



Evaluation of base ingredients for edible coating of fresh-cut apples to preserve the quality during cold storage

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Abstract

This study evaluated various ingredients and their combinations to develop an optimal edible coating for improving the quality of perishable fresh-cut apples during cold storage. Among 10 edible coating ingredients tested for color retention at 10 °C, potato starch was the most effective, followed by chitosan and carboxymethyl cellulose, as reflected in the browning index after 7 days: 32.67 ± 0.87 for potato starch, 46.05 ± 2.91 for chitosan, 51.82 ± 4.72 for carboxymethyl cellulose, and 23.70 ± 1.84 for the control, consisting of fresh-cut apples that were not stored. To optimize edible coating, a mixed solution containing 1% ascorbic acid (AA), with or without calcium chloride (CC), and 0.5–2% potato starch was applied for 1 min, and the formulation with 1% potato starch, 1% AA, 1% CC, and 2% glycerol proved most effective, preserving appearance, color, browning index, and firmness at levels comparable to the control over 15 days of storage at 10 °C.

Keywords Fresh-cut apples · Edible coating · Coating ingredient · Quality · Optimization

Introduction

Recently, the demand for fresh-cut fruit products has increased significantly due to factors such as the increase in single-person and double-income households, the spread of food consumption trends that emphasize convenience, and the growth of the simple food market (Kim et al., 2019). Minimally processed fresh-cut fruit products, such as washed and cut produce, can enhance a healthy diet by boosting agricultural productivity, adding value, and facilitating convenient fruit consumption for end-users. However,

fresh-cut fruit products deteriorate rapidly during distribution and storage, providing a favorable environment for microbial growth. Particularly, *Escherichia coli*, *Salmonella* Typhimurium, and *Listeria monocytogenes* have been reported as hazardous pathogenic bacteria due to their high acid tolerance and resistance under low-acid conditions, indicating that greater attention is required to ensure the safety of fresh-cut fruits (Yoon et al., 2024).

Apples are widely consumed and are a rich source of phytochemicals. Epidemiological studies have shown that apple consumption is associated with a reduced risk of some types of cancers, cardiovascular disease, asthma, and diabetes (Block et al., 1992). In addition, apples also contain a variety of phytochemicals, including powerful antioxidants such as quercetin, catechins, and phlorizin (Boyer and Liu, 2004). However, fresh-cut apples are highly susceptible to deterioration during storage. The main factors contributing to the deterioration of the quality of fresh-cut apples are browning and softening (caused by polyphenol oxidase and mold spores) and microbial growth (Toivonen and Brummell, 2008). Therefore, maintaining the quality and safety of fresh-cut apples during storage and distribution is a major challenge for the fresh-cut apple industry.

Recently, the demand for new and safe packaging technologies has led to an increase in the use of edible coatings (Maringgal et al., 2020). Edible coatings are soluble formulations

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applied to the surface of foods to extend their shelf life. They provide a barrier to the movement of oxygen, microorganisms from external sources, moisture, and solutes in food. Edible coatings can be applied through four main coating techniques: dipping, brushing, spraying, and wrapping. In particular, dipping technology can produce a very thick coat on fresh-cut fruit products (Tahir et al., 2019). Dipping technology also rinses enzymes and solutes from injured cells on cut surfaces (Toivonen and Brummell, 2008).

The general types of edible coating ingredients for agricultural products are polysaccharides, proteins, and lipids, which can be used alone or in combination. Polysaccharide-based edible coatings are water soluble and reduce the respiration rate, improve mechanical handling properties, and increase additive loading capacity (Raghav et al., 2016). They can be derived from plants, animals, and microorganisms. The most commonly used polysaccharide-based edible coatings are alginate, chitosan, cellulose, gums, and starch (Galus et al., 2020). Polysaccharide-based ingredients can be cross-linked after applying the coating solution on the fresh-cut apple surface to form a more compact and resistant layer to improve chemical resistance and thermal stability (Pirozzi et al., 2021). Therefore, polysaccharide-based edible coatings could help prevent cut-edge browning and microbial growth on fresh-cut apples during storage. Protein-based edible coatings have poor water vapor barrier properties, but exhibit better gas barrier properties and mechanical properties than other edible coating ingredients (Hauzoukim and Mohanty, 2020). Lipid-based edible coating ingredients, such as waxes and triglycerides, are not as frequently employed in coating fresh-cut agricultural products as other ingredients. Due to their hydrophobic nature, they either require incorporation into other edible coating ingredients or the addition of emulsifiers to enhance their water vapor barrier properties. While alginate, chitosan, and gellan are commonly utilized as edible coating ingredients for fresh-cut agricultural products and have been found to be effective in prolonging shelf life, their efficacy can vary depending on the concentration applied and the particular storage conditions. Therefore, this study aimed to evaluate various coating ingredients and determine the optimal concentration, combination, and coating method to improve the quality of perishable fresh-cut apples during cold storage. The results of this study can serve as a valuable resource for the development of edible coating technologies in the food industry to improve the quality and safety of fresh-cut apples during storage.

