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Physicochemical and sensory evaluation of fresh-cut apples treated with chitosan-based edible coatings

Pooja R. Mogarkar, Sushil Lokhande & Sheetal D. Deshmukh*

Department of Food Technology, Laxminarayan Innovation Technological University, Nagpur, Maharashtra-440 033, India

*E-mail: sheetaldheerajdeshmukh11@gmail.com

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Edible coatings provide a protective layer on minimally processed fruits and vegetables and represent an environmentally friendly preservation method. The objective of this study is to evaluate the effectiveness of chitosan-based edible coatings in extending the shelf life of fresh-cut apples. Edible coatings have been formulated with chitosan (0.6–1.2% w/v) containing 0.8% ascorbic acid, 0.5% glycerol, and 0.1% Tween-80. Fresh-cut apples were dipped in the edible coatings for 60 s, air-dried, packed in aluminum foil containers, and stored at 4 °C for 12 days. Uncoated apples without chitosan served as controls. The effects of chitosan-ascorbic acid-glycerol-Tween-80 coatings on quality parameters including weight loss, browning, texture changes, acidity, ascorbic acid content, and sensory evaluation were monitored during refrigerated storage. Results showed that by day 12, control samples lost 27.9% of their weight, while coated samples with 1.2% chitosan lost only 24.2%. Edible coating samples with chitosan showed significantly lower deterioration compared to control samples ($p<0.05$). The colour (L^* values of 63.16 for the 1.2% chitosan treatment vs. 45.75 for the control) and firmness of apples with edible coatings showed minimal changes by the end of storage. The formulation containing 0.8% chitosan with 0.8% ascorbic acid, 0.5% glycerol, and 0.1% Tween-80 demonstrated optimal overall acceptance in sensory evaluation, while the 1.2% chitosan formulation showed superior performance in objective quality parameters (weight loss and colour retention). These findings indicate that chitosan-based edible coatings effectively maintain quality and extend the shelf life of fresh-cut apples during refrigerated storage.

Keywords: Ascorbic acid, Chitosan, Edible coating, Enzymatic browning inhibition, Fresh-cut apples, Sensory evaluation, Shelf life

Introduction

In recent years, there has been growing market demand for minimally processed fruits and vegetables due to their fresh-like character, ease of handling, and human health benefits. These minimally processed fresh-cuts are ready-to-eat products that differ from whole fruits and vegetables with respect to their physiology, handling, and storage requirements. Minimal processing includes operations such as grading, washing, sorting, peeling, cutting, slicing, chopping, and packaging.

However, these operations cause mechanical damage to fruit tissues and initiate enzymatic reactions, resulting in cut-surface discolouration, tissue softening, juice leakage, water loss, aroma and flavour loss, off-flavour development, as well as microbial growth and spoilage[1]. These quality losses and safety concerns in fresh-cut produce drastically shorten shelf life, making products more perishable, increasing costs, reducing overall appearance, and affecting consumer acceptance[2]. While minimally processed fresh-cuts offer convenience and time-saving benefits, preserving them presents significant challenges. Maintaining freshness for prolonged periods remains a major challenge for food technologists.

Edible coatings and films provide a novel approach to preserve fresh-cuts of fruit and improve overall appearance with respect to food quality. Edible coating involves the formation of a thin layer of edible material on the surface of fruits, providing a semi-permeable barrier to moisture, oxygen, and carbon dioxide gas exchange. This barrier slows down ripening, retards oxidative reactions, improves mechanical and textural properties, reduces moisture loss, and prevents undesirable flavour development during minimal processing, consequently maintaining fresh aroma and flavour[3].

Edible coatings also serve as vehicles to carry active ingredients such as anti-browning agents, antimicrobials, and texture-enhancing compounds, as well as flavours and nutrients, to enhance the quality, safety, and nutritional value of fresh-cut fruits. Beyond edible coatings, biopolymer-based functional films incorporating polysaccharides and functional additives have also been developed for food packaging applications, offering tunable mechanical and barrier properties[4]. The authors' group has also investigated related functional coating and pigment systems, including ZnO-based composites for optical and thermal management applications[5,6] and anti-corrosive and flame-retardant coating formulations[7,8]. Among the many natural polysaccharide-based coating materials available, chitosan has emerged as a particularly promising option.

Chitosan is a high molecular weight, cationic polysaccharide composed of β-1,4-linked glucosamine with variable quantities of N-acetylated GlcN residues. Chitosan possesses excellent film-forming ability, antibacterial and antifungal properties, and is generally recognized as safe (GRAS). Microbial growth is inhibited by chitosan, possibly due to interactions between its positively charged molecules and the negatively charged microbial cell membrane. However, chitosan films display comparatively high water vapour permeability. Incorporation of plasticizers such as sorbitol or glycerol in chitosan makes films more resistant to moisture transfer, increases flexibility of the coatings, and decreases brittleness by reducing internal hydrogen bonds between polymer chains and increasing intermolecular spaces[9].

