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ORIGINAL PAPER

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THE EFFECT OF EDIBLE COATINGS, ASCORBIC ACID, AND THEIR COMBINATIONS ON THE ENZYMATIC BROWNING, PHYSICO-CHEMICAL PROPERTIES, AND SENSORY ACCEPTABILITY OF FRESH-CUT 'FUJI' APPLES THROUGH STORAGE

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ABSTRACT

Background. Fresh-cut fruits are highly perishable and have a shorter shelf life due to processing methods such as peeling and cutting, which lead to quality degradation. These processes can cause loss of texture and weight, increased susceptibility to browning, and microbial contamination. This study aimed to evaluate the potential of NatureSeal® (5%), shallot (S5%) or onion (O5%) edible coatings, ascorbic acid (Asc2% and Asc5%), and their combinations (S2.5%+Asc1.25% and O2.5%+Asc1.25%) in inhibiting enzymatic browning, reducing quality changes, and enhancing the quality attributes of fresh-cut 'Fuji' apples during storage.
Materials and methods. Fresh-cut apples were immersed in edible coatings, ascorbic acid, and their combination solutions, and then stored at 4 ±1°C for 16 days. Quality parameters were evaluated at 2-day intervals.
Results. Coated fresh-cut apples exhibited higher quality than the control group. The coatings inhibited the browning index, delayed firmness loss, and preserved most of the quality attributes of fresh-cut apples without significantly reducing their nutritional value. The firmness and total soluble solids content of coated fresh-cut apples remained stable over the storage period. The total phenolic content and DPPH radical scavenging activity of the coated treatments were significantly higher than those of the control group during the first 12 days of storage. By the end of the storage period, no significant difference was observed in the quality retention of fresh-cut apples treated with either S5% or O5% edible coatings, whether applied individually or in combination with ascorbic acid. All coating treatments received higher sensory scores compared to the control across all evaluated quality aspects on day 16 of storage.
Conclusion. Fresh-cut apples treated with NatureSeal®5%, Asc5%, Asc2.5%, O2.5%+Asc1.25%, O5%, and S2.5%+Asc1.25% demonstrated notable potential for preserving overall quality during storage. These coatings effectively delayed changes in sensory quality for 16 days at 4 ±1°C, with no significant differences observed in odour, taste, firmness, or overall preference among the coated treatments. However, the sensory attribute scores of the coated treatments were significantly different ($p < 0.05$) from the control group.

Keywords: ascorbic acid, edible coatings, enzymatic browning, fresh-cut apples, 'Fuji' apples, sensory acceptability

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INTRODUCTION

In recent years, there has been increasing consumer demand for fresh-cut fruits. Modern lifestyles have made consumers more aware of healthy food options, and they also seek convenient, ready-to-eat products from vendors. Fresh-cut apples are among the most popular fresh-cut fruits used in catering services, thanks to their convenience, freshness and high nutritional value (Yousuf et al., 2018). However, fresh-cut products tend to have a shorter shelf life, making them more perishable. The processing of fresh fruits through peeling, slicing, dicing, and cutting leads to quality degradation, including undesirable physico-chemical changes, loss of texture and weight, enzymatic browning, increased respiration and ethylene production, and greater susceptibility to microbial contamination (Graca et al., 2015).

Enzymatic browning is a common reaction in fresh-cut fruits and vegetables. It occurs when phenolic compounds are oxidised to ortho-quinones by polyphenol oxidases (PPOs). These ortho-quinones and their derivatives are then polymerised through a series of reactions, resulting in the formation of complex brown pigments in fruit tissues (Queiroz et al., 2008). The prevention of enzymatic browning can be approached through physical or chemical methods.

Physical methods include heat treatment, prevention of oxygen exposure (Yousuf et al., 2018), irradiation, and the use of low temperatures (Banerjee et al., 2015). PPO exhibits optimal activity within a pH range of 5–7, but it is inhibited at pH levels below 3.0 (Zemel et al., 1990).

Chemical methods for inactivating PPO activity include the use of acidulants such as ascorbic acid, citric acid, malic acid, and glutathione, which lower the pH and inhibit PPO activity (Sayavedra-Soto and Montgomery, 1986). Additionally, reducing agents, like ascorbic acid, calcium ascorbate, sulphate, and their derivatives act as irreversible inhibitors of PPO (Zambrano-Zaragoza et al., 2014; Sayavedra-Soto and Montgomery, 1986). Antioxidant agents, including N-acetyl cysteine, ascorbic acid, glutathione, and 4-hexylresorcinol, prevent melanin formation by interacting with intermediate compounds (Arias et al., 2007). Copper-chelating agents such as kojic acid, ethylenediaminetetraacetic acid (EDTA), citric acid, and oxalic acid suppress PPO activity by binding to the metal cofactors in the enzyme's active site structure (de Aguiar Cipriano et al., 2015).

Ascorbic acid is widely used to inhibit browning in fruits and vegetables, as it is inexpensive, consumer-friendly, and generally recognised as safe (Arias et al., 2007). It inhibits enzymatic browning reaction by reducing ortho-quinones to their ortho-dihydroxy phenols before they undergo secondary reactions that lead to the formation of brown polymers (Queiroz et al., 2008). However, once ascorbic acid is oxidised to dehydroascorbic acid, ortho-quinones can no longer be reduced to ortho-dihydroxy phenols, leading to their accumulation and subsequent browning (Nicolas et al., 1994). Since the effect of ascorbic acid alone is limited, other methods should be explored and evaluated to effectively control enzymatic browning.

Various strategies have been employed to extend the shelf-life of fresh-cut fruits, including processing and packaging technologies such as modified atmospheres packaging and the selection of appropriate packaging materials (Del Nobile et al., 2007). One such strategy is the application of edible coatings, which help reduce quality degradation during storage and extend shelf life. These coatings function as semi-permeable barriers that mitigate physiological disorders by reducing gas exchange, solute movement, water loss, respiration rates, and oxidation reaction rates on fresh-cut fruits (Raghav et al., 2016; Yousuf et al., 2018). Additionally, edible coatings can serve as carriers for functional food properties such as colourants, flavours, nutrients, antioxidants, anti-browning agents, and antimicrobial agents (Kumar et al., 2018).

Research has highlighted the use of individual edible coatings and anti-browning agents for maintaining the quality of fresh-cut fruit products. Moreover, the combination of edible coatings and/or anti-browning agents has proven effective in delaying quality changes and extending the shelf life of fresh-cut fruits. For example, the combination of ferulic acid as a functional ingredient in a soy protein isolate-based edible coating has shown potential in controlling weight loss, colour change and firmness, while prolonging the shelf life of fresh-cut apples (Alves et al., 2017). Nicolau-Lapeña et al. (2021) also reported that applying edible Aloe vera and alginate coatings can delay quality changes and improve the safety of fresh-cut apples. Similarly, Saba and Sogvar (2016) demonstrated that combining carboxymethyl cellulose-based coatings with ascorbic acid can help maintain the quality of fresh-cut apples by preventing browning and extending their shelf life. Previous studies have also shown that the combination of edible coatings and anti-browning agents such as ascorbic acid effectively reduces quality degradation and extends the shelf life of fresh-cut apples (Kumar et al., 2018; Qi et al., 2011; Guerreiro et al., 2017). Therefore, this study aims to investigate the potential of natural edible coatings, ascorbic acid as an anti-browning agent, and their combined effect in inhibiting enzymatic browning, reducing quality changes, and enhancing the quality attributes of fresh-cut 'Fuji' apples stored at 4 ±1°C.

MATERIALS AND METHODS

Materials

Fuji apples (*Malus pumila*) were sourced from a wholesaler-supplied supermarket in Ubon Ratchathani, Thailand, at a uniform size and maturity stage. They were promptly stored at 4 ±1°C until processing. Onions (*Allium cepa* L.) and shallots (*Allium ascalonicum* L.) were obtained from a local wholesale market. After peeling and washing thoroughly to remove any impurities, the onions and shallots were sliced into small pieces. These pieces were then dried in a hot air oven at 50–55°C until their weight remained constant. The moisture content of the dried onion and shallot samples was 2.72 ±0.48% and 2.22 ±0.19%, respectively. The dried onions and shallots were ground into fine powders, passed through a 70-mesh sieve, and stored in amber glass jars with airtight lids at –20 ±1°C for later use in edible coating solutions. A commercial edible coating, NatureSeal Fresh-Cut Produce-Inhibits Browning (NatureSeal®, Inc.), was purchased from the Amazon marketplace (Washington, U.S.) and used as a comparison treatment. Ascorbic acid was purchased from KemAus (Australia).