Materials and methods

Plant materials

Fuji apples were purchased from a commercial wholesale store in Anseong-si (Gyeonggi-do, South Korea) between

February and June 2021. The experiments were conducted on the same days of purchase. Apples of the same size were selected before the experiment without any processing or storage.

Preparation of edible coatings

Ten polysaccharide-based ingredients were employed as edible coating solutions. These solutions were prepared by dissolving 2% sodium alginate (Duksan, Ansan-si, Korea) in distilled water and stirring the mixture at 45 °C for 1 h on a heating plate to ensure proper equilibration. Furthermore, 1% low molecular weight chitosan (Sigma Aldrich, Saint Louis, MO, USA) and 3% citric acid (Duksan) were added to distilled water and stirred at 60 °C for 1 h on a heating plate. A commercially available processed liquid form of aloe vera gel was used, and 20% aloe vera gel was added to distilled water and stirred. Aloe vera gel was used at a higher concentration than other ingredients because 10–30% was used in other studies (Pinzon et al., 2020). After dissolving 2% carboxymethyl cellulose (Sigma Aldrich) in distilled water, it was equilibrated while stirring at 45 °C for 1 h on a heating plate. Moreover, 2% kappa-type carrageenan (ESfood, online market, Gunpo-si, Korea) was added to distilled water and stirred at 50 °C on a heating plate. Arabic gum (ESfood) was added to distilled water at 2% and stirred at 45 °C on a heating plate. In the case of gellan gum (ESfood), 0.5% was added to distilled water and stirred at 50 °C for 1 h or more, and when 1% or more was used, gelation occurred rapidly and was used at a low concentration. Cassava starch, corn starch, and potato starch (commercially available starch, more than 99% purity) were added to distilled water and stirred. Finally, 2% glycerol was added as a plasticizer to the edible coating solution prepared with 10 ingredients.

A cross-linking solution was prepared by adding 1% or 2% calcium chloride (CC) and 1% ascorbic acid (AA) to distilled water and stirring for approximately 5 min. A water-soluble calcium compound (typically a 1% CC dip) can be applied to maintain the firmness of fresh-cut apples (Beaulieu and Gorny, 2002). In addition, a calcium compound can delay aging, reduce post-harvest spoilage, and regulate the occurrence of physiological disorders (Sila et al., 2004). Ascorbic acid is known to delay browning more effectively when applied to edible coatings than when applied to aqueous solutions (Baldwin et al., 1996).

Edible coating of fresh-cut apples

Apples were washed with running water and air dried. Apples were then cut into eight pieces with an apple cutter without peeling, and then cut again with a sterilized

knife to make a total of 16 pieces. Prepared fresh-cut apples were submerged in 10 edible coating solutions for 2 min and then sieved to remove the remaining liquid for 1 min. Then, the apples were submerged in the cross-linking solution for 2 min and sieved to remove the remaining liquid for 1 min. Two control groups were established with apples submerged in distilled water or cross-linking solution only once for 2 min, as the existing fresh-cut apple process included vitamin C dipping. Coated fresh-cut apples were dried on a clean bench at room temperature, packaged in plastic containers, and stored at 10 °C for 7 days.

Color evaluation

The external surface color of fresh-cut apples was determined on five equidistant points of the equatorial region with a color difference meter (UltraScan PRO, Hunterlab, USA) and expressed as CIE Lab* values. The color parameters, such as color difference (ΔE , Srimagal et al., 2016) and browning index (BI, Subhashree et al., 2017) were also determined using the following equations:

$$\Delta E = \left[(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2 \right]^{1/2} \quad (1)$$

$$BI = [100(x - 0.31)] / 0.172.$$

Where:

$$x = (a^* + 1.75 \cdot L^*) / (5.645L^* + a^* - 3.012 \cdot b^*) \quad (2)$$

Three color parameters were measured in each treatment, and this was repeated three times.

Firmness evaluation

The firmness of fresh-cut apples was measured on a texture analyzer (TAHDI/500, TAHD). During the test, a 0.25 cm diameter round-head stainless steel cylindrical probe penetrated the center of the longitudinal axis of the pieces (10 mm depth) at a speed of 30 mm/s. The firmness of three pieces of each treatment was measured, and this was repeated three times.