Edible coatings as carriers of anti-browning agents have been found advantageous in lowering respiration, delaying oxidative reactions, and ultimately improving the quality of fresh-cut fruits and vegetables[10]. Ascorbic acid, cysteine, citric acid, and some sulfur-containing amino acids are anti-browning agents that have been used as substitutes for sulfite to prevent enzymatic browning, alone or in combination with firming or antimicrobial agents[11]. Numerous studies have demonstrated that ascorbic acid effectively controls enzymatic browning in fresh-cut fruits and vegetables by reducing quinones back to diphenols and inhibiting polyphenol oxidase (PPO) activity[12].

Apple (*Malus domestica*) is a sweet, pomaceous fruit cultivated worldwide. It is appreciated for its sensory characteristics and shows high commercial value. Fresh-cuts of apple in the form of cubes or slices represent one of the products with highest consumer demand among minimally processed fruits and vegetables. Being a climacteric fruit, increased respiration rate and ethylene production are often observed in apples after harvesting. However, use of fresh-cut apple slices is frequently limited by the faster rate of browning, which lowers quality. The use of anti-browning agents is a common solution to prevent enzymatic browning[13].

Despite numerous studies on individual components, the combined effects of chitosan with ascorbic acid, glycerol, and Tween-80 on fresh-cut apples stored at refrigeration temperatures have not been comprehensively investigated. This study addresses this gap by evaluating the physicochemical and sensory performance of a four-component chitosan-based coating system across multiple concentration levels during 12 days of cold storage.

Experimental Section

Materials

Apples were purchased from the local wholesale market of Nagpur with proper inspection to ensure no physical damage, pathological injuries, or visual decay. Fruits of regular shape and uniform size (diameter 70–80 mm; weight 180–220 g) without any defects were selected for the study. Chitosan with high molecular weight (M_w = 600 kDa) and degree of deacetylation greater than 80% was obtained from Merck Chemicals. Glycerol and ascorbic acid obtained from Merck Chemicals were used as plasticizer and anti-browning agent, respectively. All other chemicals were of analytical grade.

Edible coating formulations

The formulation of edible coating for application on fresh-cut apple pieces is presented in Table 1. Chitosan solutions were prepared by adding chitosan in concentrations ranging from 0.6 g to 1.2 g (w/v) in 100 mL of 1% (v/v) glacial acetic acid solution. The

Table 1 — Formulation of Chitosan-Based Edible Coating

Component	Control (Uncoated)	0.6% Chitosan	0.8% Chitosan	1.0% Chitosan	1.2% Chitosan
Chitosan (w/v)	–	0.6%	0.8%	1.0%	1.2%
Glacial acetic acid	–	1%	1%	1%	1%
Tween-80	–	0.1% (w/v)	0.1% (w/v)	0.1% (w/v)	0.1% (w/v)
Glycerol	–	0.5% (w/v)	0.5% (w/v)	0.5% (w/v)	0.5% (w/v)
Ascorbic acid	–	0.8% (w/v)	0.8% (w/v)	0.8% (w/v)	0.8% (w/v)

mixture was allowed to dissolve on a magnetic stirrer at 700 rpm for approximately 24 h. During this time, 0.1 g (w/v) of Tween-80 emulsifier was added as a surfactant and 0.5 g (w/v) of glycerol was added as a plasticizer to improve mechanical properties of the chitosan-based solution. Finally, ascorbic acid (0.8% w/v) was added as an anti-browning agent. The pH of all prepared coating solutions was measured using a calibrated pH meter and recorded as 2.82 ± 0.005 (applicable to all formulations, as the acetic acid concentration was held constant across treatments).

Preparation of fresh-cut apples

Apples were washed with plain water and air-dried naturally. They were peeled manually and cut with a stainless steel sharp knife into cubes of size 2.2 × 1.1 × 0.8 cm. Good manufacturing practices and best possible sanitary conditions were strictly adhered to during processing. All containers, cutting boards, knives, and other utensils that would be in contact with apples were washed and sanitized with 0.1% (w/v) sodium hypochlorite solution and subsequently rinsed thoroughly with potable water to remove residual chlorine before use. A total of 15 apples were used for each treatment group, providing three independent replicates of five apples each, prepared on separate occasions to ensure true replication.

