation approaches.

1. Introduction

Global fruit production has been increasing due to rising demand, improved living standards, and increased health awareness regarding fruit consumption. According to the FAO, 2022 reports, global fruit production grew by 55 % between 2000 and 2020, reaching 910 million tonnes in 2021 (FAO, 2022; FAO, 2022b). However, postharvest losses lead to reduced quantity and quality of fruits after harvest, posing a severe challenge. Post-harvest fruit losses can occur due to various factors, such as mishandling, lack of pre-cooling, improper storage temperature control, and microbial pathogens (FAO, 2004; Lieu, Phuong, Nguyen, Dang and Nguyen, 2024). Therefore, reducing post-harvest losses becomes an urgent concern that needs attention. The approach to preserving fruit by slowing down the internal metabolism and limiting the penetration of external agents through the use of packaging demonstrates a practical approach (Thakur et al., 2018; Ortiz-Duarte et al., 2019; Ruan et al., 2022; Deng, Wang, et al., 2024). Materials for fruit packing are diverse and divided into two main groups, including biodegradable and non-biodegradable. Non-biodegradable packaging, made of plastics and chemicals, is commonly used today. On the other hand, biodegradable packaging materials offer advantages over synthetic plastics, including biodegradability, compostability, and renewable resources (Yuvaraj et al., 2021). Besides, non-biodegradable packaging can cause significant environmental damage, threatening the environment and living beings (Rout & Pradhan, 2024; Yuvaraj et al., 2021). Therefore, biodegradable packaging, especially edible coatings (EC) in fruit preservation, is considered a sustainable green approach receiving much attention (Lieu, Phuong, Nguyen, Dang and Nguyen, 2024). Based on the total effect (substitution effect and income effect) of the shift from synthetic packaged food to edible packaged food, Rout and Pradhan (2024) indicated consumer preference for edible packaged food over synthetic packaged food. The edible coating would slow down ethylene production and the ripening process, reduce spoilage and weight loss, lower respiration, and delay a reduction in hardness, ultimately leading to an extension of fruit shelf life (Deng, Wang, et al., 2024; Iqbal et al., 2024; Liu et al., 2024; Ma et al., 2021;

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Zheng et al., 2024). It has also been demonstrated that using an edible coating does not affect the sensory quality of the fruit (Bersaneti et al., 2021; Treviño-Garza et al., 2017) and has no toxic effects (Li, Li, Wang and Xie, 2024; Liu et al., 2024). Besides, edible coatings can be applied to a wider variety of fruits than plastic films, especially for ready-to-eat or fresh-cut fruits (Nascimento et al., 2020; Ortiz-Duarte et al., 2019; Rather & Mir, 2023; Seididamyeh et al., 2024), increasing preservation efficiency and allowing for direct consumption without affecting the sensory characteristics (Dong et al., 2020; Rather & Mir, 2023; Treviño-Garza et al., 2017).

The components of an edible coating are diverse, including polysaccharides, proteins, etc. Extra materials, such as antagonistic microorganisms, essential oils, nanoparticles, plant extract, etc., could also inhibit or compete with microbial pathogens or maintain the fruit quality to enhance preservation efficiency (Álvarez et al., 2021; Falcó et al., 2019; Felicia et al., 2024; Kim et al., 2022; Lieu & Dang, 2021; Zidan et al., 2023). In fruit preservation, the storage efficiency depends on the interaction of the main components, extra materials, type of fruits, and their ability to adhere to the fruit surface. Besides, the combination of edible coating components affects mechanical properties, barrier function, optical properties, UV blocking ability, antimicrobial properties, antioxidant properties, etc. Therefore, selecting coating and supplement components is crucial in determining fruit preservation's effectiveness. This review focuses on the use of edible coatings for fruit preservation. It covers EC components, EC properties, the mechanism of EC on fruit preservation efficiency, and the potential fruit preservation approach.

2. Edible Coating Components

2.1. Main materials of edible coating

After treatment, the EC becomes a part of the fruit and could be eaten. Therefore, the coating material must be non-toxic, safe for health, extend the fruit's shelf life, and not affect its sensory properties. ECs, including polysaccharides, proteins, etc. (Fig. 1), are extensively used for fruit preservation, with polysaccharides particularly favored for coating applications. Polysaccharides, including alginate (Dong et al., 2020; Li et al., 2019), *aloe vera* (Ghulam Khaliq et al., 2019), carrageenan (Falcó et al., 2019), dextrin (Castro-Cegrí et al., 2023), guar gum (Goswami et al., 2024), gum Arabic (Ajay Gill et al., 2024; Seididamyeh et al., 2024), pectin (Hernández-Carrillo et al., 2021; Huang, Hong, et al., 2023; Kostić et al., 2023), chitosan (Lieu & Dang, 2021; You et al., 2022; Wang et al., 2023; Deng, Wang, et al., 2024), starch (Abera et al., 2024;Bersaneti et al., 2021 ; Li et al., 2023), carboxymethyl cellulose (Rather & Mir, 2023; Van et al., 2023), soybean polysaccharide (Liu et al., 2022), etc., were used as the main compounds of EC for fruit preservation.

Chitosan is among the most extensively researched materials for edible coatings derived from polysaccharides. The EC made from chitosan has been shown to preserve numerous types of fruit such as strawberries effectively (Rabasco-Vílchez et al., 2024; Saleem et al., 2021), mangoes (Lieu & Dang, 2021; Lieu, Ngo, Lieu, Nguyen, & Dang, 2018; Ranjith et al., 2022; Li, Bi, Dai and Ren, 2024), passion (You et al., 2022), table grape (Das et al., 2023), custard apple (Wang et al., 2023), banana (Deng, Zhang, et al., 2024), fresh-cut melon (Ortiz-Duarte et al., 2019), fresh-cut guava (Nascimento et al., 2020), mandarin fruit (Jurić et al., 2023), etc., (Table 1). Besides, ECs derived from starch have gained significant attention due to their various sources. These sources include lima bean seeds and pods (Chettri et al., 2023), corn starch (Sena et al., 2019), cassava starch (Bersaneti et al., 2021; Li et al., 2023), rice starch (Thakur et al., 2018), chayotextle starch (Martínez-Ortiz et al., 2019), and soybean starch (Chettri et al., 2024), banana pseudostem starch (Abera et al., 2024), jackfruit seed starch (Bodana et al., 2024). These starches have been proven to enhance the shelf life and preserve the quality of fruits such as sapota, cashew apples, blackberry, strawberry and fresh-cut apples, plum, guavas, sapota, apples and mangoes, white grapes, etc., In addition, the use of protein sources as ECs for preserving fruit is also quite diverse. These sources include gelatin (Moreno et al., 2020; Temiz & Özdemir, 2021; Zhang et al., 2021), soybean protein isolate (Hu et al., 2023), and whey protein (Muley & Singhal, 2020; Sezer et al., 2022; Deng, Zhang, et al., 2024).

The preservation efficiency of EC has significantly enhanced the shelf life of fruits. However, each film has its own drawbacks that require improvement. Therefore, the combination of edible coating components is being considered as a potential approach to overcome the

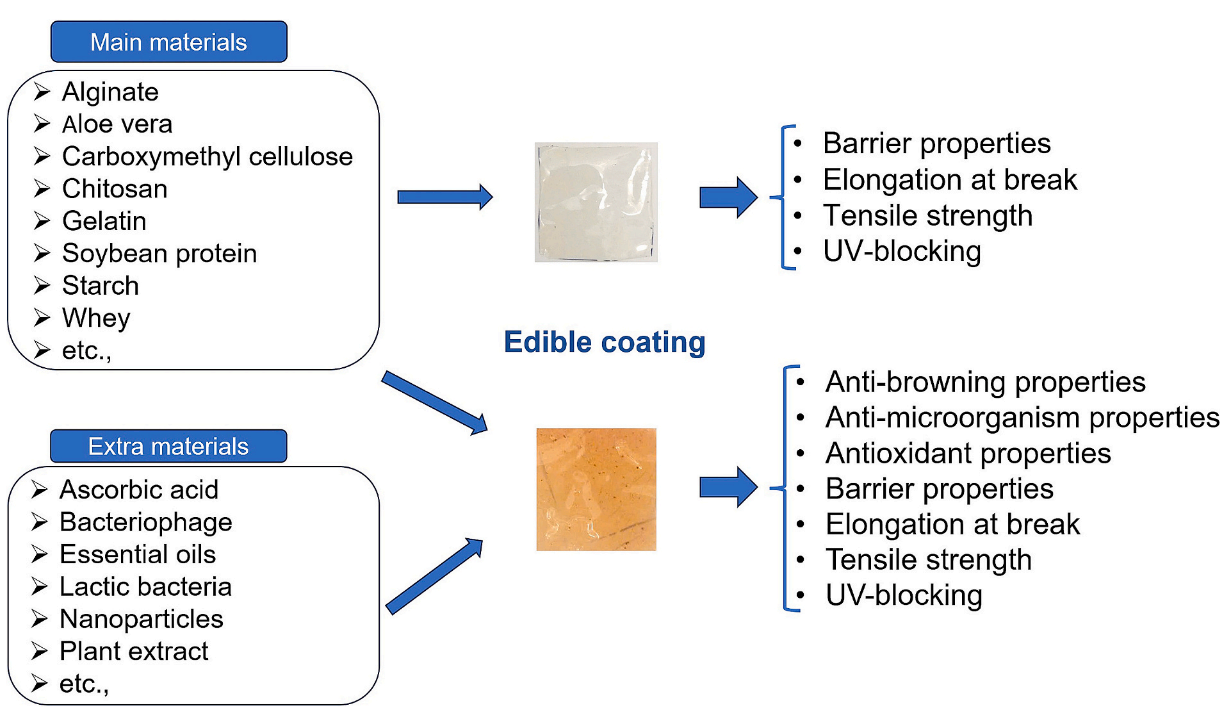

Fig. 1. Component of edible coatings for fruit preservation.

Table. 1
Edible coating application for fruit preservation.