Statistical analysis

Data were analyzed using the Statistical Analysis System (Version 9.1; SAS Institute, Cary, NC, USA) or Excel 2010 (Microsoft Office XP; Microsoft, Redmond, WA, USA).

Significant differences ($P \leq 0.05$) between the mean values of the treatment groups were determined by analysis of variance (ANOVA) and Duncan's multiple range tests.

Results and discussion

Visual appearance of fresh-cut apples treated with edible coating solutions during storage

The quality of fresh-cut apples treated with distilled water (control) or with an edible coating solution and stored for 7 or 14 days at 10 °C was assessed by visual inspection of their appearance, and the results are shown in supplement Fig. 1. The most important quality factors affecting fresh-cut apples were browning and softening. No signs of decay were observed in coated fresh-cut apples until 7 days of storage (supplement Fig. 1). However, the visual appearance of fresh-cut apples varied during storage at 10 °C, except for apples treated with a cross-linking solution and potato starch. Among the treatments, coating with the cross-linking solution and potato starch was very effective in maintaining the quality of fresh-cut apples during storage, and similar qualities of fresh-cut apples were observed after 7 days of storage at 10 °C, compared with the first day. However, since the quality of fresh-cut apples treated only with the cross-linking solution was maintained for 7 days, it was difficult to distinguish the effect of the coating treatments in this study. Additionally, 2% CC affected the flavor of fresh-cut apples (data not shown). Therefore, the concentration of CC in the cross-linking solution was reduced to 1% for further experiments. According to Luna-Guzmán et al. (1999), dipping time had little or no effect on respiration rate and ethylene production. Therefore, the experiment was conducted by reducing the dipping time from 2 to 1 min. Fresh-cut apples were stored until signs of decay were found for 14 days in the next experiment.

Color of fresh-cut apples treated with edible coating solutions during storage

Table 1 shows the changes in the color of fresh-cut apples treated with different edible coating solutions during storage for 14 days at 10 °C. Due to the decay of some coated fresh-cut apples after 14 days of storage, color quality measurements could not be performed for all coating solutions. The lightness (L^*) of fresh-cut apples coated with cassava starch and potato starch was maintained for 14 days with no significant difference compared to the negative control. For the a^* (green to red) values, the least changes were observed on fresh-cut apples coated with potato starch. For the b^* (blue to yellow)

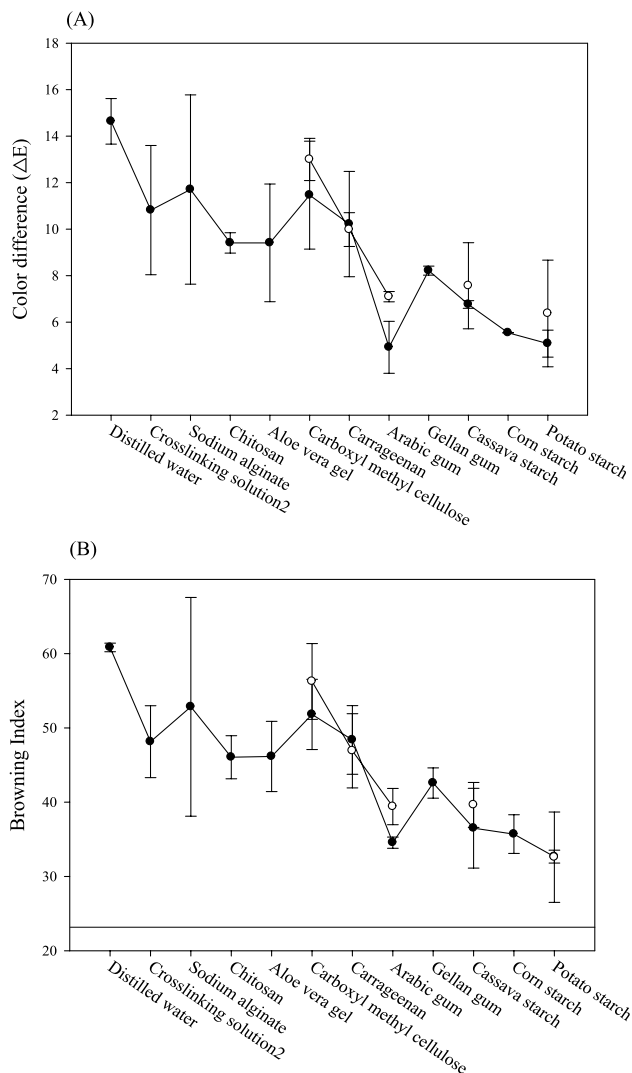


Fig. 1 Color change (A) and browning index (B) of fresh-cut apples treated with edible coating layer for 1 min during storage at 10 °C for 7 days (●) and 14 days (○), respectively. The horizontal line represents the browning index of fresh-cut apples (control) before storage