Preparation of Coating Formulations

A preliminary study was conducted to determine the optimal concentrations of shallot and onion powders (1%, 2%, 3%, 4%, and 5%) for maintaining the quality of fresh-cut apples. Based on the performance of edible coating adhesion and overall visual quality, the 5% concentration of shallot and onion was selected as the best-performing formulation. The coatings were prepared by dissolving 5 g of shallot or onion powder in 100 mL of distilled water (5%, w/v) and heating the solution at 85±2°C with magnetic stirring until the solution became clear. In preliminary sensory evaluation experiments, ascorbic acid was dissolved in distilled water to achieve final concentrations of 2.5% and 5% (w/v). Furthermore, the 5% shallot and onion coatings were combined with ascorbic acid at a 2.5% concentration in a 1:1 ratio. The commercial edible coating, NatureSeal® (5%), was prepared by dissolving NatureSeal® powder in distilled water (5%, w/v) until completely dissolved. A summary of the coating formulations and their respective codes used in the multivariate analysis is provided in Table 1 below:

Table 1. Coating formulations and codes used in multivariate analysis

Coating formulations	Codes
Distilled water	control
Shallot 5%	S5%
Onion 5%	O5%
Shallot 2.5%+Ascorbic acid 1.25%	S2.5%+Asc1.25%
Onion 2.5%+Ascorbic acid 1.25%	O2.5%+Asc1.25%
Ascorbic acid 2.5%	Asc2.5%
Ascorbic acid 5%	Asc5%
NatureSeal® 5%	NatureSeal®5%

Apple Preparation, Coating Application, and Storage Conditions

The apples were initially washed with tap water and then sanitised by immersing them for 5 minutes in a 200 µL/L sodium hypochlorite solution. After sanitation, the apples were rinsed with water to remove any residual sodium hypochlorite. The apples were then patted dry using paper towels to eliminate excess water. A sharp knife was used to cut each apple in half, and each half was further sliced into six equal pieces. The seed cavities were removed from the apple slices.

The fresh-cut apple slices were immersed in the following coating solutions for 5 minutes: S5%, O5%, S2.5%+Asc1.25%, O2.5%+Asc1.25%, Asc2.5%, Asc5%, NatureSeal®5%, and distilled water (control), all at room temperature (25°C). After immersion, the excess solution was allowed to drip off for 20 minutes at room temperature.

The coated apple slices were then placed in food-grade polypropylene storage containers, which were tightly closed to minimise air exchange. These containers also protected the samples from moisture loss and contamination. The samples were stored at 4 ±1°C with 85 ±2% relative humidity (RH) for 16 days. Every 2 days, samples were randomly selected for analysis of various quality parameters.

Colour of the Fresh-Cut Apples

The colour of the fresh-cut apples was measured every 2 days over a 16-day storage period using a portable colour measurement device (Hunter Lab, Colour Flex, VIRG, USA). Colour measurements were recorded using the CIELAB scale of L^*, a^*, and b^* parameters. Three apple slices from each treatment were selected, and colour was measured at three locations on each slice, resulting in a total of nine measurements per sample. The data were presented as the mean value of the three replications for each sample.

The measured L^*, a^*, and b^* values were used to calculate the browning index (BI) and whiteness index (WI) using the following equations (Kumar et al., 2018; Olivas et al., 2007).

$$\text{Browning index (BI)} = [100(x - 0.31)]/0.172$$

Where, $x = (a^* + 1.75L^*)/(5.646L^* + a^* - 3.012b^*)$

$$\text{Whiteness index (WI)} = 100 - [(100 - L^*)^2 + (a^{*2} + b^{*2})]^{1/2}$$

Firmness

The firmness of the fresh-cut apples was measured through penetration tests using a texture analyser (Texture ProCT V1.7 build28, Brookfield Engineering Labs. Inc., USA) with a 4.5 kg load cell. The measuring procedure was based on the method described by Rojas-Graü et al. (2006), with slight adjustments. Three apple slices from each treatment were measured using a 4.0 mm diameter probe (TA44), which was lowered at a test speed of 0.8 mm/s and penetrated 4.0 mm into the apple slices. Firmness was determined as the maximum penetration force (N) obtained from the force-versus-distance texturograms.

pH Value and Total Soluble Solids

The pH value and total soluble solids (TSS) of fresh-cut apples were measured at 25°C. Ten grams (10 g) of fresh-cut apple samples were placed in a beaker and mixed with 50 mL of boiled distilled water. The mixture was homogenised using a blender and then filtered, and the pH was measured with an FE-20 pH meter (Mettler Toledo, Switzerland). The TSS content was determined in the juice pressed from the fresh-cut apples using a hand refractometer (Atago, Tokyo, Japan), and the TSS value was expressed as °Brix (AOAC, 2006). All measurements were performed in triplicate.

Total Titratable Acidity

Total titratable acidity (TA) was determined using the titration method. Twenty grams (20 g) of fresh-cut apples were mixed with 100 mL of distilled water and blended with a mechanical blender for 90 seconds. The mixture was then filtered using filter paper. Ten millilitres (10 mL) of the filtrate were diluted with 30 mL of distilled water, and 4 drops of phenolphthalein were added as an indicator. The mixture was titrated with 0.1 N sodium hydroxide solution until a light pink colour appeared (endpoint). The TA value was calculated and expressed as a percentage.

Extraction Procedure for Phenolic Content and DPPH Scavenging Activity Analysis

Total phenolic content and DPPH radical scavenging activity were determined on fresh-cut samples every 2 days during a 16-day storage period. Ten grams (10 g) of fresh-cut samples were added to 25 mL of 80% (v/v) methanol solution and blended with a mechanical blender for 90 seconds. The mixture was then stirred for 1 hour. Each sample was centrifuged at 4,500 rpm for 30 minutes at room temperature. The supernatant was collected and filtered through Whatman No. 1 filter paper. The extraction procedure was performed in triplicate, with three separate extractions for each sample. The filtered samples were then used directly for further antioxidant analysis.

Total Phenolic Content

The total phenolic content (TPC) of fresh-cut apples was determined according to the modified method of Singleton et al. (1999) using the Folin-Ciocalteu method. Briefly, 100 µL of the extract was mixed with

1 mL of Folin-Ciocalteu reagent (diluted with distilled water, at a ratio of 1:10) and left to react for up to 4 minutes. Afterwards, 800 µL of 7.5% (w/v) sodium carbonate solution was added, and the mixture was incubated in the dark at room temperature (25 ±1°C) for 2 hours. A control solution was prepared using the same method, substituting 100 µL of distilled water for the sample. The absorbance of both the sample and the control was measured in triplicate using a UV-VIS spectrophotometer at 765 nm. A standard calibration curve of gallic acid was prepared over a concentration range of 20–120 µg/mL ($y = 0.0111x - 0.003$, $R^2 = 0.9964$) and used to determine the TPC by comparing the absorbance of the samples. The TPC of the samples was expressed as milligrams of gallic acid equivalents (GAE) per gram of fresh weight.

DPPH Radical Scavenging Activity

The DPPH radical scavenging activity of fresh-cut apples was determined using the method described by Plank et al. (2012), with some modifications. Firstly, 30 µL of the extract (prepared by homogenising 10 g of fresh-cut apple with 25 mL of 80% (v/v) methanol, resulting in a calculated concentration of 400 mg/mL) was added to 100 µL of distilled water and mixed with 3.9 mL of 60 µM DPPH solution in 80% (v/v) methanol. The mixture was allowed to react for 30 minutes.

After this, the absorbance of the mixture was measured in triplicate at 517 nm in the dark at room temperature (25 ±1°C) using a UV-VIS spectrophotometer. The percentage of DPPH radical scavenging activity was calculated the following equation:

$$\text{DPPH radical scavenging activity (\%)} = \\ = [(\text{Abs}_{\text{control}} - \text{Abs}_{\text{sample}}) \times 100]/\text{Abs}_{\text{control}}$$

Sensory Evaluation

A sensory evaluation of fresh-cut apples treated with different coating treatments, along with an uncoated control, was conducted by 30 trained panellists. The evaluation was performed every 4 days until 16 days of storage. The apple slices were served in packages that were randomly coded. The panellists assessed five apple quality attributes: colour, odour, taste, firmness, and overall preference. A 9-point hedonic scale was used for each attribute, where a score of 1 indicated "dislike extremely", 5 indicated "neither like nor dislike", and 9 indicated "like extremely". The evaluation was carried out immediately after the apple slices were removed from cold storage (4 ±1°C). Ethics approval for this study was granted by the ethics committees.

Statistical Analysis

A two-way analysis of variance (ANOVA) was performed to test the effects of treatments, storage time (days), and their interaction on the physico-chemical experiments, which were conducted in triplicate. The statistical design for the sensory evaluation was based on a randomised complete block design. The data from both the physico-chemical experiments and sensory analysis were analysed using analysis of variance. Significant differences among means ($p < 0.05$) were determined using Tukey's test. Statistical analysis was performed using Minitab software, Version 16 (State College, PA, USA). The results are presented as mean values ± standard deviation.

RESULTS AND DISCUSSION

Lightness, Whiteness Index (WI), and Browning Index (BI)

Fresh-cut fruit often exhibits browning and the loss of natural colour due to tissue damage caused by cutting or slicing, which can lead to enzymatic browning reactions. Consequently, the loss of natural colour is further accelerated (Graca et al., 2015). The results showed that the edible coatings, ascorbic acid solutions, and their combinations significantly ($p < 0.05$) affected the colour (L^*, BI, and WI) of fresh-cut apples during storage at 4 ±1°C. All related data are presented in Figure 1.