Main components Approach	Extra materials	Type of fruit Storage condition	Outcome	References
Whole fruit				
Alginate (1 % w/v) Immersion approach	Rhubarb (*Rheum rhaponticum* L.) (5 % *v*/v)	Peach fruits Room temperature	Limits the rate of spoilage caused by *Penicillium expansum* Maintains firmness and soluble solids content Reduce respiration Reduce weight loss Slows down polyphenol oxidase activity	Li et al., 2019
Alginate (2 % *w/v*) Spray	Lemongrass oil (1.25 % *w*/w)	'Rocha' pear 0 °C and 90–95 % RH	Reduce decay and color change Maintains firmness	Gago et al., 2022
Alginate Immersion approach	Titanium dioxide Mousami peel extract	Peach fruit 7 days at room temperature	Reduced weight loss and firmness loss. Inhibit yeast and mold The coatings also positively affected several quality tributes, such as color index, pH, TSS, and titratable acidity.	Khan et al., 2023
Alginate/chitosan layer-by-layer approach	NS	Strawberries Room temperature for 5 days	Decreased consumption of total soluble solids. Delayed accumulation of malondialdehyde Reduced weight loss. Preservation of antioxidant capacity.	Du et al., 2021
Aloe vera gel Chitosan Immersion approach	*Mentha piperita* L. *Satureja montana* L. *Thymus vulgaris* L.	Sweet cherries 2 ± 1 °C and 95 % relative humidity	Delaying ripening index. Improving antioxidant activity. Reducing weight loss and firmness loss.	Afonso et al., 2023
Carboxymethyl cellulose (1.5 % w/v) Hand brushing	*Morus alba* root extracts 1.5 % (*w/v*)	Banana 13 ± 2 °C 40 % RH	Delayed changes in colors, polyphenol oxidase activity, browning index, and visual quality levels.	Kim et al., 2022
Carboxymethyl cellulose and cellulose nanofibers Immersion approach	Mandarin oil	Strawberries 5 °C and 85 ± 5 % RH	Controlling weight loss and antifungal activity. Reducing the degradation of fruit quality. Mandarin oil significantly affected the properties of coating solutions and the film characteristics.	Van et al., 2023
Carboxymethyl cellulose (1.5 % w/v) Immersion approach	thyme, clove, and cardamom	Kiwi fruit 10 ± 2 °C for 30 days	Reduction of 58.23 % in bacterial count compared to the control group. After 30 days of kiwifruit storage at 10 °C	Iqbal et al., 2024
Carboxymethyl cellulose (2 % w/v) and chitosan (1.5 % w/v) Immersion approach	Oxalic acid Malic acid	Pomegranate fruit 2 °C, and 80–90 % RH for 120 days	Decreased chilling injury Reduced electrolyte leakage, malondialdehyde, and hydrogen peroxide. Total phenolic content, antioxidant activity, and catalase activity were higher in treated than control fruit during storage.	Ehteshami et al., 2019
Carboxymethyl chitosan-gelatin Immersion approach	Calcium chloride and/or ascorbic acid	Sweet cherries 0 °C for 30 days	Decreased fruit decay ratio, weight loss, respiration rate, and pedicel browning incidence; Delayed the increase of soluble solids content/ titratable acidity. Maintained high fruit firmness, pedicel moisture content, and antioxidant activity.	Zhang et al., 2021
Chitosan 1 % (w/v) Immersion approach	Ascorbic acid 1 %	Strawberry 4 °C and 85 % RH 15 days.	Reducing cell wall degrading enzymes. Maintained fruit quality by conserving higher total soluble solids, titratable acidity, ascorbic acid content, total phenolic,s and antioxidant activity Delayed fruit softening.	Saleem et al., 2021
Chitosan	1-Methylcyclopropene	Passion fruit 4 °C for 25 days	Inhibited the peroxidase and ascorbate peroxidase activity. Reduced the weight loss rate, shrinkage index, and respiratory rate.	You et al., 2022
Chitosan nanoemulsion Immersion approach	*Angelica archangelica* essential oil	Table grape 25 ± 2 °C for 30 days	Prevented contamination of *B. cinerea* and maintained the quality attributes of table grape fruit, including weight, titrable acidity, total soluble solids, phenolic content, and pH during storage.	Das et al., 2023
Chitosan 1 % w/v Immersion approach	Ascorbic acid 1 % w/v	Custard apple (*Annona squamosa*) 15 ± 1 °C for 12 days	Delay the decrease of firmness, appearance deterioration, weight loss, and accumulation of malondialdehyde content. Regulating the activities of cell wall degrading enzymes and their gene expression levels.	Wang et al., 2023
Chitosan Immersion approach	Iturin	Mangoes 12 °C for 20 days	Improved disease control, respiratory rate, weight loss, total soluble solids, titratable acidity, and fruit firmness maintenance during storage.	Li, Bi, Dai and Ren, 2024
Chitosan	Lignocellulosic nanofibers, and raspberry leaf extract	Strawberry 5 ± 1 °C for 16 days	Reducing size loss during storage. Controlling fungal development.	Rabasco-Vílchez et al., 2024

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Table. 1 (*continued*)

Main components Approach	Extra materials	Type of fruit Storage condition	Outcome	References
Spray approach				
Chitosan 1.5 % Functionalized cellulose nanofiber 1.5 % Immersion approach	NS	Kiwi fruit 10 °C for 10 days	Reduced mass loss, firmness loss, respiration rate, and microbial count.	Ghosh et al., 2021
Chitosan Dialdehyde cellulose Immersion approach	NS	Mandarin fruits 23 °C for 18 days	Maintained the firmness of fruits. Reduced the respiration rate, weight loss speed, and accumulative decay rate.	Ruan et al., 2022
Gelatin Immersion approach	Argentine propolis ethanolic extract	Raspberries 5 °C for 11 days	Exhibited antifungal properties. Reduced disease incidence during storage.	Moreno et al., 2020
Gelatin 5 % (w/v) Immersion approach	*Lactobacillus rhamnosus* (11 LogCFU/g)	Strawberries 4 °C for 16 days	Better Strawberries appearance. Reduced fungal growth and aerobic mesophilic counts during storage. Reduced spoilage.	Temiz & Özdemir, 2021
Gum Arabic Brushing approach	Cinnamic acid	Mango 12 ± 1 °C for 28 days (RH of 85–90 %)	Maintained higher firmness, total flavonoid content, and total carotenoid content. Retained the higher sensory quality of mango fruit. Suppressed activities of polygalacturonase, cellulase, and pectin methyl esterase (PME) in stored fruits.	Ajay Gill et al., 2024
Hydroxypropyl methylcellulose Chitosan Layer – by – layer approach	NS	Tangerine fruit 20 ± 2 °C and 50 % RH for 15 days	Maintained the firmness and nutrient content of the fruits. Slowed down the decay of tangerine fruits during storage.	Zhou et al., 2024
Lima bean starch Dipping, spraying, and brushing approaches		Sapota fruits 28 ± 2 °C or 3 ± 1 °C	Dipping approach exhibited better physicochemical analysis. Reduced the weight loss rate.	Chettri et al., 2024
Pectin (3 % w/v) Immersion approach	Lemon oil (2 % v/v) Reuterin (10 mM)	Strawberries at 4 °C for 31 days	Exhibited a redder color fruit. Higher moisture content. Reduced viable *Penicillium* spp.	Hernández-Carrillo et al., 2021
Pectin Immersion approach	Nisin	'Guiqi' mango fruit 25 ± 2 °C, 85 ± 2 % RH for 8 days	Inhibit the activity of polygalacturonase, β-galactosidase, and cellulase. Delaying down the microbial-induced rotting process.	Liu et al., 2024
Quaternized chitosan Spray approach	Konjac glucomannan	Banana 25 °C and 50 % RH for 10 days	Delay fruit hardness. Reduce weight loss. Reduce the oxygen permeability.	Deng, Wang, et al., 2024
Shellac Immersion approach	Tannic acid	Mangoes Room temperature for 10 days	Improvement of physical properties and chemical qualities. Improved overall quality of mangoes. Maintaining of tissue firmness. Reduced lipid peroxidation. Slowing down of respiration rate. Suppression of browning.	Ma et al., 2021
Soluble soybean polysaccharide: carboxymethyl chitosan (1:1) Immersion approach	Lavender oil 1.0 (wt%)	Banana 25 ± 2 °C 56 ± 2 % RH for 9 days	Delayed banana peel browning process. Increased antioxidant and antibacterial properties. Improved water vapor barrier and UV barrier.	Liu et al., 2022
Fresh-cut fruit				
Alginate Immersion approach	Clove essential oil nanoemulsion	Freshly cut apple 4 °C for 14 days 90 % RH	Extended the shelf life of fruits. Inhibiting microbial growth. Protecting against physical damage. Reducing moisture loss.	Pandey et al., 2023
Alginate Dipping approach	Oregano essential oil	fresh-cut papaya 4 ± 1 °C for 20 days	Retain the sensory scores till day 16 of analysis. Retarding the degradation rate of physicochemical properties.	Tabassum et al., 2023
Carboxymethyl cellulose Immersion approach	Seabuckthorn leaf extract	fresh cut "Maharaji" apple 4 °C for 10 days	Inhibiting the polyphenol enzyme activity Reducing the microbial spoilage Extended the shelf life of fresh cut fruit	Rather et al., 2023
Carboxymethyl cellulose and sodium alginate Layer-by-layer approach	Oxalic and citric acid	Pear fruit 2 ± 0.5 °C and 90 % RH for 10 days	Enhance the activities of key enzymes, including superoxide dismutase and catalase. Inhibit physiological decay.	Magri et al., 2024
Chitosan, pullulan, linseed, nopal cactus and aloe mucilage Layer-by-layer approach	NS	fresh-cut pineapple 4 °C for 18 days	Improve the firmness. Reduced weight loss. Inhibited microbial growth. Without affecting sensory characteristics.	Treviño-Garza et al., 2017

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Table. 1 (*continued*)

Main components / Approach	Extra materials	Type of fruit / Storage condition	Outcome	References
Chitosan Immersion	AgNPs	Fresh-cut melon 5 °C (90–95 % RH)	Not affect fresh-cut melon's quality, including sugars, organic acids, and vitamin C.	Ortiz-Duarte et al., 2019
Chitosan–citric acid Immersion approach	NS	Fresh-cut guava 24 °C and 4 °C for 7 and 14 days	Antifungal activity against *Colletotrichum gloeosporioides*. Maintaining quality parameters (pH, soluble solids, total sugar, etc.) during storage. Preserving their sensorial characteristics.	Nascimento et al., 2020
Citrus pectin Immersion approach	Oregano essential oil	Fresh-cut apples at room temperature for 5 days	Exhibited significant antioxidant, antibacterial, and antifungal properties. Retention of freshness and color.	Kostić et al., 2023
Gum Arabic Dipping approach	Aqueous extracts of *Syzygium aqueum*, Diploglottis bracteata, and Tasmannia lanceolata	Fresh-cut red capsicum 4 °C for 16 days	Inhibited microbial growth. Maintained a low bacterial load led to positive liking scores for appearance, aroma, and flavor. Enhanced the overall sensory experience of the capsicum.	Seididamyeh et al., 2024
Pectin NS	Quercetin	Fresh-cut apples 4 °C for 15 days	Enhanced antimicrobial activity against *S. aureus* and L. *monocytogenes*. Extended the shelf life of fresh-cut apples while maintaining good commercial quality.	Du et al., 2023

NS: not showed; RH: relative humidity; AgNPs: silver nanoparticles.

shortcomings of coatings. Studies on the combination of edible coating components are diverse (Table 1), such as chitosan-pullulan, chitosan-linseed, chitosan-nopal cactus, and chitosan-aloe mucilage (Treviño-Garza et al., 2017), rice starch-ι-carrageenan-sucrose fatty acid esters and glycerol (Thakur et al., 2018), chitosan-whey protein isolate (Muley & Singhal, 2020), cellulose nanofibers reinforced chitosan (Ghosh et al., 2021), chitosan-dialdehyde cellulose (Ruan et al., 2022), chitosan-alginate, chitosan-hydroxypropyl methylcellulose, chitosan-locust bean gum (Jurić et al., 2023), pregelatinized corn starch-cellulose nanofibers (Wigati et al., 2023b), chitosan-guar gum (Goswami et al., 2024), chitosan-*aloe vera* gel (Felicia et al., 2024), chitosan-hydroxypropyl methylcellulose (Zhou et al., 2024), banana pseudostem starch and fish-scale chitosan (Abera et al., 2024), sodium alginate and whey protein isolate (Deng, Zhang, et al., 2024), etc.