values, significantly lower b^* values were observed in the coating with Arabic gum, cassava starch, and potato starch after 14 days of storage. The color difference (ΔE , Fig. 1A) values were significantly different among the coating treatments, with the least ΔE values observed on fresh-cut apples coated with Arabic gum, potato starch, corn starch, and cassava starch after 7 days of storage, and fresh-cut apples coated with potato starch, Arabic gum, and cassava starch after 14 days of storage. The browning index (BI, Fig. 1B) was maintained with no significant difference on fresh-cut apples coated with arabic gum and potato starch until 7 and 14 days of storage, respectively.

Firmness of fresh-cut apples treated with edible coating solutions during storage

The use of CC as a cross-linking solution could minimize the softening of fresh-cut apples. Additionally, the combination of edible coating with various base ingredients and CC may show synergistic effects for preserving the texture of fresh-cut apples during storage. To evaluate the effect of various edible coating methods in preventing softening of fresh-cut apples during storage, the firmness of apples coated with various ingredients was measured during storage for 14 days at 10 °C (Fig. 2). Tissue softening was observed in fresh-cut apples treated with distilled water, chitosan, aloe vera gel, gellan gum, cassava starch, and corn starch after 14 days of storage. In contrast, the firmness values of fresh-cut apples coated with the remaining ingredients increased, presumably due to surface drying.

Optimization of an edible coating solution for fresh-cut apples

Our results suggest that the potato starch-based edible coating was very effective at maintaining both color and firmness of fresh-cut apples during cold storage. To optimize and minimize the coating process, a mixed solution (1% AA, with or without CC, and with or without 0.5, 1, or 2% potato starch) was prepared and evaluated as a coating method for fresh-cut apples by dipping samples in an edible coating solution for 1 min. Fresh-cut apples treated with the coating were stored at 10 °C for up to 15 days, and color and firmness were measured during storage. The visual quality of fresh-cut apples coated with 1 or 2% potato starch with 1% AA, 1% CC, and 2% glycerol was maintained until 9 days of storage, and a similar appearance to that of fresh-cut apples was observed before storage (supplement Fig. 2). Figure 3 shows the visual quality of coated fresh-cut apples on day 12 of storage, in which decayed surfaces were observed in Fig. 3A–G, whereas samples in Fig. 3H–J maintained superior visual quality compared with the other treatment groups. Moreover, no signs of decay were observed up to 15 days of storage in samples coated with 1% or 2% potato starch, 1% AA, 1% CC, and 2% glycerol (supplement Fig. 2). Similarly, treatments with 1% or 2% potato starch, 1% AA, 1% CC, and 2% glycerol were effective in maintaining color parameters, including ΔE and BI, and could improve the color quality of fresh-cut apples during cold storage (Fig. 4).

Table 1 Color change in fresh-cut apples with edible coating treatment during storage at 10 °C for 14 days