Application of edible coating

Fresh-cut apples (approximately 100 g per replicate) were dipped in chitosan solutions with various chitosan concentrations (0.6–1.2% w/v) for approximately 60 s, followed by air drying at room temperature for approximately 30 min (Fig. 1). Samples were then packed in aluminum foil containers and stored at 4 °C with relative humidity maintained at 85–90% (verified using a calibrated digital hygrometer, Testo 608-H1, logged every 6 h) in a refrigerator for 12 days. Quality parameters were monitored at 2-day intervals. Sensory evaluation was performed at days 0, 4, 8, and 12.

Analytical methods

Percentage weight loss

Weight loss of apple cubes was determined by comparing the weights of samples during storage with initial weights using a digital balance (±0.01 g accuracy) and expressing the results as a percentage as per the standard method of AOAC Official Method 925.10 (1994). The formula used was as follows.

$$\%\ \text{Weight loss} = \left(\frac{\textit{Weight at day 0 - Weight at day N}}{\textit{Weight at day 0}}\right) \times 100$$

Measurements were performed in triplicate for each treatment.

TSS, pH, titratable acidity, and ascorbic acid

Fresh-cut apples were homogenized and the extract was used to determine pH, TSS, and titratable acidity. pH was measured using a calibrated pH meter (Oaklon Eutech Instruments). TSS was determined using a hand refractometer (0–32 Brix) according to AOAC (1994). Titratable acidity was expressed in grams of citric acid per 100 g of apple. Ascorbic acid was determined by the 2,6-dichloroindophenol titration method (AOAC Official Method 967.21, 1994). All measurements were performed in triplicate.

Colour analysis

Colour changes were determined using a Lovibond RT series Reflectance Tintometer. Colour coordinates L*, a*, and b* were recorded according to the CIE L*a*b* colour system. Chroma (C*) was calculated as $C^* = (a^{*2} + b^{*2})^{0.5}$. Colour measurements were

Fig. 1 — Fresh-cut apples dipped in chitosan solutions with various chitosan concentrations

taken at five random positions on each sample, with three replicates per treatment per time point.

Texture analysis

Firmness was measured using a texture analyzer (TA-XT Plus; Stable Micro Systems, UK). Apples were cut into cubes of 2.2 × 1.1 × 0.8 cm and measured in the central zone using a Blade Set (HDP/BS) with a 5 kg load cell (selected for its ability to assess shear resistance of structured apple tissue, consistent with the method of Rojas-Graü *et al*.,[14]). Test speed: 1.0 mm/s, penetration depth: 5 mm. Fruit pieces (n=10 per replicate) were analyzed after 0, 2, 4, 6, 8, 10, and 12 days.

Sensory evaluation

Sensory evaluation was carried out using a 9-point hedonic scale by a trained panel of 15 assessors (8 female, 7 male, ages 22–45). Panel members were trained in three formal sessions conducted prior to the study, following ISO 11136:2014 guidelines, to familiarize them with the evaluation criteria, reference standards, and scoring system. Sensory characteristics were evaluated after 0, 4, 8, and 12 days of storage for taste, colour, flavour, texture, appearance, mouthfeel, aftertaste, and overall acceptability. Samples were presented in random order (Williams Latin Square design) in coded containers under white light at room temperature. Panelists rinsed with water between samples.

Statistical analysis

All experiments were conducted in triplicate, and results were expressed as mean ± standard deviation (SD). Data were subjected to one-way analysis of variance (ANOVA) using SPSS software (version 20.0). Duncan's multiple range test was used to determine significant differences between means at $p<0.05$ significance level. Linear regression analysis was performed to evaluate trends in quality parameters over storage time.

Results and Discussion

Percentage weight loss

Weight loss in fruits is mainly associated with respiration and moisture evaporation through the skin[15]. When apple slices without any coating were exposed to an environment with lower relative humidity, considerable weight loss occurred. The results obtained in this study showed that all fruit samples lost weight during storage, which is consistent with several previous studies[16, 17]. However, the rates of weight loss were significantly greater for uncoated fruits than for coated fruits ($p<0.05$).

At the end of 12 days, the control group lost 27.898 ± 1.34% of total weight, while samples treated with 0.6%, 0.8%, 1.0%, and 1.2% chitosan lost 24.337 ± 1.12%, 25.011 ± 0.98%, 24.998 ± 1.05%, and 24.192 ± 0.89% of total weight, respectively, at 4°C (Fig. 2). Statistical analysis (Duncan's MRT)