2.2. Extra materials

The EC serves as a physical barrier to prevent fruit exchange with the environment. To enhance fruit preservation efficiency and improve the properties of the EC structure, extra materials should be added. Extra materials are components that cannot form the film themselves but are added to enhance the beneficial properties of EC (Fig. 1). The components of extra materials are diverse depending on the preservation goals, including antimicrobial agents (e.g., essential oils, nanoparticles, plant extract, etc.), antioxidants (e.g., essential oils, plant extract, etc.), anti-browning agents (e.g., ascorbic acid, citric acid, essential oil, oxalic acid, plant extract, etc.), ethylene signaling inhibitors (e.g., 1-Methylcyclopropene), and antagonistic microorganisms (e.g., bacteriophage, lactic bacteria, etc.). Different materials are selected for optimal preservation results depending on the type of fruit and its intended preservation. However, these extra materials could impact the coating structure, necessitating research on suitable extra materials for the EC is necessary.

3. Properties of edible coating

3.1. General characteristics

The EC acts as a physical film that covers the surface of the fruit, blocking the fruit surface with the ambient environment. Barrier properties are essential properties that prevent the exchange activity between fruit and the ambient environment. Scanning electron microscope (SEM) analysis revealed that uncoated strawberries displayed visible lines and stomata on their surface, while the coated fruits appeared smoother with a uniformly distributed coating solution and no visible stomata (Fig. 2a-b) (Wigati et al., 2023a). Similarly, the morphological observations revealed that the combination of rice starch, ι-carrageenan, sucrose fatty acid esters, and glycerol effectively formed a solid semi-permeable membrane on the coated plum fruit, while the uncoated fruit exhibited visible cracks on its surface (Thakur et al., 2018) (Fig. 2c-f). These properties reduce respiration, metabolism, and transpiration, leading to a slow-down ripening process.

The ability of EC to decelerate fruit metabolism during storage has been documented in numerous previous studies. In plum fruit, a significant increase ($p < 0.05$) in ethylene production in uncoated fruit was recorded at 9.76 μL C_2H_2/Kg/h, which was 8.08 μL C_2H_2/Kg/h higher than coated fruit by rice starch-ι-carrageenan-sucrose fatty acid esters and glycerol at 21 days of storage (Thakur et al., 2018). The EC made of chitosan could create a steady-state atmosphere in packages with 12.6–16.2 kPa of CO_2 and 2.3–3.7 kPa of O_2 after 9–10 days of fresh-cut melon storage (Ortiz-Duarte et al., 2019). Similarly, chitosan nanoparticles with konjac glucomannan as a dispersant were shown to reduce the oxygen permeability of film with 1.93×10^{-13} (cm^3.cm)/(cm^2.s.Pa) which is much lower than the oxygen permeability of chitosan, gelatin, gelatin/chitosan, gelatin/chitosan/montmorillonite and starch films (Deng, Wang, et al., 2024). Similarly, the oxygen barrier property of the chitosan/dialdehyde cellulose film was enhanced eightfold compared to chitosan alone (Ruan et al., 2022). Besides, UV light-induced free radicals in food materials cause color degradation, nutrient loss, and lipid damage, making UV protection crucial for preserving fresh fruits. The EC improves the UV absorption capacity (Li et al., 2023; Deng, Wang, et al., 2024), which prevents UV rays from reaching the fruit peel, affecting fruit quality during storage. The transmittance at 600 nm of EC based on starch was higher than 60 %, and adding ferulic acid to cassava starch coating positively impacts fruit preservation, minimally affects the appearance of coated fruit, and provides protection against UV damage (Li et al., 2023). These results indicate that using EC provides many benefits in fruit preservation. However, to improve preservation efficiency, adding extra materials to EC is necessary.

3.2. Improving the properties of edible coatings using extra materials

ECs are biodegradation materials, and various fungi in the soil could break down a significant amount of natural polymers. Therefore,

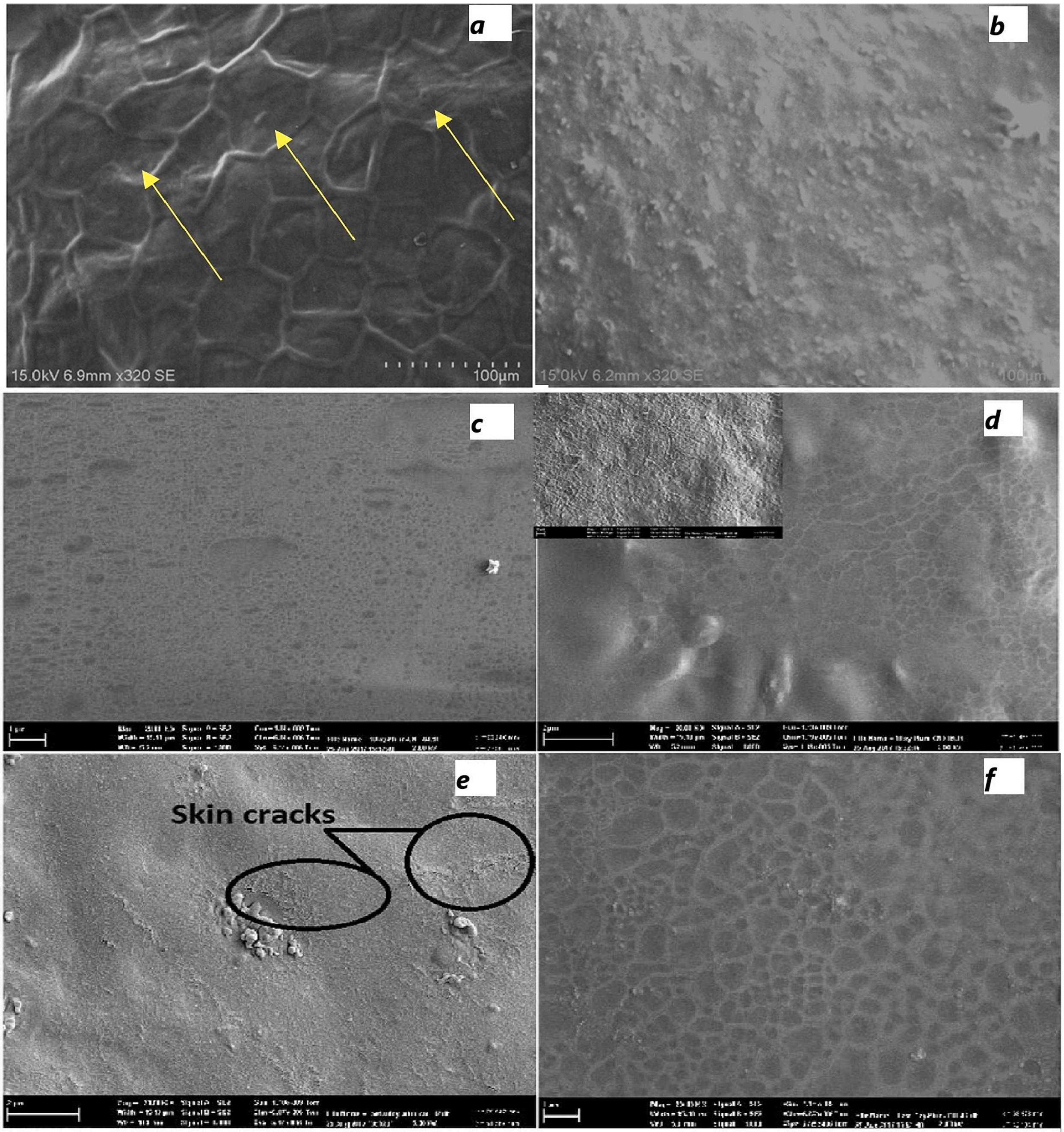

Fig. 2. SEM images of uncoated strawberries (a) and coated strawberries by yam bean starch, agarwood bouya oil, and calcium propionate (b). Stomata on strawberry surface (indicated with yellow arrows) (Wigati et al., 2023a). Coated plum fruit by starch 3 %, carrageenan 1.5 %, and fatty acid esters 2 %, control fruit day 1 (c), coated fruit day 1 (d), control fruit day 21 (e), coated fruit (f) were stored for three weeks at 20 °C (Thakur et al., 2018). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

supplementing extra materials could prevent and inhibit the spoilage caused by fungi. Moreover, this approach could enhance the favorable properties for fruit preservation, such as antioxidants, anti-browning, etc. Furthermore, the extra materials also increased EC's thickness and UV-blocking ability (Kumar et al., 2020).

3.2.1. *Anti-microorganism properties*

Previous studies have shown that incorporating antimicrobial agents into EC significantly improves its ability to combat fruit pathogens (Liu et al., 2022; Moreno et al., 2020; Ranjith et al., 2022; Zidan et al., 2023). Extra materials containing antimicrobial properties are diverse, including essential oils, plant extracts, nanoparticles, antagonistic microorganisms, fermentation products, etc.

The essential oils possess broad-spectrum antimicrobial properties (Lieu, Dang and Nguyen, 2018; Gago et al., 2022; Liu et al., 2022; Chen et al., 2024), enhancing the coating's antimicrobial efficiency when combined with EC. There are many sources of essential oils such as cinnamon (Lieu & Dang, 2021), basil (Wigati et al., 2023b), clove (Pandey et al., 2023), lemongrass (Lieu, Ngo, Lieu, Nguyen and Dang, 2018; Gago et al., 2022), oregano (Kostić et al., 2023), Rosemary (*Rosmarinus officinalis* L.) and thyme (*Thymus vulgaris*) (Quintana et al., 2021), lemon (Hernández-Carrillo et al., 2021), etc. The ECs based on a 1:1 mixture of soluble soybean polysaccharide and carboxymethyl chitosan, containing 1 % lavender essential oil, exhibited excellent antibacterial effects against Gram-positive and Gram-negative bacteria (Liu et al., 2022). Similarly, chitosan/*aloe vera* gel coatings with a 4:1 ratio, including orange peel essential oils, demonstrated antimicrobial activity against *Klebsiella pneumoniae, Escherichia coli*, and *Staphylococcus aureus*, in contrast to coatings without essential oils, which did not show antimicrobial effects (Felicia et al., 2024). Lemongrass oil at a concentration of 2.5 % (*w*/w), incorporated into sodium alginate coating 2 % (w/w), resulted in more significant decay and weight loss in 'Rocha' pears compared to 1.25 % w/w (Gago et al., 2022). Besides, the antibacterial effectiveness of the nanocomposite coating against *E. coli* and *S. aureus* was significantly increased by 57.13 % and 62.18 %, respectively, due to the addition of carvacrol into chitosan-cellulose nanocrystals coating (Li, Li, Wang and Xie, 2024). In addition, essential oils not only exhibit antimicrobial activity but also contain a high total phenol and antioxidant content due to their bioactive compounds (Lieu & Dang, 2021; Gago et al., 2022; Wigati et al., 2023a; Wigati et al., 2023b; Li, Li, Wang and Xie, 2024). However, at high concentrations, essential oils could have a negative impact on the peel or pulp fruit (Kostić et al., 2023; Lieu & Dang, 2021). Furthermore, using EC combined with antimicrobial agents, especially essential oils, which have a strong odor for fresh-cut fruit preservation, would mask the original flavor. Therefore, the appropriate essential oil concentration is necessary to ensure antifungal efficiency but not negatively impact the fruit.