Treatment	Storage time (days)	L*	a*	b*	Color difference (ΔE)	Browning Index
None	0	67.24 ± 0.43 ^{ABCd}	0.31 ± 0.34D	14.67 ± 0.88F	0.00 ± 0.00H	23.70 ± 1.84H
Distilled water ^a	7	59.26 ± 1.43G	3.90 ± 0.12A	26.20 ± 0.41A	14.64 ± 0.98A	60.84 ± 0.57A
	14	— ^e	—	—	—	—
Cross-linking solution ^a	7	60.13 ± 2.67FG	3.04 ± 0.34ABC	22.13 ± 0.71BCDE	10.82 ± 2.78ABCD	48.15 ± 4.84BCD
	14	—	—	—	—	—
Sodium alginate ^b	7	63.41 ± 2.47DEF	3.62 ± 2.64A	24.91 ± 3.65AB	11.71 ± 4.07ABC	52.84 ± 14.73ABC
	14	—	—	—	—	—
Chitosan ^b	7	64.64 ± 1.66CDE	3.35 ± 0.17ABC	22.91 ± 1.82ABCD	9.41 ± 0.44BCDEF	46.05 ± 2.91BCDEF
	14	—	—	—	—	—
Aloe vera gel ^b	7	64.15 ± 2.09CDE	2.91 ± 0.19ABC	22.95 ± 1.16ABCD	9.41 ± 2.53BCDEF	46.16 ± 4.73BCDEF
	14	—	—	—	—	—
Carboxyl methyl cellulose ^b	7	62.43 ± 1.10EFG	3.37 ± 0.47ABC	24.41 ± 1.22ABC	11.46 ± 2.32ABC	51.82 ± 4.72ABC
	14	62.00 ± 0.40EFG	3.51 ± 0.79AB	25.91 ± 1.41A	13.00 ± 0.91AB	56.26 ± 5.10AB
Carrageenan ^b	7	63.21 ± 0.42DEF	3.50 ± 1.07 AB	23.26 ± 1.23ABCD	10.22 ± 2.26BCDE	48.38 ± 4.62BCD
	14	66.49 ± 1.27BCD	3.96 ± 0.69A	23.65 ± 1.40A	9.98 ± 0.73BCDE	46.92 ± 4.99BCDE
Arabic gum ^b	7	65.47 ± 1.09BCDE	1.46 ± 0.12BCD	18.90 ± 0.04E	4.92 ± 1.12G	34.55 ± 0.75FGH
	14	67.24 ± 0.90ABC	3.07 ± 0.78 ABC	20.92 ± 0.45DE	7.10 ± 0.22DEFG	39.41 ± 2.44 DEFG
Gellan gum ^b	7	63.67 ± 1.93CDEF	2.67 ± 0.24BC	21.39 ± 1.47E	8.22 ± 0.19CDEFG	42.58 ± 2.04CDEFG
	14	—	—	—	—	—
Cassava starch ^b	7	68.73 ± 2.84AB	2.46 ± 0.82ABC	20.24 ± 1.3DE	6.76 ± 0.16DEFG	36.50 ± 5.37DEFG
	14	68.41 ± 0.91AB	3.53 ± 0.95AB	21.17 ± 0.66CDE	7.57 ± 1.85CDEFG	39.64 ± 3.03DEFG
Corn starch ^b	7	66.41 ± 1.79BCD	1.99 ± 0.35ABCD	19.43 ± 0.53E	5.54 ± 0.02FG	35.71 ± 2.61EFG
	14	—	—	—	—	—
Potato starch ^b	7	69.07 ± 0.04AB	1.35 ± 0.04 CD	19.08 ± 0.49E	5.08 ± 0.58G	32.67 ± 0.87GH
	14	70.78 ± 1.18A	2.02 ± 0.95BCD	19.09 ± 2.38E	6.37 ± 2.30EFG	32.59 ± 6.08GH

^aSamples were dipped in distilled water or cross-linking solution (1 g/L calcium chloride 1 g/L ascorbic acid) for 1 min and drained off for 1 min

^bSamples were dipped in edible coating solution for 1 min and drained for 1 min. Next, samples were dipped in cross-linking solution for 1 min and drained for 1 min

^cMeans ± standard deviation

^dA ~ H means with no significant difference among the same letters in the same column ($P > 0.05$)

^eNot determined

However, there were no significant differences in color parameters as a function of potato starch concentration ($P > 0.05$). Treatments with AA alone, the combination of AA and CC, or 2% potato starch AA were effective in maintaining color parameters in the initial storage phase up to 6 days of storage, but their effectiveness was lower than that of the combination of potato starch, CC, and AA. Finally, when the firmness of the coated apples was evaluated, the coating treatments with the combination of CC and AA, the combination of 1% potato starch and AA, and the combination of 0.5, 1, and 2% potato starch, CC,

and AA, respectively, were effective in improving the firmness of fresh-cut apples during storage (Fig. 5). Treatment with the combination of potato starch, AA, and CC exhibited an increase in firmness immediately after the coating treatment on day 0. This indicates that coating with these combinations directly influenced the firmness of fresh-cut apples. Furthermore, there were no signs of tissue softening until 9 days of storage in fresh-cut apples treated with the combination of potato starch, AA, and CC. From the results of this study, the method of dip coating in a solution containing 1% potato starch, 1% AA, 1% CC, and 2% glycerol for 1 min was effective in improving color quality