Additionally, as shown in Figure 3, these colour changes are reflected in the visual appearance of the fresh-cut apples under different treatments during 16 days of storage at 4 ±1°C. The lightness (L^*) value of the fresh-cut apples treated with edible coatings, ascorbic acid solutions, and their combinations decreased slightly during storage (Fig. 1a). However, it remained significantly higher than that of the fresh-cut apples treated with distilled water (control) ($p < 0.05$), indicating that the decrease in lightness was less pronounced in the treated groups compared to the control.

Following the treatments, the fresh-cut surfaces showed changes in appearance due to the application

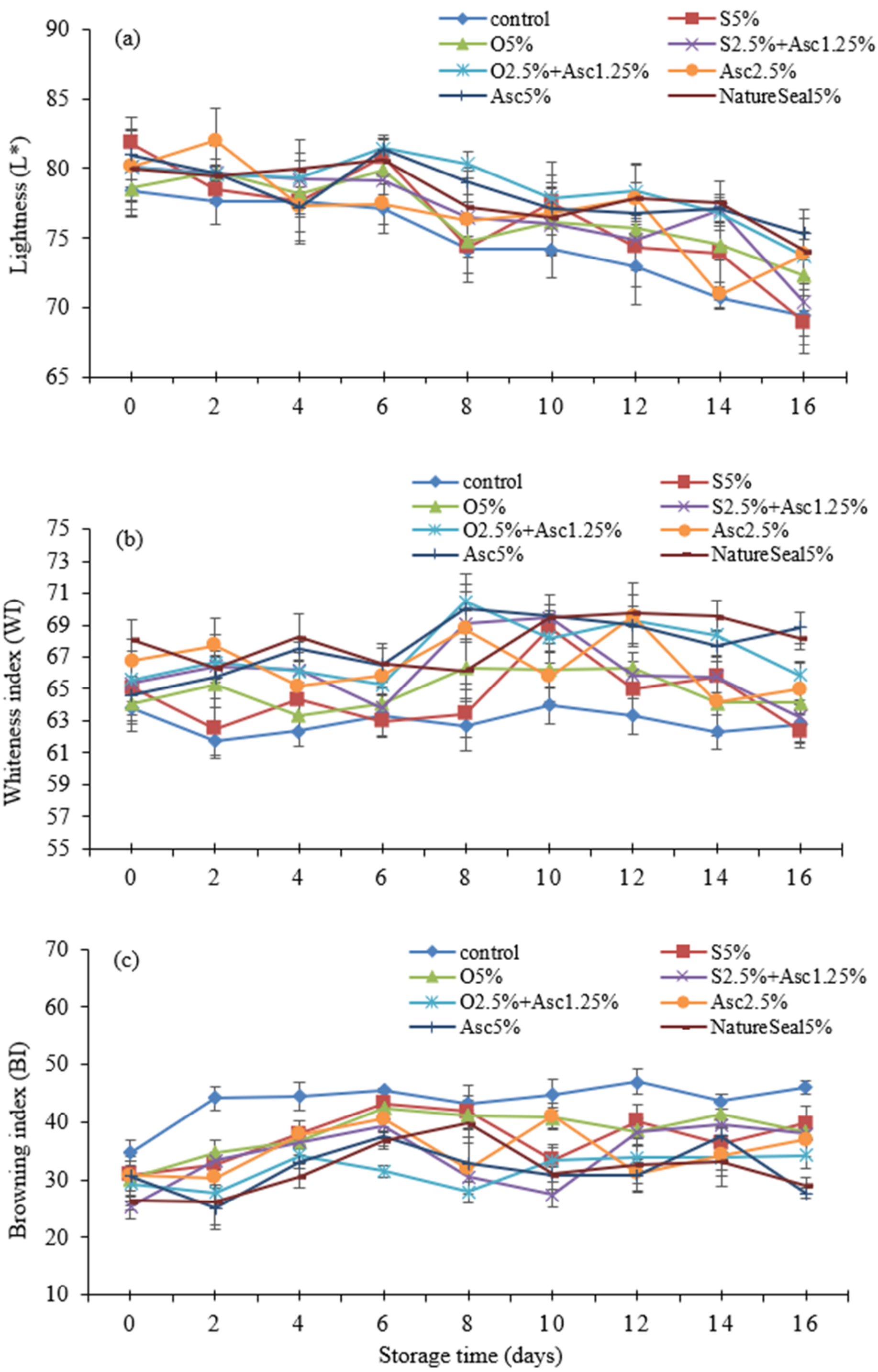

Fig. 1. Changes in lightness (L^*) (a), whiteness index (b), and browning index (c) of fresh-cut apples under different treatments during storage at 4 ±1°C for 16 days. Vertical bars indicate standard deviations

of coating solutions, with an initial increase in L^*-values during storage. On the 16th day of storage, the fresh-cut apples coated with Asc5% had the highest L^*-value (75.33). However, this value was not significantly different from those coated with NatureSeal®5% (74.08), Asc2.5% (73.82), O2.5%+Asc1.25% (73.69), O5% (72.35), and S2.5%+Asc1.25% (70.36). Thus, the study demonstrated that these treatments caused minimal changes in the L^*-values.

These findings align with those of Lee et al. (2003), who reported that the L^*-values of fresh-cut Fuji apples coated with carrageenan combined with ascorbic acid initially ranged from 79 to 76 before dropping to 76 after storage. Soliva-Fortuny et al. (2003) suggested that changes in the L^*-value of fresh-cut fruit are primarily caused by tissue surface alterations due to polyphenol oxidase (PPO) activity, leading to enzymatic browning after cutting. Surface coatings help mitigate this by forming a protective barrier, reducing PPO activity, and preserving the fruit's appearance and quality.

Figure 1b shows the effect of coating formulations on the whiteness index (WI) of fresh-cut apples during storage at 4 ±1°C. For all treatments, the WI values of fresh-cut apples tended to remain stable during the first 6 days, with a significant increase observed after 8 days of storage. After 8 days, the sample treated with O2.5%+Asc1.25% showed the highest WI value (70.45), followed by Asc5% (70.02), S2.5%+Asc1.25% (69.05), and Asc2.5% (68.76), with no statistically significant differences among these treatments. The samples treated with O5% (66.28) and NatureSeal®5% (66.16) also exhibited similar WI values, with no significant differences between them. Meanwhile, the control sample (62.67) had the lowest WI value, which was not significantly different from the sample treated with S5% (63.44). Following this, the WI values remained stable for the next 8 days of storage. On the 16th day, the sample coated with Asc5% had the highest WI value (68.85), with no significant difference from NatureSeal®5% (68.19). This was followed by O2.5%+Asc1.25% (65.85), Asc2.5% (65.0), O5% (64.04), and S2.5%+Asc1.25% (63.25), with no significant differences among these treatments.

An effective measure of colour change during storage at 4±1°C is the browning index (BI). Figure 1c shows the effect of coating formulations on the BI values of fresh-cut apples throughout storage. The BI values of the control sample increased continuously from the beginning until the 16th day, consistently showing the highest values throughout the storage period, indicating its high sensitivity to colour changes. In contrast, the BI values of the coated samples mostly increased during the initial period (0–6 days) but stabilised or slowed down during the later period (8–16 days).

The Asc5% and NatureSeal®5% treatments consistently exhibited the lowest BI values from the 8th day onwards. On the 12th and 14th days of storage, the BI values of the treatments O2.5%+Asc1.25%, Asc2.5%, Asc5%, and NatureSeal®5% ranged from 30.68–33.85 and 33.21–33.96, respectively, with no statistically significant differences among these treatments on either day. On the 16th day, the BI values of fresh-cut apples were significantly different among treatments ($p < 0.05$). The control sample (46.01) had the highest BI value, followed by treatments with moderate BI values, including S5%, O5%, and S2.5%+Asc1.25% (BI range: 38.08–39.91). Treatments with lower BI values included O2.5%+Asc1.25% and Asc2.5% (BI range: 34.26–36.88), while the lowest BI values were observed in Asc5% and NatureSeal®5% (BI range: 27.71–28.98). Although significant differences ($p < 0.05$) were observed between the BI range groups, no significant differences were found within the same group.