Besides essential oils, plant extracts such as raspberry leaf extract (Rabasco-Vílchez et al., 2024), turmeric extracts or green tea extracts (Yang et al., 2022), pomegranate peel extract (Bodana et al., 2024), Fagonia indica (Ghulam Khaliq et al., 2019), quercetin (a natural plant flavonoid) (Du et al., 2023) also received much attention. A study by Zidan et al. (2023) showed that date palm fruit waste extract with antibacterial, yeast, and mold resistance when added to a chitosan/polyethylene glycol coating, significantly improved the storage efficiency of strawberries (Zidan et al., 2023). According to Moreno et al. (2020), the addition of ethanolic extract of propolis to gelatin film exhibited significant antifungal properties against major fungal pathogens that affect fruits and vegetables, including *Penicillium digitatum, Penicillium expansum, Penicillium italicum, Botrytis cinerea, Alternaria alternata,* and *Aspergillus carbonarius*.

Another strategy for providing extra sources of antimicrobials to EC that is receiving much attention is the use of antagonistic microorganisms. Álvarez et al. (2021) suggested that incorporating *Lactiplantibacillus plantarum* into the EC helped extend the shelf life of cherry tomatoes by protecting them from fungal decay. Lactic acid bacteria added to EC suppressed coliform, mold, and yeast, with no colonies detected during cherry tomato storage (Álvarez et al., 2021). Incorporating bacteriophages into ECs has significantly enhanced their antimicrobial properties. Similarly, the antimicrobial activity against *Salmonella* of bacteriophage in different ECs such as whey protein concentrate, carboxymethyl cellulose, chitosan, and sodium alginate in which whey protein showed the most efficiency (Sezer et al., 2022). In this approach, antagonistic microorganisms must be present inside the EC at high concentrations. Additionally, the integrity of the fruit peel is crucial. If the fruit peel is damaged during transportation or/and storage, causing juice leakage, antagonistic microorganisms would firstly be the primary cause of fruit damage. Besides, using fermented products combined with EC is another potential approach receiving attention. In a study by Ranjith et al. (2022), chitosan demonstrated superior antifungal ability, peptide release, and degradability when incorporated with probiotic-fermented palm kernel cake compared to other polysaccharides such as starch potato, pectin, carrageenan powder, microcrystalline cellulose, sodium alginate, and carboxymethyl-cellulose. Similarly, flaxseed mucilage coating supplemented with postbiotics obtained from *Lactobacillus acidophilus* LA-5 showed a significantly reduced fungal count during strawberry storage (Sharafi et al., 2024a, 2024b). Iturin, the lipopeptides generated through the fermentation process of *Bacillus* ssp. showed high antifungal activity against *C. gloeosporioides*, enhancing the antifungal activity of edible coating-based chitosan to preserve mangoes (Li, Bi, Dai and Ren, 2024).

Another promising approach is using additional silver nanoparticles (AgNPs) in EC for fruit and vegetable preservation, which has been proven to be a potential and sustainable approach (Alharbi et al., 2024; Lieu, Dang and Nguyen, 2024; Zhang et al., 2024). AgNPs synthesized from plants not only have a high spectrum board anti-microorganism activity but also have been proven to be non-toxic (Alharbi et al., 2024; Zhang et al., 2024) and have been applied in whole fruit and fresh-cut fruit preservation (Ortiz-Duarte et al., 2019; Zhang et al., 2024). Furthermore, incorporating AgNPs into EC resulted in a UV-blocking capacity (Kumar et al., 2020).

3.2.2. Antioxidant properties

The antioxidant properties of fruit could be enhanced by incorporating a supplementary composition into EC such as essential oil (Kostić et al., 2023; Goswami et al., 2024; Li, Li, Wang and Xie, 2024; Oliveira et al., 2024), turmeric or green tea extracts (Yang et al., 2022), date palm fruit waste extract (Zidan et al., 2023), organic acids such asascorbic acid (Martínez-Ortiz et al., 2019; Saleem et al., 2021; Wang et al., 2023). Li, Li, Wang and Xie, 2024 suggested that carvacrol incorporated into chitosan-cellulose nanocrystal EC gives an antioxidant effect attributed to its phenolic hydroxyl group, which exhibits a superior antioxidant capacity. Increasing the amount of essential oil would enhance the antioxidant activity of the EC (Kostić et al., 2023). A study by Liu et al. (2022) found that incorporating lavender oil into soluble soybean polysaccharide-based coatings with carboxymethyl chitosan improved the antioxidant and antibacterial properties. Additionally, this incorporation enhanced the EC's water vapor barrier, UV barrier, and mechanical properties (Liu et al., 2022). Similarly, the polyphenols, alkaloids, flavonoids, tannins, and steroids present in the date palm fruit waste extract have been found to exhibit antibacterial and antioxidant properties, effectively inhibiting the growth of microbial cells (Zidan et al., 2023).

3.2.3. Anti-browning properties

One of the main challenges in preserving fruit, especially fresh-cut fruit, is the development of flesh browning due to polyphenol oxidase activity, influencing customers' purchasing decisions. The factors causing the browning of fruit peel resulting in the polyphenol oxidase activity include water loss, chilling injury, disease, and mechanical damage (Zhang et al., 2023). The polyphenol oxidase activity values increased gradually throughout the storage period (Khan et al., 2023; Rather & Mir, 2023. The EC was improved by adding ingredients such as ascorbic acid, citric acid, essential oil, oxalic acid, plant extract, sodium chlorite, oleuropein, olive oil, etc., to enhance anti-browning (Castro-Cegrí et al., 2023; Guerreiro et al., 2017; Kim et al., 2022; Liu et al., 2022; Magri et al., 2024; Murmu & Mishra, 2018; Rather & Mir, 2023).

Changes in polyphenol oxidase activity of the exocarp of zucchini fruit were significantly reduced in fruit coated by dextrin plus olive oil (0.2 %), as Castro-Cegrí et al. (2023) reported. The ECs with soluble soybean polysaccharide and carboxymethyl chitosan (ratio 1;1) containing lavender oil (1 wt%) could slow down banana peel browning during nine days of storage at 25 °C and 56 ± 2 % RH (Liu et al., 2022). Similarly, combining sodium alginate and whey protein isolate significantly inhibited the browning of bananas after 8 days of storage at 25 °C compared to control and commercial polyethylene samples (Deng, Zhang, et al., 2024) (Fig. 3i). The anti-browning agent ascorbic acid 0.1 % (*w*/*v*) proved to be very efficient when combined with the EC eugenol 2 % (*w*/w) combined with eugenol 0.1 % (w/v) that maintained 'Bravo de Esmolfe' fresh-cut apple quality (Guerreiro et al., 2017). Plant extract in which *Morus alba* root extracts (1.5 % w/v) were incorporated into carboxymethyl cellulose (1.5 % w/v) showed anti-browning in bananas with a peel color difference (ΔE) had more than twice the difference in color difference values compared to uncoated samples (Kim et al., 2022). Khan et al. (2023) indicated that the reduction in browning of peach surface can be obtained by applying coatings that protect the

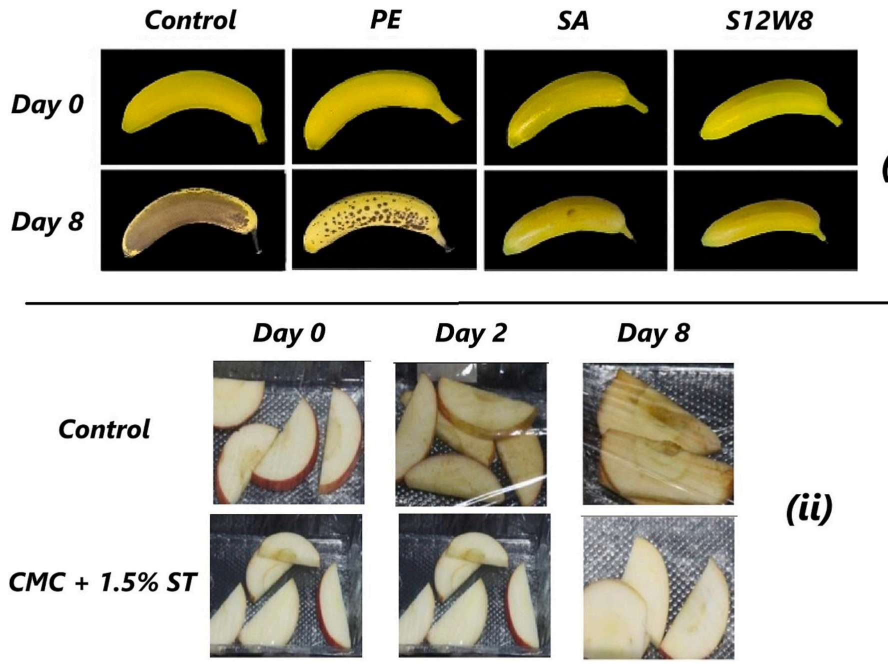

Fig. 3. Effect of edible coatings on the browning of banana (i) and fresh-cut apple slices (ii). (i). PE: polyethylene; SA: sodium alginate; S12W8: sodium alginate + whey protein isolate (Deng, Zhang, et al., 2024). (ii). CMC: carboxymethylcellulose; ST: Seabuckthorn leaves (Rather & Mir, 2023).

structure and integrity of the cell membrane. Seabuckthorn leaves (1.5 % w/v) have been proven to have an anti-browning property incorporating into carboxymethylcellulose (1 % w/v) inhibited the polyphenol enzyme activity in fresh-cut "Maharaji" apple for eight days at 4 °C (Rather & Mir, 2023) (Fig. 3 ii). These results indicated that adding extra materials significantly improved the fruit preservation efficiency of EC. However, the effect of extra materials on film structure should be evaluated to ensure the preservation efficiency.

3.3. *Effect of extra materials on film structure*

Extra materials significantly improve fruit preservation efficiency. However, the presence of these materials could also change EC's properties. To evaluate the properties of EC, a substantial amount of EC materials is utilized to pour into the mold to create thick films for testing characteristics such as elongation at break, optical properties, tensile strength, water vapor permeability, etc. Previous studies have shown that combining coating materials enhances the film structure. Huang, Hong, et al. (2023) found that the covalent grafting of epigallocatechin gallate significantly enhanced the wetting and adhesion properties of pectin coatings on the surface of grape skin. Similarly, Oliveira et al. (2024) suggested that the carboxymethylcellulose (CMC) coating, combined with essential oil (*Lippia sidoides*), positively impacted the physicochemical characteristics of the fruit for eighteen days under refrigerated storage while enhancing strawberries' color. According to Moreno et al. (2020), Argentine propolis ethanolic extract (PEE) incorporated into gelatin showed some stretch marks and no phase separation. The authors also indicated that interactions between proteins and polyphenols such as chalcones, phenolic acids, and flavonoids could occur and might favor the integration of the PEE in the biopolymer matrix (Moreno et al., 2020). The coating with low water vapor permeability is preferred because it helps maintain the moisture content of food and fruit products. A study conducted by Zidan et al. (2023) demonstrated that including palm fruit waste extract in chitosan/polyethylene glycol coatings increased water solubility and decreased water vapor permeability. However, incorporating supplement materials into ECs could potentially impact the overall film structure (Das et al., 2023; Moreno et al., 2020). Deng, Zhang, et al. (2024) indicated that the tensile strength and elongation at break were significantly enhanced when whey protein isolate, and gluconolactone were added to sodium alginate film. The authors also showed that the high whey protein isolate affected the gel structure, decreasing the film's tensile strength (Deng, Zhang, et al., 2024). Bodana et al. (2024) incorporating pomegranate peel extract 0.1 % (g/ml) into jackfruit seed starch 5 % (*w/v*) enhanced the total phenolic content and antioxidant activity, but also had negative impacts on the water vapor permeability, oxygen permeability, and tensile strength. Similarly, the addition of propolis ethanolic extract did not significantly impact gelatin films' microstructural and water barrier properties but significantly affected the mechanical behavior, making the films more elastic and stretchable than the control film (Moreno et al., 2020). A study by Kostić et al. (2023) found that the control pectin film had a relatively homogeneous structure, while the structures of oregano oil -oil-containing films were porous, and larger micro-pores were formed at higher oil concentrations (0.5 % and 1 %). Similarly, Liu et al. (2022) indicated that Incorporating lavender essential oil into the film made from soluble soybean polysaccharide and carboxymethyl chitosan resulted in the surface of the blended film exhibiting numerous crater-like pits (Fig. 4i). Yang et al. (2022) found that high concentrations of 5 % (*v*/v) of turmeric or green tea extracts caused film agglomeration, reduced elongation at break, increased tensile strength, and caused discontinuities in the matrix polymer (Fig. 4 ii).