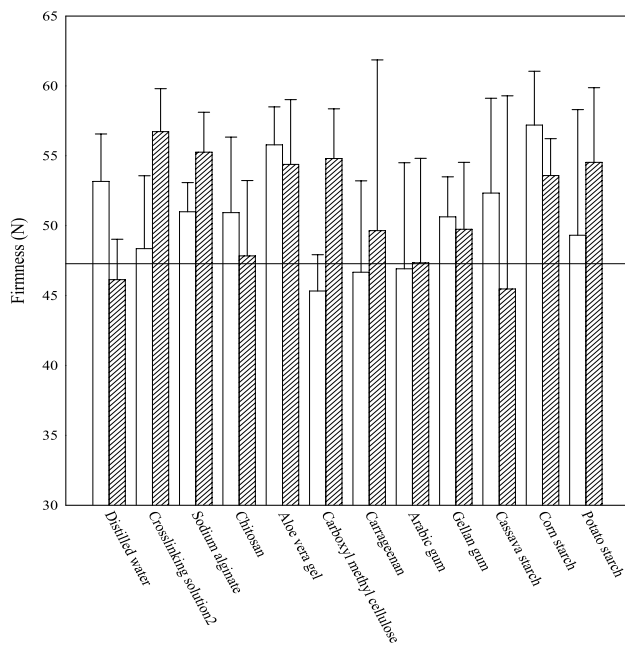


Fig. 2 Firmness of fresh-cut apples treated with edible coating layer for 1 min during storage at 10 °C for 7 days (□) and 14 days (▨). The horizontal line represents the firmness of fresh-cut apples (control) before storage

with no signs of tissue softening of fresh-cut apples during cold storage. Even at a concentration of 2%, potato starch demonstrated the ability to maintain sufficient quality, but the minimum concentration to maintain quality was set to the optimal concentration.

The choice of ingredients for edible coatings should depend on the properties of the fresh-cut fruit. Therefore, this study evaluated various base ingredients for edible coatings on perishable fresh-cut apples before optimizing the coating for each type of fruit.

A total of 10 base ingredients (sodium alginate, chitosan, aloe vera gel, carboxymethyl cellulose, carrageenan, arabic gum, gellan gum, cassava starch, corn starch, and potato starch) were used to coat fresh-cut fruits, which were then stored at 10 °C for 7 days. Among the visual appearance and color results, coating with potato starch was highly effective in maintaining the quality of fresh-cut apples during storage, followed by chitosan and CMC. Reducing the concentration of CC in the cross-linking solution to 1% provided better confirmation of the quality maintenance effect of the 10 ingredients. As the storage period of fresh-cut apples extended to 14 days, localized browning occurred, unlike the 7 days storage period. This could be attributed to secondary browning caused by fungal spores rather than enzymatic browning, as discussed by Toivonen (2006). Among the treatments, coating with potato starch was the most effective in maintaining the quality of fresh-cut apples during storage at 10 °C. Fresh-cut apples coated with potato starch retained their quality without signs of decay for up to 14 days of storage. The viscosity of the coating solution plays a vital role in preserving color parameters during storage. Potato starch, with its higher solubility, paste clarity, and viscosity compared to other commercial starches, emerges as a suitable choice for fresh-cut apples.