Therefore, Asc5% and NatureSeal®5%, which exhibited the lowest BI values, were the most effective in preventing browning reactions. Other treatments, including S5%, O5%, and ascorbic acid (whether in aqueous solutions or combined with onion or shallot), also showed effectiveness in reducing BI values, though not to the same extent as Asc5% and NatureSeal®5%. These findings are consistent with a previous study by Qi et al. (2011), which reported that edible coatings (chitosan 1%), ascorbic acid 2%, and their combination helped maintain lower BI values in apple wedges. Similarly, Saba and Sogvar (2016) found that fresh-cut apples treated with an edible coating (carboxymethyl cellulose) or combined with ascorbic acid showed a significant reduction in BI values. Guerreiro et al. (2017) reported that edible coatings (alginate 2% mixed with eugenol 0.1%) combined with ascorbic acid 1% significantly reduced BI values in fresh-cut apples. Additionally, Perez-Gago et al. (2006) observed that adding antioxidants (ascorbic acid or cysteine) to edible coatings (beeswax or whey protein concentrate) lowered BI values compared to using antioxidants alone. Furthermore, increasing the concentration of ascorbic acid further reduced the BI values of coated fresh-cut apples. Ascorbic acid, a widely used antioxidant to inhibit browning in vegetables and fruits (Arias et al., 2007), is highly effective in preventing enzymatic browning in apples (Gil et al., 1998). Its effectiveness stems from its ability to reduce oxidised substrates, prevent the decline of phenolic compounds in fruits and vegetables (Altunkaya and Gokmen, 2008), and convert ortho-quinones back into ortho-dihydroxy phenols (Nicolas et al., 1994; Perez-Gago et al., 2006).

In addition, Negishi et al. (2002) found that *Allium* species (onion, shallot, and garlic) contain various natural volatile organosulphur compounds, such as sulfhydryl (SH) groups or thiols. Specifically, Griffiths et al. (2002) noted that onions are rich in propene disulphide, thiosulfinates, and S-alk(en)yl-L-cysteine sulfoxides (ACSO). Ding et al. (2002) further reported that sulphur or thiol compounds have been shown to inhibit polyphenol oxidase activity. Similarly, Lee et al. (2002) observed that heated onion extract significantly inhibited potato polyphenol oxidase non-competitively while reducing the intensity of browning in potatoes. Consistent findings were reported by Kim et al. (2005), who noted that heated onion extract effectively inhibited pear polyphenol oxidase and significantly reduced browning in pears. Moreover, (Phaiphan et al., 2019) demonstrated that adding shallot to heated apple juice resulted in the most significant browning inhibition when compared to other treatments, while also improving its nutritional quality. Thivya et al. (2021) found that onion and shallot waste extracts could prevent browning in fresh-cut apples for up to 12 days, attributed to their high antioxidant and polyphenol content. Therefore this study demonstrates that applying edible coatings, ascorbic acid solutions, and their combinations significantly enhanced the preservation of L^*-values and WI-values while minimising the browning index in fresh-cut 'Fuji' apples.

Firmness

The effect of coating formulations on the firmness (N) of fresh-cut apples during storage (4 ±1°C) was evaluated. The firmness values of fresh-cut apples coated with edible coatings, ascorbic acid solutions, and their combinations remained relatively constant throughout the storage period, indicating their effectiveness in maintaining firmness (Table 2). The fresh-cut apples coated with O5% and O2.5%+Asc1.25% showed relatively stable firmness throughout storage, with their firmness values on the final day slightly higher than those on day 0. Similarly, the final firmness values of fresh-cut apples coated with Asc2.5% and NatureSeal®5% were fairly comparable to the firmness values measured on the first day of storage. On the 16th day of storage, the control group had the lowest firmness value (7.94 N), while the samples coated with edible coatings, ascorbic acid solutions, and their combinations exhibited higher firmness values, ranging from 8.81 to 9.92 N.

For the preservation of fresh-cut fruit quality throughout storage, consistent firmness levels are essential. In this study, samples coated with edible coatings, ascorbic acid solutions, and their combinations showed reduced firmness loss ($p < 0.05$), demonstrating that the coatings effectively preserved the texture of fresh-cut apples over an extended period. The control group exhibited the lowest firmness by the end of storage, likely due to acid hydrolysis of pectic acid in cell walls (Saba and Sogvar, 2016). Some treatments showed a slight increase in firmness, likely due to moisture loss during storage, which could have affected the structural integrity of cell walls, and contributed to the drying and hardening characteristics of fresh-cut apples (Rupasinghe et al., 2005). Similar results were reported by Guerreiro et al. (2017), who found that edible coatings, such as alginate and pectin, helped preserve firmness in fresh-cut apples. When combined with ascorbic acid, these edible coatings produced comparable firmness values. Saba and Sogvar (2016) also demonstrated that carboxymethyl cellulose-based coatings with ascorbic acid effectively maintained the firmness of fresh-cut apples. Similarly, Qi et al. (2011) reported that edible coatings improved or maintained the firmness of fresh-cut 'Fuji' apples.

Table 2. Changes in firmness of fresh-cut apples under different treatments during storage at 4±1°C for 16 days

Treatments	Firmness (N)								
	Storage time (days)								
	0	2	4	6	8	10	12	14	16
Control	8.51 $\pm0.77^{bABC}$	7.14 $\pm0.52^{bC}$	8.92 $\pm1.59^{ns\ ABC}$	10.95 $\pm0.13^{abA}$	9.28 $\pm0.93^{bABC}$	10.07 $\pm1.94^{aAB}$	9.34 $\pm0.72^{nsABC}$	7.51 $\pm0.08^{cdBC}$	7.94 $\pm0.72^{bBC}$
S5%	9.35 $\pm0.72^{b\ NS}$	8.97 $\pm1.08^{ab}$	9.57 ±0.51	9.22 $\pm0.21^{bc}$	7.05 $\pm0.34^{c}$	9.28 $\pm0.98^{ab}$	8.26 ±0.52	8.90 $\pm0.17^{ab}$	8.81 $\pm2.04^{ab}$
O5%	8.93 $\pm0.79^{b\ NS}$	8.46 $\pm1.27^{ab}$	9.99 ±1.07	9.25 $\pm1.45^{bc}$	9.64 $\pm1.00^{b}$	9.39 $\pm0.19^{ab}$	8.59 ±0.78	8.27 $\pm0.97^{bcd}$	9.08 $\pm0.84^{ab}$
S2.5% +Asc1.25%	9.18 $\pm0.95^{bB}$	8.61 $\pm0.79^{abB}$	11.27 $\pm1.92^{A}$	12.01 $\pm1.15^{aA}$	11.69 $\pm1.33^{aA}$	8.43 $\pm0.85^{abB}$	8.59 $\pm0.80^{B}$	7.35 $\pm0.32^{dB}$	8.83 $\pm0.87^{abB}$
O2.5% +Asc1.25%	8.44 $\pm0.30^{b\ NS}$	9.42 $\pm1.33^{ab}$	8.13 ±1.26	8.55 $\pm0.73^{c}$	9.65 $\pm1.35^{b}$	7.87 $\pm1.06^{bc}$	8.20 ±1.67	9.57 $\pm0.23^{a}$	9.92 $\pm1.20^{a}$
Asc2.5%	9.89 $\pm1.51^{abAB}$	10.15 $\pm2.90^{aA}$	10.51 $\pm0.53^{A}$	8.94 $\pm0.36^{bcAB}$	8.54 $\pm0.98^{bcAB}$	6.62 $\pm0.61^{cB}$	8.47 $\pm0.58^{AB}$	8.12 $\pm0.62^{bcdAB}$	9.88 $\pm0.47^{aAB}$
Asc5%	11.00 $\pm1.00^{aAB}$	8.53 $\pm0.22^{abAB}$	11.28 $\pm2.16^{A}$	8.65 $\pm1.40^{cAB}$	9.06 $\pm0.95^{bAB}$	8.02 $\pm1.09^{bcB}$	8.37 $\pm0.42^{AB}$	8.14 $\pm0.84^{bcAB}$	8.75 $\pm0.05^{abAB}$
NatureSeal®5%	9.34 $\pm0.78^{bAB}$	10.94 $\pm1.66^{aAB}$	10.35 $\pm0.37^{AB}$	10.36 $\pm2.24^{abcAB}$	11.88 $\pm1.66^{aA}$	9.21 $\pm0.08^{abAB}$	8.09 $\pm0.34^{B}$	8.79 $\pm0.52^{abAB}$	9.18 $\pm0.97^{abAB}$

The data are presented as means ± standard deviations. Mean values with different superscripts (lowercase letters) within the same column indicate significant differences ($p < 0.05$) among treatments at a given storage time. Mean values with different superscripts (uppercase letters) within the same row indicate significant differences ($p < 0.05$) among storage times (days) within a given coating. NS indicates no significant difference ($p > 0.05$) within the same rows, while ns indicates no significant difference ($p > 0.05$) within the same columns.

Total Soluble Solids (TSS) Content, pH Value, and Total Titratable Acidity (TA)

Maintaining the natural TSS content is crucial for preserving the sensory quality of fresh-cut apples. The effect of coating formulations on the TSS content of fresh-cut apples during storage (4 ±1°C) is presented in Table 3. The TSS content of coated fresh-cut apples remained relatively stable throughout the storage period, while the control group exhibited a noticeable decline. The coatings demonstrated varying levels of effectiveness in preserving TSS content. Among the coatings, NatureSeal®5%, O5%, and O2.5%+Asc1.25% were the most effective, showing minimal changes from the beginning to the end of storage. Samples coated with S5%, S2.5%+Asc1.25%, Asc2.5%, and Asc5%, showed moderate performance, with some variability observed during storage. Nevertheless, these coatings still performed better than the control group in preserving TSS.