In another report by Van et al. (2023), mandarin oil added to coatings (made by carboxymethyl cellulose and cellulose nanofibers) significantly affected the properties of coating solutions and the film characteristics, as shown in b*, and roughness values increased strongly. Besides, adding essential oil would impact the coating properties, resulting in a darker color of EC and a decrease in the water vapor barrier (Liu et al., 2022). These results suggest that combining supplements with extra materials at high concentrations affects the bonding network of the EC and weakens its structure. Therefore, choosing a suitable concentration of supplement components is essential to ensure preservation efficiency. Furthermore, since the coated fruit may be eaten directly, the coating materials must be safe at all levels.

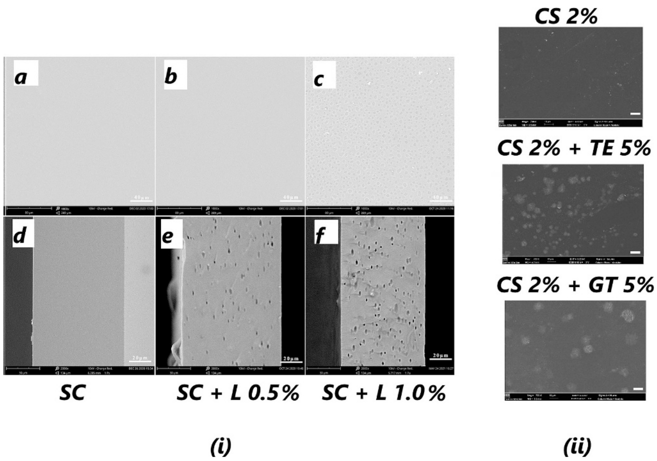

Fig. 4. Effect of extra materials on the film. (ii). The SEM images of the films' surface (a-c) and cross-section (d-f). SC: soluble soybean polysaccharide (1.5 %) + carboxymethyl chitosan (1.5 %); L: lavender oil (Liu et al., 2022). (ii). The SEM images of the films' surface. CS: Chitosan; TE: turmeric extract; GT: green tea extract (Yang et al., 2022). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.4. Sensory properties

In preserving agricultural products, particularly fruits, sensory properties play a vital role in influencing consumers' purchasing decisions. One significant advantage of using coatings for fruit preservation is that these coatings not only do not affect the sensory appearance but also maintain the quality of the fruit throughout the preservation process (Ajay Gill et al., 2024; Chettri et al., 2024; Li et al., 2019). Additionally, ECs can be applied to fruits eaten directly (without peeling) or to fresh-cut fruits without compromising their sensory quality (Nascimento et al., 2020; Oliveira et al., 2024; Rather & Mir, 2023; Saleem et al., 2021; Yang et al., 2022).

A study conducted by Ajay Gill et al. (2024) found that mango fruit treated with a composite coating comprising gum Arabic 20 % (*w/v*) and cinnamic acid 0.2 % (w/v) did not show a significant difference in sensory quality on the first day. However, after 28 days of storage at 12 °C, these treated mangoes registered a higher sensory score (Ajay Gill et al., 2024). Coated sapota fruits treated with soybean starch showed improved visual and sensory characteristics compared to uncoated samples stored under ambient conditions, according to Chettri et al. (2024). Additionally, the use of sodium alginate (1 % w/v) coating for peach fruit preservation maintained sensory scores of appearance, aroma, sweetness, juiciness, texture, and flavor were 6.3, 6.1, 6.7, 6.4, 5.1, 4.8 compared to 3.5, 3.6, 3.1, 3.4, 3.3, 3.2, respectively in control samples stored at room temperature for 7 days (Li et al., 2019). These benefits are due to EC serving as a barrier, slowing the ripening process, and improving sensory quality compared to uncoated fruit.

Previous studies have also demonstrated the benefits of ECs in preserving fruits that can be eaten directly (without peeling) or as fresh-cut products. Yang et al. (2022) indicated that chitosan-based coating containing turmeric and green tea extracts did not significantly affect the flavor and taste of strawberries. Similarly, fresh-cut guava coated with chitosan-citric acid (5 mg/mL) showed no sensory differences such as appearance, color, and flavor compared to control samples (coated with glycerol 0.5 %) (Nascimento et al., 2020). Moreover, the EC significantly better preserves the quality value of fruit during storage compared to the control sample (Nascimento et al., 2020; Oliveira et al., 2024; Rather & Mir, 2023; Saleem et al., 2021). Saleem et al. (2021) indicated that strawberries coated by chitosan 1 % (w/v) and ascorbic acid 1 % (w/v) demonstrated significant improvements after 15 days of storage at 4 °C, achieving 1.72-fold higher taste scores, 2.67-fold higher color scores, 2.00-fold higher glossiness scores, and 1.95-fold higher overall acceptability scores compared to uncoated samples. Another study by Oliveira et al. (2024) suggested that coated strawberries by carboxymethylcellulose exhibited a more pronounced brightness than the control ones and maintained a characteristic strawberry color intensity until the sixth day of storage at 4 °C. EC based on carboxymethylcellulose incorporated with seabuckthorn leaf extract maintaining the fresh-cut apple quality including appearance, color, aroma, texture, taste, overall acceptability after 10 days storage at 4 °C, as reported by Rather and Mir (2023). Research results indicate that edible coatings do not negatively impact the sensory appearance of fruits, particularly fresh-cut and directly consumed varieties, and they help maintain fruit quality during storage.

4. Application of edible coating for fruit preservation

4.1. Causes of fruit damage during storage

The spoilage of fruits is caused by two main factors (Fig. 1S). Firstly, internal factors such as metabolism and respiration inside the fruit. Secondly, external factors such as the attack of microorganisms cause damage to the peel, especially through wounds on the fruit and improper preservation. Internal factors during fruit preservation are primarily caused by reactive oxygen species (ROS). Besides, the total suspended solids increase due to the hydrolysis of polysaccharides into simple sugars and other soluble compounds. These factors lead to processes such as membrane lipid peroxidation and the activity of enzymes like polygalacturonase, cellulase, and pectin methyl esterase. Along with internal ones, external factors contribute to post-harvest losses. These include improper handling, inadequate control of storage temperature, and attacks by microorganisms. These factors significantly affect the quality of fruit, especially microbial attacks that can cause rapid damage and spread on the fruit. These effects impact the quality of the fruit by reducing firmness, hastening spoilage, and causing weight loss. Additionally, they can affect key quality indicators such as Brix, pH, titratable acidity, and total soluble solids.

Previous studies have demonstrated that EC significantly extends the shelf life of fruit by accelerating the activity of ROS-scavenging enzymes and inhibiting microorganisms. One of the significant advantages of applying EC in fruit preservation is the simple process, ease of carrying out, etc. There are various approaches to apply EC in fruit preservation (Fig. 5), the most popular of which are immersion/ dipping (Chettri et al., 2024;), spray (Gago et al., 2022; Chettri et al., 2024; Deng, Wang, et al., 2024; Rabasco-Vílchez et al., 2024), brushing (Chettri et al., 2024; Kim et al., 2022), and layer-by-layer (Du et al., 2021; Ghosh et al., 2021; Jurić et al., 2023; Magri et al., 2024; Treviño-Garza et al., 2017; Zhou et al., 2024). Chettri et al. (2024) indicated that sapota fruits were coated with extracted soybean starch by different coating approaches, including dipping, spraying, and brushing, in which the dipping approach exhibited better physiochemical analysis results than other approaches. Still, the effectiveness of fruit preservation also depends on the type of fruit, the EC components, and the adhesion of these components to the fruit skin, and from there, the appropriate approach is chosen. ECs have been proven to maintain fruit quality by reducing weight loss, respiration rates, and ethylene production, maintaining firmness, inhibiting pathogens, slowing ripening, decreasing chilling injury, and reducing electrolyte leakage, malondialdehyde, and hydrogen peroxide during storage (Afonso et al., 2023; Álvarez et al., 2021; Chettri et al., 2023; Ehteshami et al., 2019; Iqbal et al., 2024; Kim et al., 2022; Liu et al., 2024; Ma et al., 2021; Tabassum et al., 2023; Zheng et al., 2024).

4.2. Mechanism of edible coating on fruit preservation efficiency

During storage, the EC significantly affects fruit metabolism (Fig. 6). Malondialdehyde is a secondary end-product of membrane lipid peroxidation and serves as an indicator of oxidative stress. This process