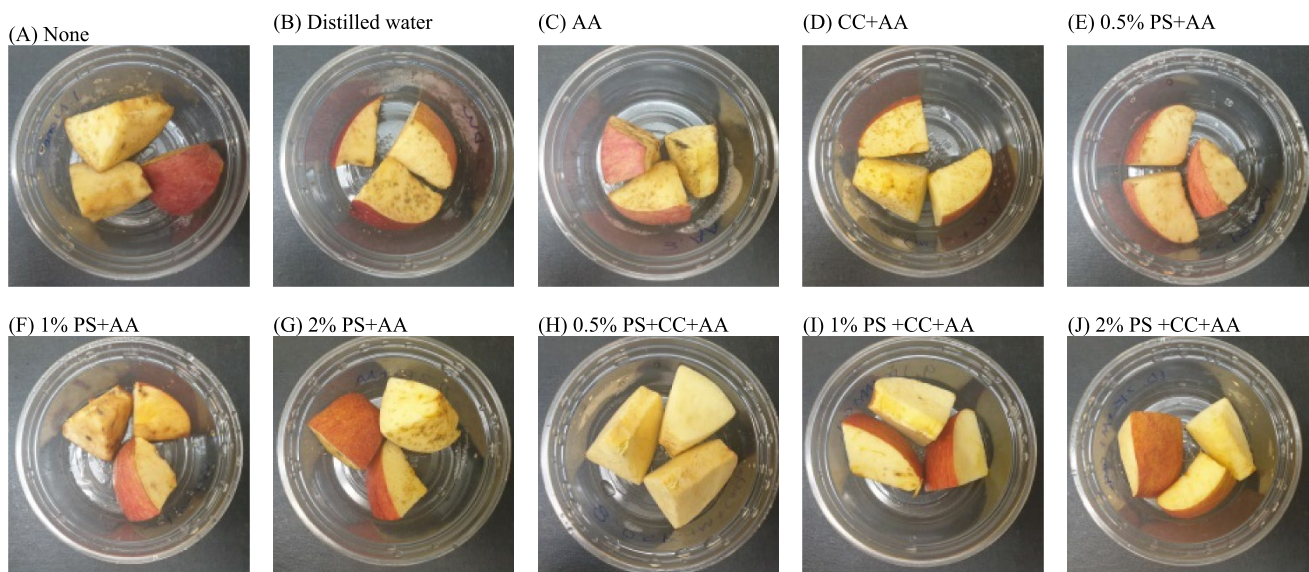


Fig. 3 Visual quality changes of fresh-cut apples coated with a potato starch-based edible coating for 1 min during storage at 10 °C for 12 days; Samples dipped in distilled water or a mixed edible coat-

ing solution for 1 min and drained for 1 min; PS=potato starch; CC=calcium chloride; AA=ascorbic acid

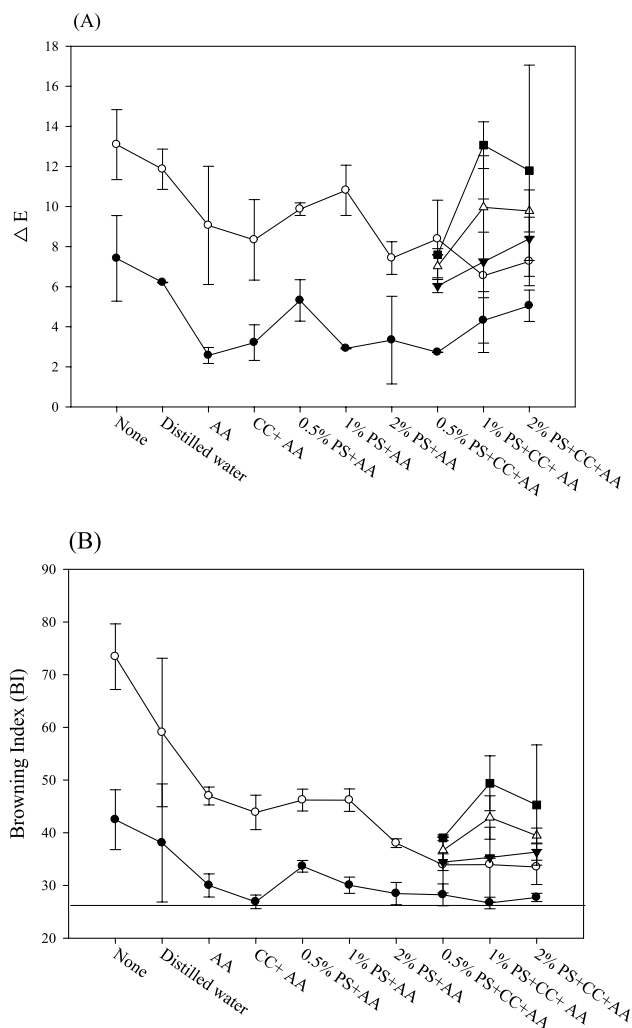


Fig. 4 Color change difference (ΔE , A) and browning index (BI, B) in fresh-cut apples during optimized edible coating for 1 min during storage at 10 °C for 3 days (●), 6 days (○), 9 days (▼), 12 days (△), and 15 days (■). The horizontal line represents the browning index of fresh-cut apples (control) before storage. PS = potato starch; CC = calcium chloride; AA = ascorbic acid