These findings align with previous studies (Osuga et al., 2021; Wu et al., 2012), which showed that fresh-cut apples stored at 1–4°C did not experience significant changes in their soluble solid contents. Similarly, Rupasinghe et al. (2005) and Chiabrando and Giacalone (2013) found that coating solutions, including NatureSeal®5%, effectively preserved the TSS content of fresh-cut apples due to the low respiration rate of the fruit. Since coatings help preserve fruit sweetness without significantly increasing it, they are thought to positively impact TSS levels in fruit (Marghmaleki et al., 2021).

The effect of coating formulations on the pH values of fresh-cut apples during storage (4 ±1°C) is presented in Table 4. At the start of storage, no significant

Table 3. Changes in total soluble solids content of fresh-cut apples under different treatments during storage at 4 ±1°C for 16 days

Treatments	Total soluble solids content (°Brix)								
	Storage time (days)								
	0	2	4	6	8	10	12	14	16
Control	11.27 ±0.81^{bcB}	10.93 ±0.50^{bB}	10.80 ±0.35^{bB}	13.20 ±0.60^{aA}	11.20 ±0.35^{aB}	11.87 ±0.42^{bB}	11.80 ±0.35^{aB}	11.93 ±0.12$^{ns\ AB}$	10.67 ±0.23^{bB}
S5%	11.20 ±0.35^{cBC}	10.60 ±0.35^{bC}	13.33 ±0.61^{aA}	12.07 ±0.12^{bcB}	10.53 ±0.12^{aC}	11.13 ±0.58^{cBC}	11.67 ±0.12^{aBC}	11.60 ±0.35^{BC}	10.80 ±0.60^{bC}
O5%	12.00 ±0.00^{abBC}	10.67 ±0.12^{bD}	10.60 ±0.20^{bD}	13.47 ±1.00^{aA}	11.20 ±0.35^{aCD}	13.00 ±0.20^{aAB}	12.00 ±0.00^{aBC}	11.27 ±0.81^{CD}	11.80 ±0.20^{abBCD}
S2.5% +Asc1.25%	10.20 ±0.00^{dBC}	10.60 ±0.35^{bBC}	13.20 ±0.60^{aA}	12.00 ±0.20^{bcAB}	9.20 ±1.51^{bC}	10.73 ±0.12^{cBC}	12.00 ±0.00^{aAB}	11.13 ±0.58^{B}	11.27 ±0.64^{abB}
O2.5% +Asc1.25%	11.60 ±0.35^{bcABC}	11.07 ±0.50^{bBC}	10.53 ±0.23^{bC}	12.73 ±0.81^{abA}	10.93 ±0.42^{aBC}	12.00 ±0.00^{bAB}	11.73 ±0.31^{aABC}	11.67 ±0.58^{ABC}	11.53 ±0.64^{abABC}
Asc2.5%	12.47 ±0.70^{aA}	11.33 ±0.50^{bB}	10.40 ±0.20^{bC}	12.07 ±0.23^{bcA}	10.47 ±0.12^{aC}	12.27 ±0.31^{bA}	12.00 ±0.00^{aA}	11.40 ±0.53^{B}	10.60 ±0.35^{bC}
Asc5%	11.33 ±0.42^{bcAB}	11.00 ±0.20^{bB}	11.07 ±0.58^{bAB}	11.20 ±0.35^{cAB}	9.27 ±0.64^{bC}	12.07 ±0.12^{bAB}	11.27 ±0.23^{bAB}	11.27 ±0.23^{AB}	12.13 ±0.23^{aA}
NatureSeal®5%	11.40 ±0.60^{bcAB}	12.47 ±1.10^{aAB}	12.67 ±0.76^{aA}	12.07 ±0.42^{bcAB}	11.40 ±0.00^{aAB}	12.13 ±0.23^{bAB}	11.13 ±0.31^{bAB}	11.33 ±0.12^{AB}	11.07 ±0.42^{abB}

The data are presented as means ± standard deviations. Mean values with different superscripts (lowercase letters) within the same column indicate significant differences ($p < 0.05$) among treatments at a given storage time. Mean values with different superscripts (uppercase letters) within the same row indicate significant differences ($p < 0.05$) among storage times (days) within a given coating. ns indicates no significant difference ($p > 0.05$) within the same columns.

differences were observed in the pH values among the samples. Fresh-cut apples coated with S5% and O5% exhibited minor changes in pH values, showing a slight decrease on the 14th day, followed by a slight increase on the 16th day. Other treatments, including S2.5%+Asc1.25%, O2.5%+Asc1.25%, Asc2.5%, Asc5%, NatureSeal®5%, and control, also showed a slight decrease in pH values, during storage, followed by a slight increase on the 16th day of storage.

The pH value of fruits reflects the concentration of hydrogen ions and is influenced by several factors, including organic acids and total titratable acidity (TA). Organic acids contribute to the availability of hydrogen ions, which directly affect the pH. As fruits ripen, the organic acid content typically decreases as these acids are converted into sugars or used as substrates for respiration (Islam et al., 2013). Consequently, it is expected that the pH values will slightly increase by the end of storage.

Fruit flavour is strongly influenced by TA, which plays a key role in flavour profile. For all treatments, the TA values (expressed as malic acid content) of fresh-cut apples tended to slightly decrease during storage ($p < 0.05$). However, no significant differences in TA were found between the control and coated samples on the 12th and 16th days of storage (Table 5). According to Olivas et al. (2007), the TA values of fresh-cut apples typically decrease during storage, a change associated with metabolic processes and fruit maturation, with variation depending on the coating composition. Additionally, factors such as storage conditions, fruit variety, and treatment can significantly influence the degree of acidity change (Cortez-Vega et al., 2008; Islam et al., 2013).

Table 4. Changes in pH of fresh-cut apples under different treatments during storage at 4 ±1°C for 16 days

Treatments	pH								
	Storage time (days)								
	0	2	4	6	8	10	12	14	16
Control	4.15 ±0.08$^{ns\ BC}$	4.37 ±0.03^{abAB}	4.48 ±0.07^{aA}	4.31 ±0.05^{abABC}	4.19 ±0.11^{cdBC}	4.10 ±0.03^{cC}	4.27 ±0.19^{abcABC}	4.37 ±0.01^{aAB}	4.33 ±0.11^{aABC}
S5%	4.16 ±0.06^{B}	4.37 ±0.14^{abAB}	4.42 ±0.07^{aA}	4.43 ±0.08^{aA}	4.37 ±0.03^{bAB}	4.38 ±0.05^{bAB}	4.29 ±0.09^{abAB}	4.13 ±0.02^{bcB}	4.34 ±0.14^{aAB}
O5%	4.20 ±0.17^{NS}	4.17 ±0.003^{d}	4.32 ±0.04^{ab}	4.39 ±0.07^{a}	4.23 ±0.08^{cd}	4.39 ±0.09^{b}	4.34 ±0.01^{a}	4.23 ±0.12^{b}	4.36 ±0.13^{a}
S2.5% +Asc1.25%	4.33 ±0.04^{AB}	4.25 ±0.09^{bcdB}	4.23 ±0.03^{bcB}	4.19 ±0.04^{bcB}	4.53 ±0.09^{aA}	4.34 ±0.02^{bAB}	4.15 ±0.06^{bcBC}	3.86 ±0.04^{fD}	3.90 ±0.21^{cCD}
O2.5% +Asc1.25%	4.33 ±0.32^{AB}	4.17 ±0.01^{dABC}	4.12 ±0.06^{cdBC}	4.36 ±0.05^{abABC}	4.17 ±0.05^{dABC}	4.49 ±0.05^{aA}	4.20 ±0.06^{abcABC}	4.06 ±0.02^{cdC}	4.14 ±0.05^{abBC}
Asc2.5%	4.13 ±0.03^{AB}	4.31 ±0.09^{abcA}	4.05 ±0.04^{dB}	4.01 ±0.08^{cB}	4.30 ±0.04^{bcA}	3.99 ±0.04^{dB}	4.11 ±0.15^{cdAB}	3.95 ±0.07^{efB}	4.06 ±0.02^{bcB}
Asc5%	4.45 ±0.04^{A}	4.20 ±0.03^{cdAB}	4.13 ±0.11^{cdBC}	4.03 ±0.06^{cBC}	3.96 ±0.06^{eBC}	3.87 ±0.05^{eC}	3.96 ±0.05^{dBC}	3.98 ±0.09^{deBC}	4.08 ±0.22^{bcBC}
NatureSeal®5%	4.40 ±0.11^{A}	4.40 ±0.09^{aA}	4.46 ±0.04^{aA}	4.09 ±0.07^{cC}	4.20 ±0.04^{cdBC}	4.10 ±0.05^{cC}	4.19 ±0.02^{abcBC}	4.19 ±0.01^{bBC}	4.34 ±0.02^{aAB}

The data are presented as means ± standard deviations. Mean values with different superscripts (lowercase letters) within the same column indicate significant differences ($p < 0.05$) among treatments at a given storage time. Mean values with different superscripts (uppercase letters) within the same row indicate significant differences ($p < 0.05$) among storage times (days) within a given coating. NS indicates no significant difference ($p > 0.05$) within the same rows, while ns indicates no significant difference ($p > 0.05$) within the same columns.