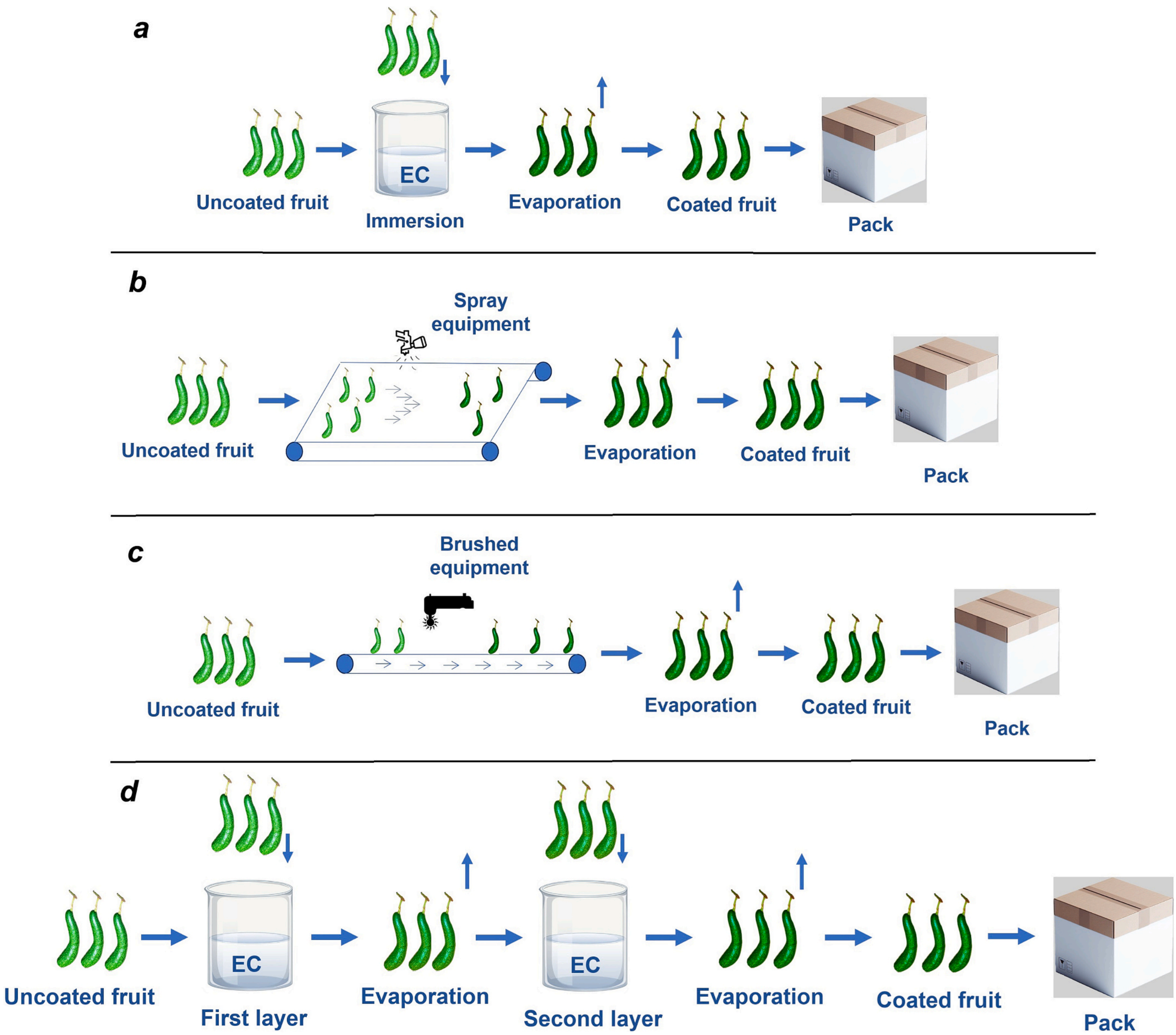

Fig. 5. Schematic representation of the coating preparation process and its application. (a): Immersion approach; (b): Spray approach; (c): Brushed approach; (d): Layer-by-layer approach.

damages cell membranes, reduces the membrane integrity of the fruit cell, and reduces the quality and nutritional value of the fruit. Chitosan EC with ascorbic acid delays malondialdehyde accumulation from lipid peroxidation, maintaining custard apple quality during storage (Wang et al., 2023). Similarly, applying a sodium alginate/chitosan coating to strawberries resulted in a significantly delayed accumulation of malondialdehyde compared to the uncoated group (Du et al., 2021). Konjac glucomannan/low-acyl gellan gum coating significantly reduced malondialdehyde production during the lipid peroxidation process during blueberry storage with 27.25 μ mol/g compared to 41.06 μ mol/g in uncoated samples (Huang, Ding, et al., 2023). The coating material type also affects the lipid peroxidation activity level over the fruit storage time. Lipid peroxidation activity during storage of zucchini fruit covered with dextrin (1 %), starch (1 %), chitosan (1 %), and carboxymethylcellulose (1 %) after 14 days of storage at 4 °C were 408; 403; 434; and 437 μg MDA/kg fresh weight, respectively that compared to 578 μg MDA/kg fresh weight in control samples (Castro-Cegrí et al., 2023).

Li, Bi, Dai and Ren (2024) found that adding iturin (a product by *Bacillus* ssp. fermentation) to chitosan coatings on mangoes boosts stress defense enzymes such as glutathione reductase, catalase, ascorbate peroxidase, and peroxidase, significantly improving resistance to pathogen infection and enhancing preservation. Incorporating ascorbic acid (1 % *w/v*) into the EC based on chitosan (1 % w/v) reduced cell wall degrading enzyme activities such as polygalacturonase, cellulase, and pectin methyl esterase during strawberry preservation, as reported by Saleem et al. (2021). Similarly, a study conducted by Wang et al. (2023) found that incorporating ascorbic acid (1 % w/v) into chitosan coating (1 % w/v) inhibited the expression of cell wall degrading enzymes during custard apple storage. Saleem et al. (2021) also indicated that ascorbic acid incorporation catalyzed ROS scavenging enzymes (ascorbate peroxidase, catalase, peroxidase, and superoxide dismutase) activities that maintained fruit quality under cold storage. Magri et al. (2024) demonstrated the ability of EC based on carboxymethyl cellulose and sodium alginate containing oxalic and citric acid to enhance the activities of key enzymes, including superoxide dismutase, catalase, and the entire AA-GSH cycle, while simultaneously reducing the activities of guaiacol peroxidase and polyphenol oxidase. Previous studies also

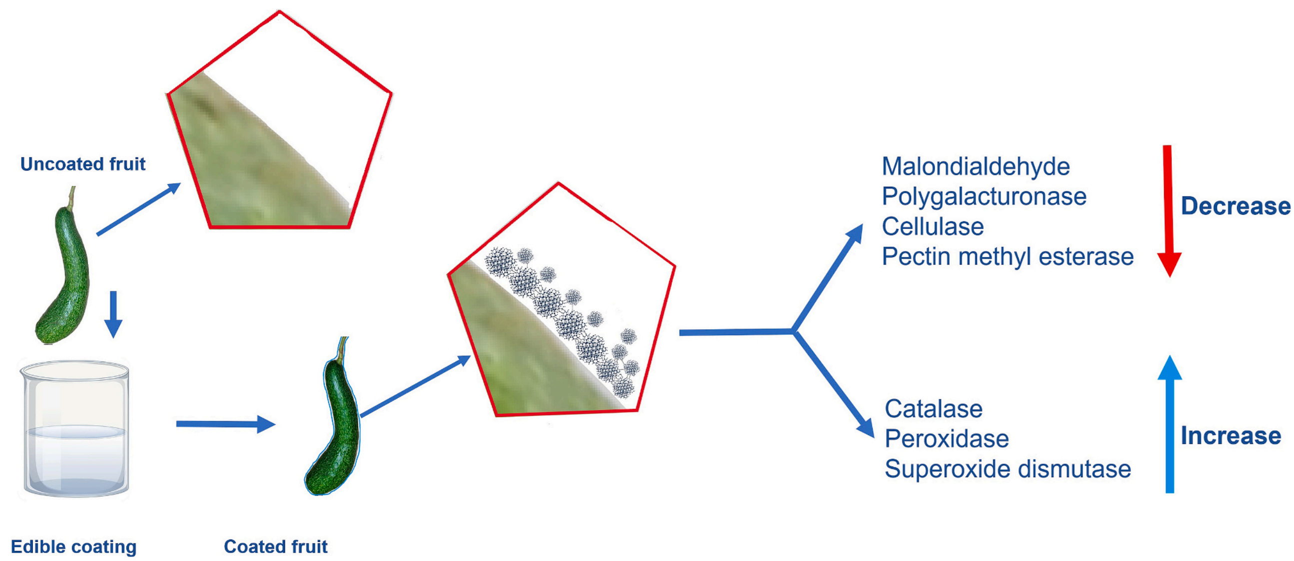

Fig. 6. Mechanism of edible coating on fruit preservation efficiency.

demonstrated that applying an EC to the fruit's surface can seal the stomata on the fruit surface, preventing quantity loss and maintaining the fruit's shelf-life. Besides, the application of a sodium alginate/chitosan coating on strawberries resulted in significant reductions in weight loss, preservation of antioxidant capacity, decreased consumption of total soluble solids, and titratable acidity compared to the uncoated group (Du et al., 2021). Moreover, the EC could improve control of the respiration rates and enzymatic and oxidative reactions of the fruit, which would conserve the color of the fruit (Zhou et al., 2023). The processes primarily relate to the barrier property of the EC, which prevents the exchange of metabolites between the fruit and the environment. The EC can be applied to both whole and fresh-cut fruits for preservation. Depending on the type of fruit and the preservation purpose, choose the appropriate coating materials and extra materials.

4.3. EC for whole fruit preservation

The application of EC provides many benefits in whole fruit preservation (Fig. 7). The indexes to consider in whole fruit preservation include weight loss, firmness, damage level, and other quality indexes such as pH, acidity, and Brix. The specific requirements for these indexes vary depending on the type of fruit.

4.3.1. Main benefits of EC

The weight loss of fruit is an essential factor closely linked to water loss. Additionally, limiting enzyme activity and minimizing water loss is essential for maintaining fruit firmness, a critical characteristic for fruit preservation. Previous studies have demonstrated that applying an EC could decrease the amount of weight loss in fruit during storage (Abera et al., 2024; Chettri et al., 2024; Jurić et al., 2023; Kim et al., 2022; Li et al., 2019; Quintana et al., 2021; Sharafi et al., 2024a, 2024b; Temiz & Özdemir, 2021; Wang et al., 2023; Zheng et al., 2024). Coated sapota fruits by lima bean starch showed a weight loss percentage of 15.28 % compared to 28.79 % in control samples (Chettri et al., 2023). Bodana et al. (2024) found that incorporating of pomegranate peel extract 0.1 % (g/ml) into jackfruit seed starch 5 % (*w/v*) reduced weight loss and maintained firmness in white grapes. A study by Deng, Wang, et al. (2024) indicated that the weight loss rate of bananas in the control group was as high as 14.42 ± 0.69 % after seven days, while that in the chitosan nanoparticles with konjac glucomannan as a dispersant group was only 7.59 ± 0.56 %. Similarly, banana coating by carboxymethyl cellulose 1.5 % (*w/v*) showed 24.25 % weight loss compared to 32.26 % in control samples after 15 days of storage at 13 °C ± 2 °C (Kim et al., 2022). The weight loss of strawberries coated by flaxseed mucilage extraction of 5 % (w/v) after 12 days of storage at 4 °C significantly

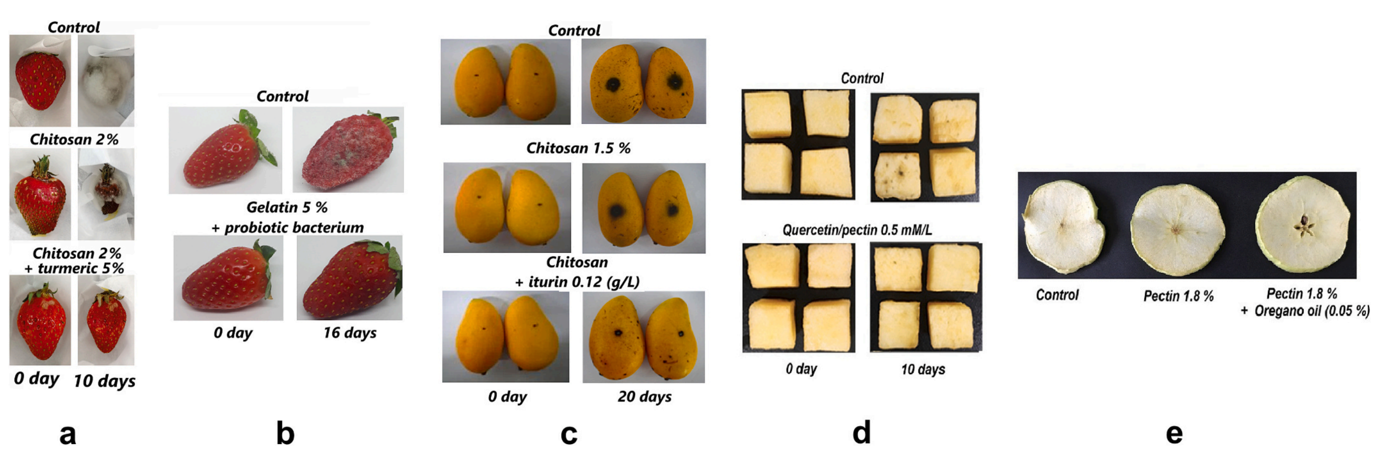

Fig. 7. Effect of edible coating on whole fruit and fresh-cut fruit appearance during storage. (a). strawberries during 10 days of storage at 20 °C (Yang et al., 2022); (b) strawberries during 16 days of storage at 4 °C (Temiz & Özdemir, 2021); (c). Mangoes (infected by *Colletotrichum gloeosporioides*) during 20 days of storage at 12 °C (Li, Bi, Dai and Ren, 2024); (d). Fresh-cut apples coated by Quercetin/pectin 0.5 mM/L (Du et al., 2023); (e). Fresh-cut apples coated by pectin 1.8 % and Oregano oil (0.05 %) (Kostic et al., 2023).

reduced by 1.7 % compared to 8.06 in uncoated samples (Sharafi et al., 2024a, 2024b). Also, carboxymethyl cellulose and cellulose nanofibers EC containing mandarin oil have proven to reduce weight loss and the degradation of strawberry quality during storage at 5 °C (Van et al., 2023). Rabasco-Vílchez et al. (2024) found that chitosan supplements lignocellulosic nanofibers and raspberry leaf extract significantly reduced fruit size loss and managed fungal development compared to uncoated strawberries after 16 days of storage at 5 °C (Rabasco-Vílchez et al., 2024). Similarly, chitosan-based EC 1 % (*w/v*) also showed to reduce the weight loss of custard apple (*Annona squamosa*) after 12 days of storage at 15 °C with 9.10 % compared to 14.66 % in the uncoated sample (Wang et al., 2023).