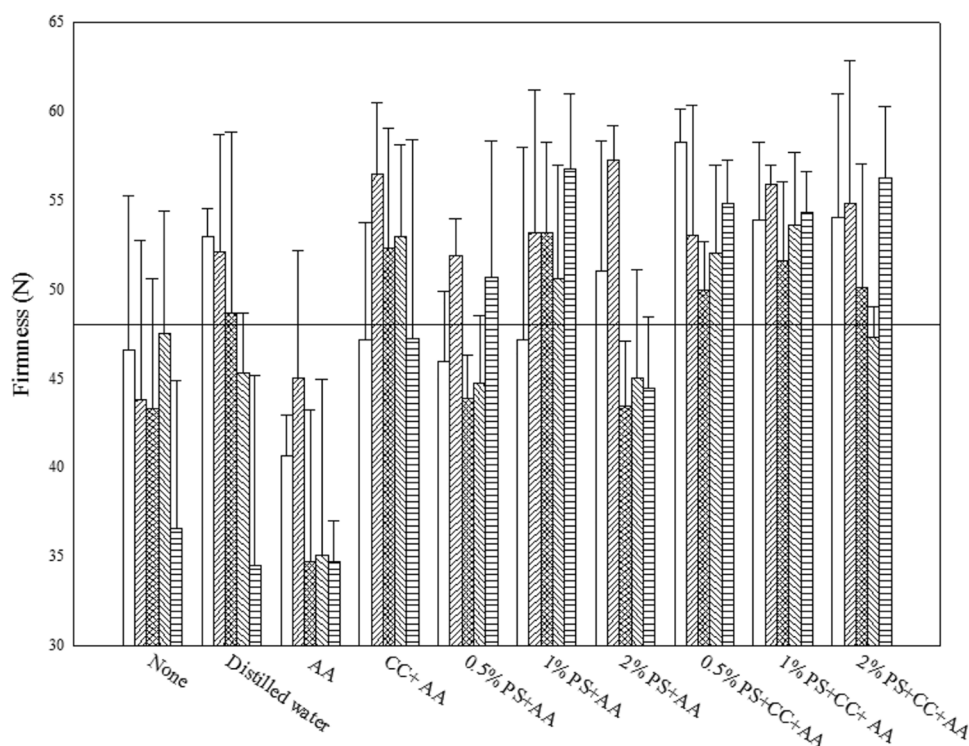
Fresh-cut apples firmness is considered an important quality parameter during storage. In firmness results, the group with an edible coating that exhibited firmness comparable to the negative control and showed no signs of decay consisted of a combination of arabic gum and potato starch (Fig. 2). Additionally, El-Anany et al. (2009) noted that fresh-cut apples coated with Arabic gum exhibited

significantly delayed aging and subsequent slow decay. Another study by Wijewardane et al. (2009) showed that applying 2% potato starch effectively maintained firmness of whole apples at room temperature. Our findings align with this, despite variations in sample conditions between the two studies. The relatively higher firmness of fresh-cut apples under arabic gum or potato starch coating could be attributed to the prolonged transport of CC and AA by the coating components, resulting in delayed aging.

Potato-based edible coating ingredients were selected and optimized to determine the most suitable options for fresh-cut apples. The advantages of potato starch-based edible coating are its tastelessness, reasonable price, and easy coating method as it does not require a layer-by-layer coating process. In addition, the appearance and firmness of fresh-cut apples coated with this optimized edible coating solution (containing 1% potato starch, 1% AA, 1% CC, and 2% glycerol) were maintained at similar levels to un-stored apples for up to 9 days of storage, demonstrating excellent quality maintenance ability. However, the range of edible coating ingredients for fresh-cut apples extends beyond these choices. Other ingredients might enhance fresh-cut apple quality through concentration adjustments or different combinations. For instance, in the Oriani et al. (2014) study, cassava starch was combined with cinnamon bark or fennel essential oil to exhibit vapor barrier properties, antioxidant activity, and antimicrobial effects.

In this study, we evaluated various base ingredients used in edible coatings for perishable fresh-cut apples. The edible coating made with potato starch was found to be highly effective in maintaining the color quality of fresh-cut apples during storage. The coating based on Arabic gum and potato starch was highly effective in maintaining the firmness quality of fresh-cut apples during storage. Therefore, potato starch-based edible coating can be used as a method to improve the color and firmness quality of fresh apple products and extend their shelf-life. The optimized edible coating solution for fresh-cut apples contained 1% potato starch, 1% AA, 1% CC, and 2% glycerol. The fresh-cut apples coated with this solution retained their color quality for up to 9 days of storage and exhibited no signs of tissue softening. However, this study did not include sensory or microorganism evaluations. Therefore, before implementing this technology to the food industry, it is essential to assess the developed edible coating method on sensory quality and microorganism growth. The findings of this study can provide foundational

Fig. 5 Firmness change in fresh-cut apples after optimized edible coating for 1 min, during storage at 10 °C for 3 d (□), 6 d (▨), 9 d (▩), 12 d (▧), and 15 d (▦). The horizontal line represents the firmness of fresh-cut apples (control) before storage. PS=potato starch; CC=calcium chloride; AA=ascorbic acid



data for the advancement of edible coating technology to enhance the quality and safety of fresh-cut apple products during cold storage.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10068-025-02036-1>.

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Author contributions A-Ra Jang: Investigation, Writing—Original draft. Hana Song: Methodology, Validation. Sun-Young Lee: Conceptualization, Project administration, Supervision.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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