Total Phenolic Content and DPPH Radical Scavenging Activity

The effect of coating formulations on the total phenolic content (TPC) and DPPH radical scavenging activity of fresh-cut apples during storage (4 ±1°C) is shown in Figure 2. Coated treatments demonstrated significantly ($p < 0.05$) higher TPC than the control during the first 12 days of storage. Fresh-cut apples coated with Asc2.5%, Asc5%, and NatureSeal®5% maintained stable TPC levels during the first 8 days, followed by a slight decrease on days 10–12, and a subsequent increase on day 14. By day 16, the fresh-cut apples coated with NatureSeal®5% exhibited significantly higher TPC (402.35 mg GAE/100 g FW) compared to other treatments ($p < 0.05$), followed by Asc2.5% (357.5 mg GAE/100 g FW) and Asc5% (346.14 mg GAE/100 g FW). Coated samples with S5%, S2.5%+Asc1.25%, O5%, O2.5%+Asc1.25%, and the control showed a rise in TPC during the first 6 days, but after day 8, the TPC of apples coated with S5% and S2.5%+Asc1.25% gradually decreased throughout the storage period, while the TPC in apples coated with O5% and O2.5%+Asc1.25% decreased initially then plateaued for the remainder of the storage (Fig. 2a). Apples coated with Asc5% consistently exhibited higher TPC values than the control group throughout the storage period. This could be attributed to the ascorbic acid in Asc5%, which acts as both an antioxidant and a reducing agent, potentially reacting with the Folin reagent and leading to an overestimation of the TPC value.

The TPC of all samples tended to increase during the first 6 days of storage. On day 14, TPC values also increased in apples coated with O5%, Asc2.5%,

Table 5. Changes in total titratable acidity of fresh-cut apples under different treatments during storage at 4 ±1°C for 16 days

Treatments	Total titratable acidity (TA, %)								
	Storage time (days)								
	0	2	4	6	8	10	12	14	16
Control	0.21 ± 0.01^{abAB}	0.17 ± 0.01^{dB}	0.22 ± 0.02^{bcAB}	0.20 ± 0.02^{bcAB}	0.23 ± 0.04^{abAB}	0.27 ± 0.02^{aA}	0.22 ± 0.06^{nsAB}	0.16 ± 0.02^{bB}	$0.17 \pm 0.06^{ns\ B}$
S5%	0.26 ± 0.02^{aAB}	0.27 ± 0.02^{cA}	0.18 ± 0.05^{cBC}	0.17 ± 0.02^{cC}	0.15 ± 0.02^{dC}	0.18 ± 0.04^{bcBC}	0.16 ± 0.02^{C}	0.17 ± 0.01^{abC}	0.14 ± 0.01^{C}
O5%	0.23 ± 0.02^{abBCD}	0.27 ± 0.01^{cAB}	0.30 ± 0.01^{abcA}	0.20 ± 0.02^{bcCDE}	0.25 ± 0.03^{aABC}	0.16 ± 0.03^{bcDE}	0.18 ± 0.01^{DE}	0.21 ± 0.02^{abBCDE}	0.15 ± 0.04^{E}
S2.5% +Asc1.25%	0.17 ± 0.003^{bC}	0.29 ± 0.00^{bcA}	0.21 ± 0.04^{bcBC}	0.24 ± 0.03^{abAB}	0.14 ± 0.02^{dC}	0.15 ± 0.01^{cC}	0.17 ± 0.04^{BC}	0.19 ± 0.02^{abBC}	0.21 ± 0.03^{BC}
O2.5% +Asc1.25%	0.18 ± 0.05^{bBC}	0.25 ± 0.02^{cAB}	0.33 ± 0.02^{abA}	0.21 ± 0.02^{bcB}	0.19 ± 0.01^{bcdBC}	0.12 ± 0.00^{cC}	0.17 ± 0.03^{BC}	0.21 ± 0.05^{abB}	0.19 ± 0.02^{BC}
Asc2.5%	0.22 ± 0.01^{abBC}	0.18 ± 0.02^{dCD}	0.39 ± 0.06^{aA}	0.29 ± 0.02^{aB}	0.16 ± 0.01^{cdCD}	0.18 ± 0.01^{bcCD}	0.14 ± 0.05^{D}	0.23 ± 0.00^{aBC}	0.22 ± 0.02^{BC}
Asc5%	0.19 ± 0.003^{bB}	0.36 ± 0.02^{aA}	0.36 ± 0.09^{aA}	0.21 ± 0.02^{bcB}	0.20 ± 0.01^{abcB}	0.23 ± 0.01^{abB}	0.24 ± 0.04^{B}	0.21 ± 0.03^{abB}	0.16 ± 0.03^{B}
NatureSeal®5%	0.20 ± 0.02^{abC}	0.32 ± 0.02^{abA}	0.19 ± 0.04^{cC}	0.28 ± 0.02^{aB}	0.26 ± 0.02^{aB}	0.28 ± 0.04^{aB}	0.20 ± 0.03^{C}	0.21 ± 0.03^{abC}	0.14 ± 0.01^{D}

The data are presented as means ± standard deviations. Mean values with different superscripts (lowercase letters) within the same column indicate significant differences ($p < 0.05$) among treatments at a given storage time. Mean values with different superscripts (uppercase letters) within the same row indicate significant differences ($p < 0.05$) among storage times (days) within a given coating. ns indicates no significant difference ($p > 0.05$) within the same columns.

Asc5%, and NatureSeal®5%, which could be due to the activation of phenylalanine ammonia-lyase (PAL) after cutting. PAL is typically induced in response to wounding, promoting the production of phenolic compounds as a defence mechanism against pathogens or to prevent water loss (Reyes et al., 2007). Additionally, ascorbic acid, a potent antioxidant (Gil et al., 1998; Arias et al., 2007), and other antioxidants in edible coatings act as reducing agents, converting ortho-quinones back into ortho-diphenols (Nicolas et al., 1994; Perez-Gago et al., 2006; Queiroz et al., 2008), helping to prevent the decline of phenolic compounds (Altunkaya and Gokmen, 2008).

The antioxidant activity of fresh-cut apples was measured through DPPH radical scavenging activity (Fig. 2b). DPPH activity closely mirrored the TPC levels, as both were strongly correlated. During the first 12 days of storage, all coated treatments exhibited significantly ($p < 0.5$) higher DPPH activity than the control. Over the first 6 days, DPPH activity increased in all samples. Samples treated with NatureSeal®5% showed the highest DPPH activity on day 6 (76%), followed by Asc5% (74%), with no significant difference between them. By day 6, DPPH activity in samples treated with S5%, O5%, O2.5%+Asc1.25%, S2.5%+Asc1.25%, and Asc2.5% ranged from 43% to 51% with no significant differences among these treatments. On day 14, DPPH activity increased in samples coated with O5%, Asc5%, and NatureSeal®5%, but decreased by the final day of storage.

This study demonstrated that the edible coatings, ascorbic acid solutions, and their combinations significantly ($p < 0.05$) enhanced TPC during the early storage period, and were associated with an increase in DPPH activity in samples. Similar findings were reported by Oms-Oliu et al. (2008), who observed an increase in