Some reports, however, indicated that EC did not reduce fruit weight loss. A study by Sena et al. (2019) showed that using edible corn starch-based coating 4 % (*v*/v) was ineffective in reducing weight loss in cashew apples during storage. Pectin EC (3 % w/v) did not reduce weight loss in strawberries during 31 days of storage at 4 °C compared to uncoated samples, as Hernández-Carrillo et al. (2021) reported. Seid-idamyeh et al. (2024) indicated that gum Arabic coating for fresh-cut red capsicum preservation did not reduce the weight loss compared to control during 16 days of storage at 4 °C.

Besides the weight loss index, the firmness of fruit is one of the primary physical factors that significantly affect consumer acceptability. The fruit's cell wall serves as a protective function, and its degradation leads to fruit softening. Fruit firmness is related to the activity of the enzyme β-galactosidase during storage. Previous studies have demonstrated that EC significantly reduces fruit softness during storage (Afonso et al., 2023; Bersaneti et al., 2021; Das et al., 2022; Li et al., 2019; Liu et al., 2024; Zheng et al., 2024). A study by Zheng et al. (2024) showed that ECs delayed the production of β-Galactosidase during fruit storage, which maintained fruit firmness better than the control. Liu et al. (2024) indicated that ECs may reduce the activity of cell wall degrading enzymes such as polygalacturonase, β-galactosidase, and pectin lyase, thus delaying the softening process and maintaining firmness. Bersaneti et al. (2021) found that starch coatings effectively delayed the increase in pH and maintained the firmness and anthocyanin content of the blackberry fruits. The firmness of peach fruit coated with alginate 1 % (*w/v*) was better maintained than that of the control after seven days of storage (Li et al., 2019). Similarly, the firmness of the control and tomato coated with carboxymethyl cellulose-based cardamom essential oil nanoemulsion decreased by 2.3 and 1.3 times after 15 days of storage at 25 ± 2 °C, respectively (Das et al., 2022). Uncoated guavas experienced the highest firmness loss (219 N, 12 days), while all guavas covered with chayotextle starch exhibited increased firmness values (270 N, 12 days) during storage (Martínez-Ortiz et al., 2019). Coating 'Rocha' pears with alginate enriched with lemongrass oil 1.25 % (*w*/w) reduced decay and color change while maintaining firmness better than the control samples, as Gago et al. (2022) reported. Li et al. (2019) suggested that the firmness maintained in the samples coated by the rhubarb supplementing alginate was attributed to its higher antibacterial activity, which slowed down intracellular matrix decomposition and reduction of the central vacuole.

Besides, the storage temperature has a significant impact on fruit firmness. Low-temperature storage helps maintain fruit firmness better than high-temperature storage (Álvarez et al., 2021). The decay rate of fruits is impacted by the storage temperature for the same type of coatings, in which a cool temperature of 4 °C was more effective in reducing the decay rate compared to room temperature (Araújo et al., 2024). This is due to the low temperatures that can inhibit metabolic enzyme activity, leading to fruit firmness maintenance. Jurić et al. (2023) indicated that low temperatures slow down metabolic enzymes during mandarin fruit storage, and the efficiency was significantly improved when combined with the EC approach. The low temperature also reduces the weight loss during storage. According to a study by Chettri et al. (2024), sapota fruit experienced weight losses of 29.89 % and 17.26 % at ambient temperature (28 ± 2 °C) and cool temperature (3 ± 1 °C), respectively, on the 15th day of storage. However, the preservation effect also depends on different ripening states, and applying this method would cause varying degrees of cold injury. This occurrence is linked to alterations in cell membrane integrity due to oxidative stress resulting from the high production of reactive oxygen species (Valenzuela et al., 2017). Therefore, it is necessary to evaluate the appropriate storage temperature for each type of fruit. Another approach to maintaining fruit firmness during storage is using calcium in film formation (Sena et al., 2019; Zhang et al., 2021). The EC of corn starch 4 % (v/v) enriched with calcium 2 % (w/v) improved cashew apple preservation, resulting in firmer fruit, reduced pectin methylesterase and polyphenol oxidase activity, and increased soluble solids content (Sena et al., 2019). Similarly, all the $CaCl_2$ and coating treatments based on carboxymethyl chitosan-gelatin limited fruit weight loss and maintained freshness and firmness during storage compared with untreated sweet cherry fruit during 30 days of storage at 0 ± 0.5 °C (Zhang et al., 2021).

However, some research has reported that using EC for fruit preservation did not maintain the firmness of the fruit during storage. A study by Wang et al. (2023) showed that chitosan-based EC 1 % (w/v) did not enhance the firmness of custard apples compared to uncoated samples. Similarly, the firmness of mandarin fruits did not show any significant difference between coated fruits (chitosan, alginate/chitosan, hydroxypropyl methylcellulose/chitosan, and locust bean gum/chitosan) and uncoated fruits at room temperature or cool temperature during storage, as indicated by Jurić et al. (2023). According to Seid-idamyeh et al. (2024), the firmness of fresh-cut red capsicum coated with gum Arabic did not improve compared to uncoated samples during 16 days of storage at 4 °C. These results suggested that the fruit firmness during storage depends on the type of fruit, coating materials, and storage condition.

The rate of fruit damage is a crucial factor in assessing the effectiveness of preservation. EC has been shown to reduce fruit spoilage during storage. A study by Zhou et al. (2024) indicated that EC based on hydroxypropyl methylcellulose 1 % (w/v) and chitosan 1.5 % (w/v) not only reduced the decay rate of tangerine fruit by 45 % compared to the uncoated samples but also maintained a high content of ascorbic acid. Similarly, the decay rate of strawberries was significantly reduced to 23.51 % with the sodium alginate/chitosan coating, compared to 41.31 % in uncoated groups (Du et al., 2021). One of the main causes of fruit spoilage is due to microorganisms. Therefore, extra materials with anti-microorganism properties are often added to extend the shelf life of fruits. Using extra materials to supplement ECs has been proven to enhance anti-microorganism effectiveness. Various extra materials have been applied in fruit preservation, such as essential oils, plant extracts, antagonistic microorganisms, fermentation broth, nanoparticles, etc.,

Strawberries (inoculated with *Penicillium* sp.) coated by pectin coating containing lemon oil and reuterin decreased up to 2 Log of fungal spores, and there is no mycelial growth was observed during storage compared to the control sample, which was fully covered by fungal growth after 17 days of storage at 4 °C (Hernández-Carrillo et al., 2021). A study by Iqbal et al. (2024) indicated that nano-emulsions formulated with Carboxymethyl cellulose 1.5 % (*w/v*) and a blend of essential oils (thyme, clove, and cardamom in a 1:1:1 ratio) exhibited a 58.23 % reduction in bacterial count compared to the control group after 30 days of kiwifruit storage at 10 °C. Also, the decay incidence of blueberries was significantly decreased when thymol was incorporated into Konjac glucomannan/low-acyl gellan gum coating with 6.35 % compared to 18.84 % in uncoated samples (Huang, Ding, et al., 2023).

Using plant extracts incorporated into EC has also proven to enhance anti-microorganism effectiveness in preserving fruit. Zidan et al. (2023) found that adding date palm fruit waste extract to chitosan/polyethylene glycol coating effectively inhibited fungal growth on strawberries after ten days of storage at 25 °C. In another study by Yang et al. (2022), adding turmeric extracts to chitosan, EC improved antifungal activity against *Botrytis cinerea* during ten days of strawberries storage at

20 °C, while 100 % of uncoated samples exhibited symptoms of gray mold disease (Fig. 7a). Moreno et al. (2020) indicated that raspberries treated with gelatin coatings containing ethanolic extract of Propolis presented a disease incidence of 20 % compared to 90 % in control samples after seven days of storage at 5 °C.

Another approach using antagonistic microorganisms added to EC has also been shown to reduce the rate of microbial spoilage during fruit storage. Adding *Lactobacillus rhamnosus* into gelatin coatings reduced fungal growth and aerobic mesophilic counts in strawberries during storage, resulting in a better appearance than control samples and reduced spoilage (Temiz & Özdemir, 2021) (Fig. 7b). Research by Sezer et al. (2022) demonstrated that strawberries coated with bacteriophage-infused materials substantially reduced *Salmonella* counts during storage, highlighting the effectiveness of this approach in enhancing the safety and longevity of ECs.

Besides, the use of fermented products also showed significant improvement in fruit preservation efficiency. Chitosan coating containing palm kernel cake (PKC) fermented by probiotic bacterium for mango (injected by *Colletotrichum gloeosporioides* and *Botryodiplodia theobromae*) preservation showed disease-free status compared to pure chitosan which had disease lesions 6.5 and 4 mm, respectively after nine days of storage at 25 °C (Ranjith et al., 2022). During storage at 4 °C and 85 % relative humidity for 12 days, strawberries coated with flaxseed mucilage supplemented with postbiotics (P) from *Lactobacillus acidophilus* LA-5 showed a significant increase in total phenolic content, total flavonoid content, antioxidant capacity, and total anthocyanin content compared to uncoated strawberries (Sharafi et al., 2024a, 2024b). Similarly, incorporating 0.12 g/L of iturin (lipopeptides generated through the fermentation process of *Bacillus* ssp.) into chitosan at a concentration of 15 g/L had a synergistic effect in preventing the expansion of lesions infected by *Colletotrichum gloeosporioides* in mangoes after 20 days of storage at 12 °C (Li, Bi, Dai and Ren, 2024) (Fig. 7c). Adding fermented product by the bacterium to chitosan coatings resulted in improved disease control, reduced respiratory rate, lower weight loss, higher total soluble solids, increased titratable acidity, and better fruit firmness maintenance during storage (Li, Bi, Dai and Ren, 2024). Incorporating ε-polylysine into soy protein isolate coating also showed a decrease in disease incidence of citrus fruit by 16.67 % compared to 78.67 % in control samples, as Hu et al. (2023) reported. Studies have shown that extra materials offer numerous benefits, including diverse sources, high anti-microorganism activity, and safety. Depending on the type of coating, type of fruit, and storage conditions, appropriate extra materials should be selected.