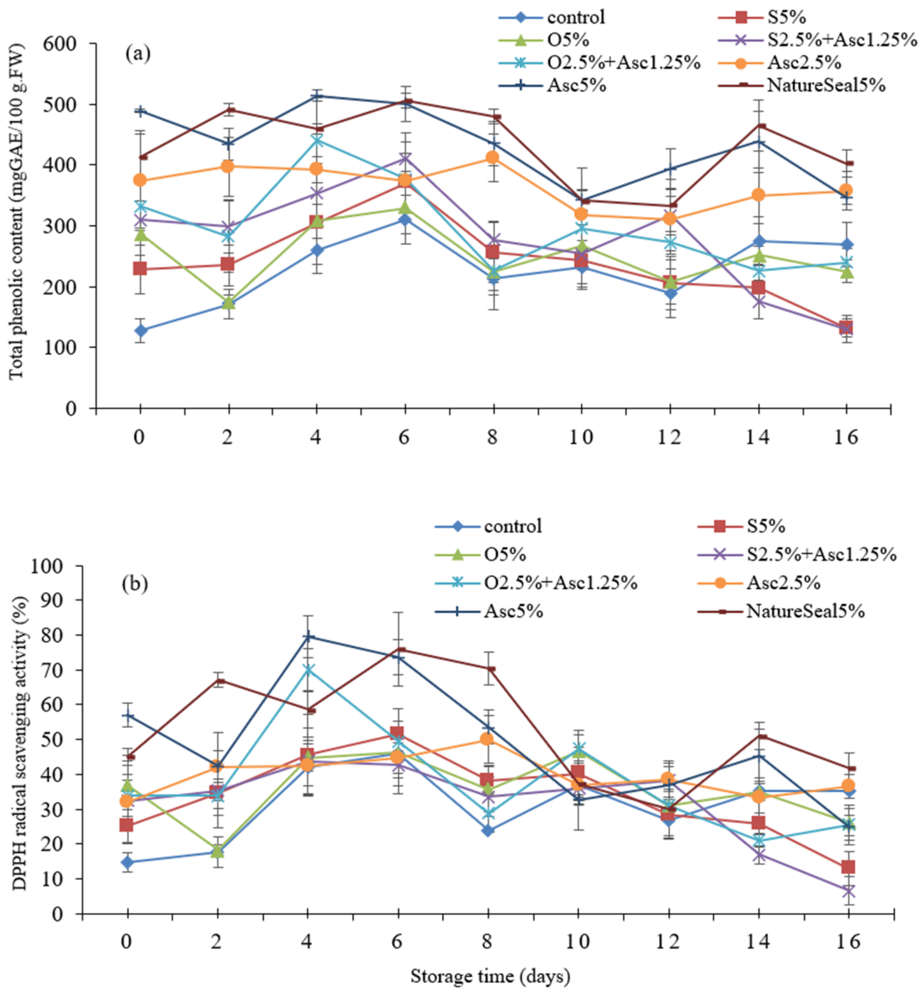

Fig. 2. Changes in total phenolic content (a) and DPPH radical scavenging activity (b) of fresh-cut apples under different treatments during storage at 4 ±1°C for 16 days. Vertical bars indicate standard deviations

phenolic content and antioxidant activity in fresh-cut melon after the application of coatings. Research on fresh-cut kiwi fruit (Antunes et al., 2010) and mangoes (Robles-Sánchez et al., 2013) also found increased antioxidant levels when ascorbic acid was incorporated into the coating formula. It has been noted that antioxidant activity can vary depending on the type of coating and fruit variety (Oms-Oliu et al., 2008).

Sensory Evaluation

The sensory evaluation results for the fresh-cut apples treated with different coating formulations are presented in Table 6. Sensory tests were conducted on days 4, 8, 12, and 16 of storage. The results revealed that fresh-cut apples treated with edible coatings, ascorbic acid solutions, and their combinations, consistently received higher sensory scores than the control, particularly on the 16th day of storage. Notably, these coatings resulted in a significant ($p < 0.05$) increase in sensory scores across all evaluated quality attributes.

Colour scores for the coated treatments were higher than those of the control throughout the storage period. On the 16th day of storage, fresh-cut apples coated

Table 6. Sensory evaluation results of fresh-cut apples treated with different treatments during storage at 4±1°C for 16 days

Storage time (days)	Treatments	Scores				
		Colour	Odour	Taste	Firmness	Overall preference
4	control	5.27 ±1.72[c]	6.37 ±1.47[ns]	7.30 ±1.39[a]	6.83 ±1.80[ab]	7.13 ±1.55[ns]
	S5%	5.93 ±1.87[bc]	5.83 ±1.78	6.07 ±1.78[ab]	6.30 ±1.84[b]	6.60 ±1.79
	O5%	6.90 ±1.49[ab]	6.07 ±1.64	6.07 ±1.95[ab]	7.23 ±1.33[ab]	6.80 ±1.65
	S2.5%+Asc1.25%	7.37 ±1.59[a]	5.67 ±1.77	5.77 ±1.91[b]	6.53 ±1.70[ab]	6.70 ±1.58
	O2.5%+Asc1.25%	7.60 ±1.50[a]	6.10 ±1.37	6.27 ±2.00[ab]	7.13 ±1.57[ab]	7.13 ±1.50
	Asc2.5%	7.37 ±1.35[a]	6.80 ±1.45	7.20 ±1.73[a]	7.47 ±1.22[ab]	7.17 ±1.37
	Asc5%	7.87 ±1.41[a]	6.43 ±1.76	7.23 ±1.31[a]	7.17 ±1.34[ab]	7.43 ±1.31
	NatureSeal®5%	8.00 ±1.31[a]	6.80 ±1.45	7.23 ±1.22[a]	7.63 ±1.19[a]	7.67 ±1.18
8	control	4.90 ±1.32[c]	6.00 ±1.05[ab]	6.33 ±1.47[ab]	6.50 ±1.23[c]	6.47 ±1.17[c]
	S5%	6.37 ±1.54[b]	5.73 ±1.57[b]	6.10 ±1.83[b]	6.97 ±1.10[abc]	6.73 ±1.41[abc]
	O5%	6.53 ±1.36[b]	6.03 ±1.00[ab]	6.43 ±1.31[ab]	6.90 ±1.42[abc]	6.80 ±1.35[abc]
	S2.5%+Asc1.25%	7.03 ±1.35[ab]	6.30 ±1.29[ab]	6.37 ±1.25[ab]	6.97 ±1.10[abc]	6.77 ±1.31[abc]
	O2.5%+Asc1.25%	6.90 ±1.63[ab]	6.07 ±1.23[ab]	6.40 ±1.79[ab]	6.70 ±1.51[bc]	6.67 ±1.63[bc]
	Asc2.5%	6.50 ±1.61[b]	6.00 ±1.20[ab]	6.30 ±1.86[ab]	6.63 ±1.19[c]	6.50 ±1.46[bc]
	Asc5%	7.80 ±1.10[a]	6.87 ±1.17[a]	7.13 ±1.36[ab]	7.60 ±0.97[ab]	7.53 ±1.07[ab]
	NatureSeal®5%	7.93 ±1.14[a]	6.87 ±1.41[a]	7.43 ±1.17[a]	7.70 ±1.09[a]	7.77 ±1.10[a]
12	control	4.60 ±1.43[c]	5.33 ±1.24[c]	5.30 ±1.58[b]	6.03 ±1.50[c]	6.03 ±1.40[c]
	S5%	5.37 ±1.07[bc]	5.80 ±1.13[bc]	6.13 ±0.94[ab]	6.30 ±0.92[bc]	6.37 ±0.89[bc]
	O5%	5.73 ±1.08[b]	5.60 ±1.22[bc]	6.30 ±1.24[ab]	6.87 ±1.01[abc]	6.33 ±1.21[bc]
	S2.5%+Asc1.25%	5.73 ±1.39[b]	6.00 ±1.29[abc]	6.43 ±1.52[a]	6.30 ±1.12[bc]	6.43 ±1.31[bc]
	O2.5%+Asc1.25%	5.17 ±1.62[bc]	5.23 ±1.43[c]	6.03 ±1.67[ab]	6.30 ±1.26[bc]	5.93 ±1.26[c]
	Asc2.5%	5.93 ±1.23[b]	6.23 ±1.17[abc]	6.33 ±.32[ab]	6.37 ±1.25[bc]	6.40 ±1.10[bc]
	Asc5%	7.73 ±1.23[a]	6.40 ±1.43[ab]	5.87 ±1.59[ab]	7.07 ±1.20[ab]	6.93 ±1.48[ab]
	NatureSeal®5%	7.67 ±1.35[a]	6.97 ±1.38[a]	6.63 ±1.30[a]	7.53 ±0.63[a]	7.47 ±1.07[a]
16	control	4.77 ±1.41[e]	5.30 ±1.15[c]	5.30 ±1.56[b]	5.70 ±1.26[c]	5.73 ±1.02[c]
	S5%	5.73 ±1.36[d]	5.87 ±1.33[bc]	6.03 ±1.25[a]	6.03 ±1.27[bc]	6.17 ±1.26[bc]
	O5%	6.50 ±0.78[bcd]	6.50 ±1.03[ab]	6.43 ±0.97[a]	6.53 ±1.03[ab]	6.60 ±1.00[ab]
	S2.5%+Asc1.25%	6.13 ±1.48[cd]	6.07 ±1.14[abc]	6.37 ±1.40[a]	6.20 ±1.35[abc]	6.40 ±1.28[ab]
	O2.5%+Asc1.25%	6.90 ±1.09[abc]	6.50 ±1.23[ab]	6.33 ±1.77[a]	6.40 ±1.00[ab]	6.73 ±1.20[ab]
	Asc2.5%	7.13 ±1.07[ab]	6.67 ±1.06[ab]	6.53 ±1.07[a]	6.57 ±1.04[ab]	6.80 ±1.06[a]
	Asc5%	6.87 ±1.22[abc]	6.47 ±1.36[ab]	6.53 ±1.59[a]	6.77 ±1.38[a]	6.93 ±1.23[a]
	NatureSeal®5%	7.73 ±1.02[a]	6.97 ±1.07[a]	6.80 ±1.54[a]	6.80 ±1.30[a]	7.07 ±1.17[a]

The data are shown as means ± standard deviations. Mean values with different superscripts (lowercase letters) in the same column indicate significant differences ($p < 0.05$) among treatments at a given storage time (days). ns indicates no significant difference ($p > 0.05$) within the same columns.