4.3.2. Improve fruit quality with extra materials

During fruit storage, changes in fruit components such as pH, titrable acidity, total soluble solids, phenolic content, etc., also significantly affect the quality of the fruit and influence the consumer's purchasing decision. In general, over time, the values such as total phenol content, total antioxidant content, etc., tend to decrease, while values such as pH, total soluble solids content, etc., show an increase recorded in some fruits such as custard apple, guava, peach, strawberries (Khan et al., 2023; Martínez-Ortiz et al., 2019; Temiz & Özdemir, 2021; Wang et al., 2023; Zhou et al., 2023). In the case of grapes fruit, the pH, total soluble solids content, and reducing sugar values remained unchanged, while titratable acidity tended to increase during storage at 12 °C for 24 days (Melo et al., 2018). This suggests that these parameters will vary depending on the fruit type and storage conditions. Additionally, the use of extra materials has been shown to enhance effectiveness against spoilage microorganisms and positively affect fruit quality during storage.

Adding cinnamon (2 %) into EC based on Arabic gum (5 %) and sodium caseinate (1 %) led to lower activity of polyphenol oxidase and peroxidase, higher DPPH radical scavenging activity, improved retention of ascorbic acid, phenol, and flavonoid content, and extended the shelf-life of guava to 40 days compared to the uncoated samples, which only lasted for seven days (Murmu & Mishra, 2018). Ajay Gill et al. (2024) indicated that the quality of mangoes was improved by EC based on gum Arabic (20 %) and cinnamic acid (2 %), which suppressed the activities of polygalacturonase, cellulase, and pectin methyl esterase during storage. Correspondingly, EC based on chitosan nanoemulsion and *Angelica archangelica* oil prevented contamination of *Botrytis cinerea* and maintained the quality attributes of table grape fruit, including weight, titrable acidity, total soluble solids, phenolic content, and pH during 30 days of storage at 25 ± 2 °C (Das et al., 2023). Furthermore, Li, Bi, et al. (2024) demonstrated that uncoated bananas and mangoes showed random spots, enzymatic browning, and decay, which were significantly reduced in fruits coated with a chitosan-cellulose nanocrystals-carvacrol blend.

Plant extracts have also been shown to maintain fruit quality effectively (Castro-Cegrí et al., 2023; Ghulam Khaliq et al., 2019; Li et al., 2019). The addition of rhubarb (*Rheum rhaponticum* L.) 5 % (*v/v*) to alginate coating 1 % (*w/v*) reduced weight loss, maintained firmness and soluble solids content, reduced respiration, and slowed polyphenol oxidase activity on peach fruits compared to samples without rhubarb (Li et al., 2019). Similarly, sapodilla fruit coated by *Aloe vera* 100 % and *Fagonia indica* 1 % significantly reduced weight loss, decay incidence, and soluble solids concentration, and preserved firmness and acidity compared to uncoated fruit over 12 days of storage at 20 °C (Ghulam Khaliq et al., 2019). Moreover, in zucchini fruit coating based on dextrin 1 % (w/v) plus oleuropein 0.3 % (w/v), superoxide dismutase activity was about 20 % higher than the control after 14 days of storage at 4 °C (Castro-Cegrí et al., 2023).

The presence of lactic acid bacteria in EC affected ethylene products and enzymes involved in fruit ripening. Álvarez et al. (2021) found that an exopolysaccharide-based EC supplemented with lactic bacteria significantly reduced ethylene production by 45 % compared to control samples during the storage of cherry tomatoes. Liu et al. (2024) indicated that EC made by pectin containing nisin may inhibit the activity of enzymes responsible for fruit decay, such as polygalacturonase, β-galactosidase, and cellulase, slowing down the microbial-induced rotting process.

Besides, adding nanoparticles to EC also effectively maintained fruit quality during storage (Khan et al., 2023; Melo et al., 2018; Zhang et al., 2024). Zhang et al. (2024) indicated that the bananas' appearance was maintained when treated with AgNPs incorporated in sodium alginate coating, compared to uncoated samples, which had more black senescent spots after nine days of storage at 25 °C. Edible chitosan nanoparticle coatings on grapes effectively delayed ripening, minimized weight loss and sugar content, enhanced moisture retention, and preserved acidity levels and taste characteristics (Melo et al., 2018). The coatings made by sodium alginate supplemented with green synthesized titanium dioxide nanoparticles and mousami peel extract positively affected several quality tributes, such as color index, pH, TSS, and titratable acidity (Khan et al., 2023).

On the same fruit, the quality of fruit during storage also varies depending on the type of coating materials. Jurić et al. (2023) found that coating materials such as chitosan, alginate/chitosan, hydroxypropyl methylcellulose/chitosan, and locust bean gum/chitosan have varying effects on the bioactive compounds and organic acids of mandarin fruits during storage at room temperature and in cold storage. Similarly, different polysaccharide-based coatings, including carboxymethylcellulose, chitosan, dextrin, and starch, showed significant differences in firmness index, the percentage of weight loss, and chilling-injury index of zucchini fruit at 4 °C in which dextrin showed to be the most effective (Castro-Cegrí et al., 2023).

4.4. EC for Fresh-cut fruit preservation

One of the outstanding advantages of EC compared to other fruit packaging approaches is that EC can be directly consumed with the fruit. To achieve this, the materials must be safe, not affect the sensory properties, and ensure preservation efficiency. EC materials are widely used to preserve fresh-cut fruits, such as alginate, carboxymethyl cellulose, chitosan, gum Arabic, pectin, etc. (Table 1) Besides, extra materials are also diverse, such as AgNPs, essential oils, and plant extract. Previous studies have shown that EC efficiently extends the shelf life and maintains fresh-cut quality during storage. The fresh-cut pineapple was coated with ECs such as chitosan-pullulan, chitosan-linseed, chitosan-nopal cactus, and chitosan-aloe mucilage by layer-by-layer technique showed to improve the firmness, reduced weight loss, inhibited microbial growth, and did not affect sensory characteristics compared to uncoated samples (Treviño-Garza et al., 2017). Similar to whole fruit, low temperatures also have a positive effect on the weight loss of fresh-cut fruit. A study by Nascimento et al. (2020) found that fresh-cut guava coated with chitosan–citric acid experienced a weight loss of 8.37 % and 3.58 % after 7 days of storage at 24 °C and 4 °C, respectively.

Combining extra materials into EC has also been proven to enhance preservation efficiency (Du et al., 2023; Kostić et al., 2023; Magri et al., 2024; Nascimento et al., 2020; Ortiz-Duarte et al., 2019; Rather & Mir, 2023; Tabassum et al., 2023). Rather and Mir (2023) found that incorporating seabuckthorn leaves 1.5 % (w/v) into carboxymethylcellulose 1 % (w/v) effectively inhibits polyphenol enzyme activity in freshly cut "Maharaji" apples for ten days at 4 °C, compared to control or carboxymethylcellulose alone, without compromising the apples' firmness, soluble solids, titratable acidity, and sensory qualities. A study by Du et al. (2023) showed that fresh-cut apples coated with pectin solution that includes quercetin significantly enhanced their resistance to bacterial infections and extend their shelf life to 10 days while preserving desirable attributes such as color, 100 % hardness, and 80 % of their sugar content during storage at 4 °C (Fig. 7d). Tabassum et al. (2023) indicated that fresh-cut papaya samples coated with nanoemulsion coating made by sodium alginate 2 % (v/v) containing oregano oil were not only able to retain the sensory scores till day 16 of analysis but also proved more efficient in retarding the degradation rate of physicochemical properties. Moreover, bacterial count in the fresh-cut papaya coated by sodium alginate 2 % (v/v) containing oregano oil 1 % (v/v) showed not exceed 3 log CFU/g till day 16 of storage compared to that of exceeding 12 log CFU/g in uncoated samples (Tabassum et al., 2023). Kostić et al. (2023) discovered that fresh-cut apples coated with pectin-oregano oil not only demonstrated significant antioxidant, antibacterial, and antifungal properties but also maintained their freshness better than the uncoated ones during storage (Fig. 7e). Similarly, adding clove essential oil to alginate coating reduced weight loss and increased fresh-cut apple pieces' total phenolic and antioxidant content stored at 4 °C for 14 days (Pandey et al., 2023).

Extra organic acid materials also played a vital role in enhancing fresh-cut fruit quality. A study by Magri et al. (2024) indicated that the EC, which is based on carboxymethyl cellulose and sodium alginate and contains oxalic and citric acid, showed a significant inhibitory effect on the physiological decay of fresh-cut pear. The EC also minimized the total soluble solid and pH increase, prevented titratable acidity decrease, hindered decay, and significantly extended the storage period of Williams' pear fruit in cold storage at 2 ± 0.5 °C for 10 days (Magri et al., 2024). Fresh-cut guava coated with chitosan–citric acid maintained quality parameters (pH, soluble solids, total sugar, etc.) during storage at 24 °C and 4 °C for 7 and 14 days and preserved their sensory characteristics (Nascimento et al., 2020). Also, the sensory quality of fresh-cut melons coated by chitosan with Ag-chitosan (extracted) nanocomposites was better, with lower translucency and texture/firmness degradation after 13 days at 5 °C (Ortiz-Duarte et al., 2019). The use of EC with barrier properties and UV-blocking capabilities, combined with extra materials possessing antimicrobial, antioxidant, and anti-browning properties, has greatly enhanced the effectiveness of fruit preservation. It is essential to select the appropriate EC based on the type of fruit and storage conditions for optimal preservation results.

5. Conclusion and Future Trends

Edible coating shows many outstanding advantages, including extended fruit shelf life, no toxic effects, and no effect on the sensory quality. ECs, such as polysaccharides and proteins, come in various forms and are widely used to preserve fruits. Polysaccharides are especially popular for this purpose due to their many benefits, including barrier properties and UV blocking. Besides, extra materials can be added to ECs to enhance their beneficial properties, such as improving film structure, antimicrobial and antioxidant properties, and preventing browning. ECs have been proven to maintain fruit quality by reducing weight loss, respiration rates, and ethylene production, maintaining firmness, inhibiting pathogens, slowing ripening, decreasing chilling injury, and reducing electrolyte leakage, malondialdehyde, and hydrogen peroxide during storage. EC has significant effects on fruit metabolism membrane lipid peroxidation boosts stress defense enzymes such as glutathione reductase, catalase, ascorbate peroxidase, peroxidase, and superoxide dismutase reduced enzyme activities such as polygalacturonase, cellulase, and pectin methyl esterase. The EC can be applied to both whole and fresh-cut fruits for preservation. Choosing the appropriate coating and extra materials depends on the type of fruit and the preservation purpose. Combining coating materials and extra materials to reduce fruit metabolism, maintain fruit quality, inhibit damage pathogens, anti-browning, and antioxidants would be tended for the green potential of fruit preservation approaches.

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CRediT authorship contribution statement

Dong My Lieu: Writing – review & editing, Writing – original draft, Software, Formal analysis, Data curation, Conceptualization. **Thuy Thi Kim Dang:** Writing – review & editing. **Huong Thuy Nguyen:** Writing – review & editing, Supervision.

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Data availability

The data that has been used is confidential.

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