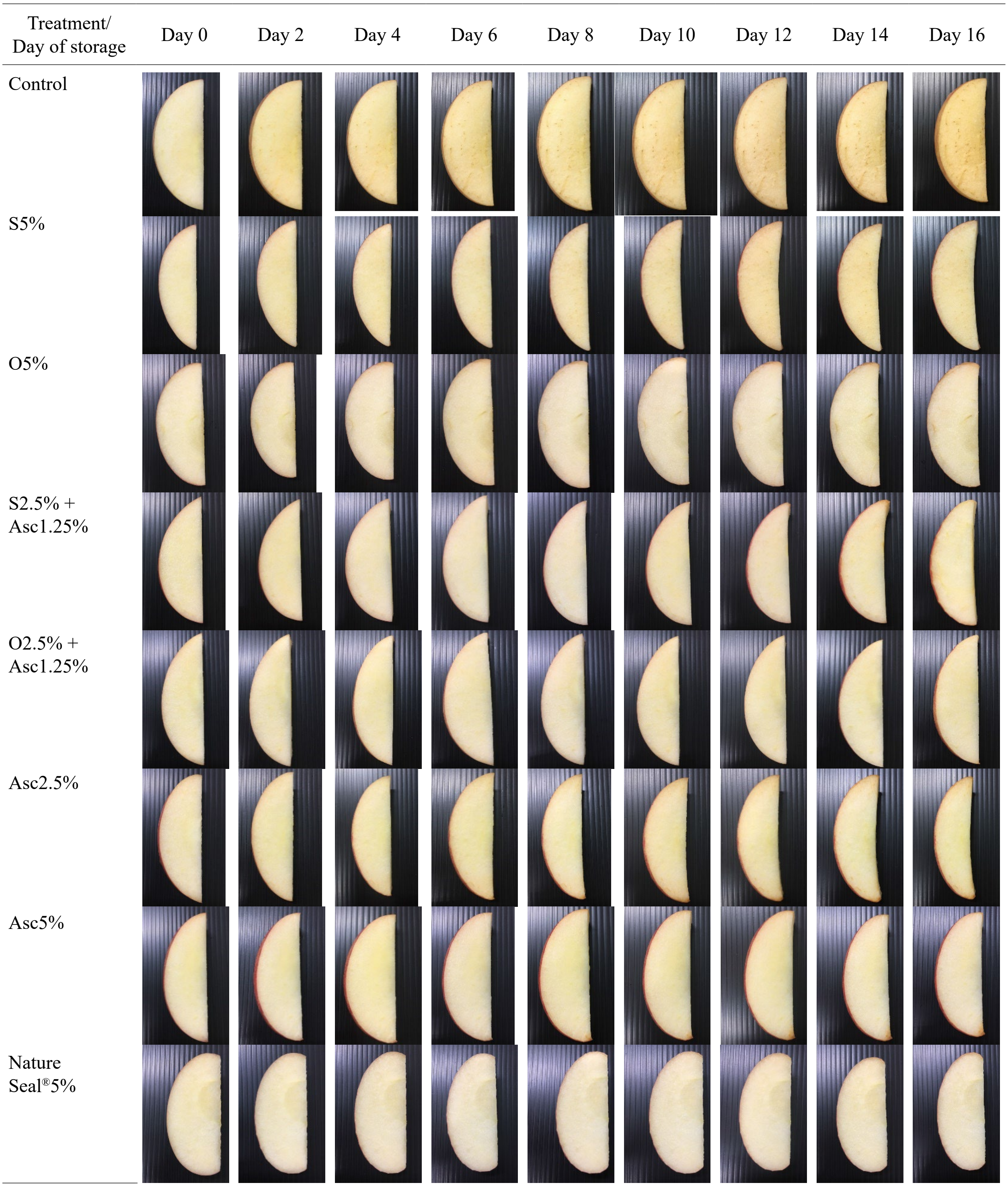

Fig. 3. Changes in the visual appearance of fresh-cut apples under different treatments during storage at 4 ±1°C for 16 days

with NatureSeal®5%, Asc2.5%, O2.5%+Asc1.25%, and Asc5% had colour scores of 7.73, 7.13, 6.90, and 6.87, respectively, with no significant differences among the treatments.

Odour scores on day 4 of storage showed no significant differences between treatments. By the 16th day of storage, odour scores ranged from 6.07 to 6.97 for samples treated with NatureSeal®5%, Asc2.5%, O5%, O2.5%+Asc1.25%, Asc5%, and S2.5%+Asc1.25%. Again, no significant differences were observed among the treatments.

Taste scores on the 12th and 16th days of storage were higher for all coated treatments compared to the control, with no significant differences among them. On the 16th day, the taste scores for the sample coated with NatureSeal®5%, Asc5%, Asc2.5%, O5%, S2.5%+Asc1.25%, O2.5%+Asc1.25%, and S5% ranged from 6.03 to 6.80, while the control had the lowest taste scores of 5.30.

The instrumental firmness results (Table 2) were confirmed by the sensory firmness assessment (Table 6). On the 16th day of storage, the firmness scores for apples coated with NatureSeal®5%, Asc5%, Asc2.5%, O5%, O2.5%+Asc1.25%, and S2.5%+Asc1.25% were 6.80, 6.77, 6.57, 6.53, 6.40, and 6.20, respectively. No significant differences were observed between the treatments.

Overall preference scores on day 4 showed no significant differences among the treatments. Similarly, on day 16, no significant differences were observed among the treatments. The overall preference scores for fresh-cut apples coated with NatureSeal®5%, Asc5%, Asc2.5%, O2.5%+Asc1.25%, O5%, and S2.5%+Asc1.25%, were 7.07, 6.93, 6.80, 6.73, 6.60, and 6.40, respectively, while the control had the lowest score of 5.73.

In conclusion, this study demonstrated that edible coatings, ascorbic acid solutions, and their combinations significantly ($p < 0.05$) delayed sensory quality deterioration, including colour, odour, taste, firmness, and overall acceptability of the fresh-cut apples. These results align with previous research by Moreira et al. (2015), which showed that a combination of edible coatings and pulsed light helps maintain sensory attribute scores above the rejection threshold (a score of 3 on a 5-point scale) during extended storage. Benítez et al. (2013) also found that Aloe vera coatings on fresh-cut kiwi fruit delayed browning and slowed the deterioration of sensory qualities over an extended storage period.

CONCLUSION

This study demonstrated that fresh-cut 'Fuji' apples treated with NatureSeal® (5%) (a commercial edible coating), shallot (S5%) or onion (O5%) edible coatings, ascorbic acid solutions (Asc2% and Asc5%), and their combinations (S2.5%+Asc1.25% and O2.5%+Asc1.25%) effectively preserved the quality of fresh-cut apples stored at 4 ±1°C for 16 days. These treatments inhibited colour changes, improving lightness and whiteness index while reducing the browning index. They also delayed changes in firmness, maintaining the texture of the apples and preserving most of their quality attributes.

For all treatments, the total titratable acidity (TA) of fresh-cut apples tended to slightly decrease during storage ($p < 0.05$), while the total soluble solid (TSS) content and firmness remained stable throughout the storage period. The apples coated with O5% and O2.5%+Asc1.25% exhibited relatively stable firmness, with their firmness values on the final day of storage slightly higher than those on the first day (day 0).

Furthermore, total phenolic content (TPC) and DPPH radical scavenging activity of the coated treatments were significantly higher than those of the control group during the first 12 days of storage. These treatments did not reduce phenolic content or antioxidant activity, thus preserving the nutritional value of the apples. Among the treatments, the apples coated with Asc5% and NatureSeal®5% exhibited the highest TPC values throughout the storage period.

The coated samples also showed significantly delayed changes in sensory quality characteristics, maintaining higher scores in colour, firmness, taste, and overall acceptability compared to the control, particularly on the 12th and 16th days of storage. On day 16, all coated treatments received higher sensory scores than the control in all evaluated quality aspects.

Importantly, the quality of fresh-cut apples at the end of storage was not significantly affected by the use of S5% or O5% edible coatings, either alone or in combination with ascorbic acid. In conclusion, based on the analysis of physico-chemical properties and sensory acceptability, fresh-cut 'Fuji' apples treated with NatureSeal®5%, Asc5%, Asc2.5%, O2.5%+Asc1.25%, O5%, and S2.5%+Asc1.25% demonstrated significant potential for preserving overall quality during storage. Further research is recommended to explore the effects of hydrocolloids and ascorbic acid, individually or in combination, as anti-browning agents for fresh-cut apples.

DECLARATIONS

Data statement

All data supporting this study has been included in this manuscript.

Ethical Approval

Not applicable.

Competing Interests

The authors declare that they have no conflicts of interest.

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