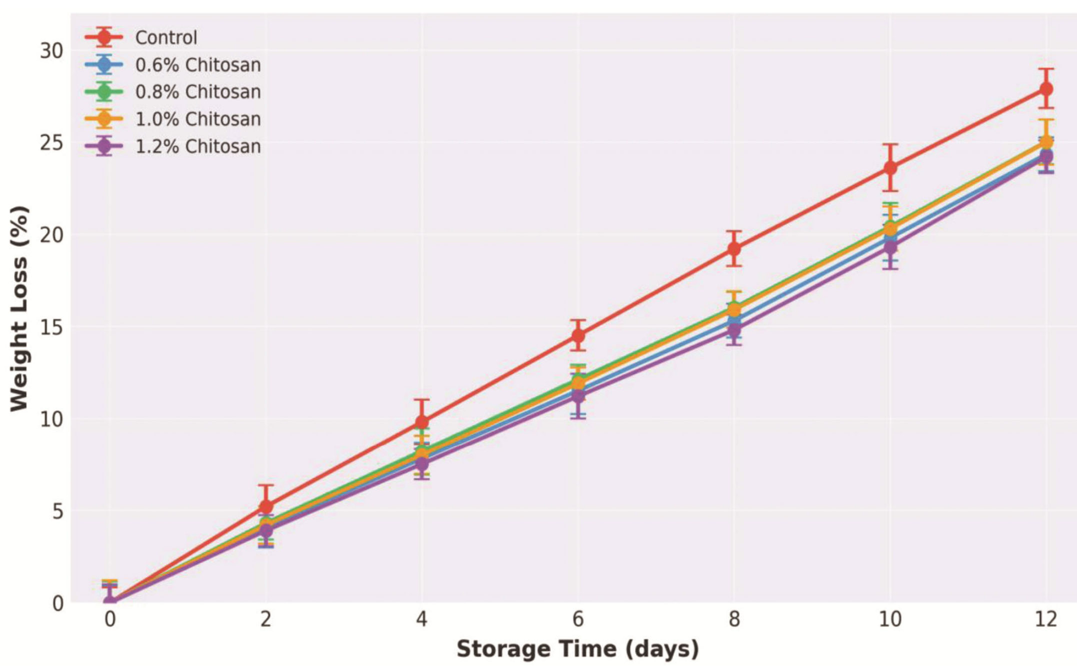

Fig. 2 — Percentage weight loss in apple slices during 12 days of storage at 4 °C. Error bars represent standard deviation (n=3). Different letters indicate significant differences ($p<0.05$)

indicated that while all coated treatments differed significantly from the control ($p<0.05$), the differences among the 0.6%, 0.8%, and 1.0% chitosan treatments were not statistically significant from one another ($p>0.05$). The non-monotonic pattern observed, where 0.6% performed comparably to 0.8% and 1.0% is therefore attributable to experimental variation within statistically equivalent groups, rather than a true dose-response reversal. Only the 1.2% treatment showed a significantly lower weight loss than all other coated groups ($p<0.05$).

Firmness

Firmness significantly decreased during storage for all samples ($p<0.05$), as shown in Fig. 3. These changes, attributable to tissue senescence, cell wall breakdown, and water loss, were significantly less marked in coated apples. The major reasons for softening are acid hydrolysis and enzymatic degradation of cell wall components such as pectin and cellulose. Edible coatings can preserve texture by reducing water loss and preventing dehydration[18]. Chitosan coating has been reported as efficient in avoiding tissue softening in cut fruits by maintaining cell wall integrity and reducing enzymatic activity[19].

The firmness of chitosan-coated slices did not significantly decrease over 12 days compared to day-0 values, while uncoated slices showed faster softening (firmness decreased from 15.2 ± 0.8 N to 8.3 ± 0.6 N), indicating that the coating effectively retarded tissue softening. These results are consistent with findings reported by Chien et al.[2] and Rojas-Graü et al.[14]. The mechanism of texture preservation may be related to the calcium-binding properties of chitosan and its ability to form a protective matrix around fruit tissue [14,20,21]. The importance of rheological and mechanical optimization in coating systems more broadly has also been underscored by Chanpurkar *et al.*[21], whose work on lactide-based polyester coatings highlights that controlled formulation parameters are essential to achieving consistent mechanical performance.

Colour

In general, decreased colour value of fresh-cut apples during storage is caused by increased respiration rate and enzymatic browning. Colour parameters L*, a*, b*, and chroma (C*) of coated and uncoated fresh-cut apples during 12 days of storage at 4 °C are shown in Figs 4–7.

L* values for control samples were 45.75 ± 2.31, while for 0.6%, 0.8%, 1.0%, and 1.2% chitosan, they were 61.16 ± 1.89, 61.92 ± 2.12, 62.27 ± 1.95, and 63.16 ± 2.04, respectively, on day 12. These higher L* values indicate better colour retention and reduced browning in coated samples. Ascorbic acid in the formulation contributes by reducing quinones back to diphenols and lowering oxygen availability[23,24].

The a* values at day 12 were 2.64 ± 0.45, 8.54 ± 0.67, 4.92 ± 0.58, 6.73 ± 0.61, and 4.97 ± 0.53

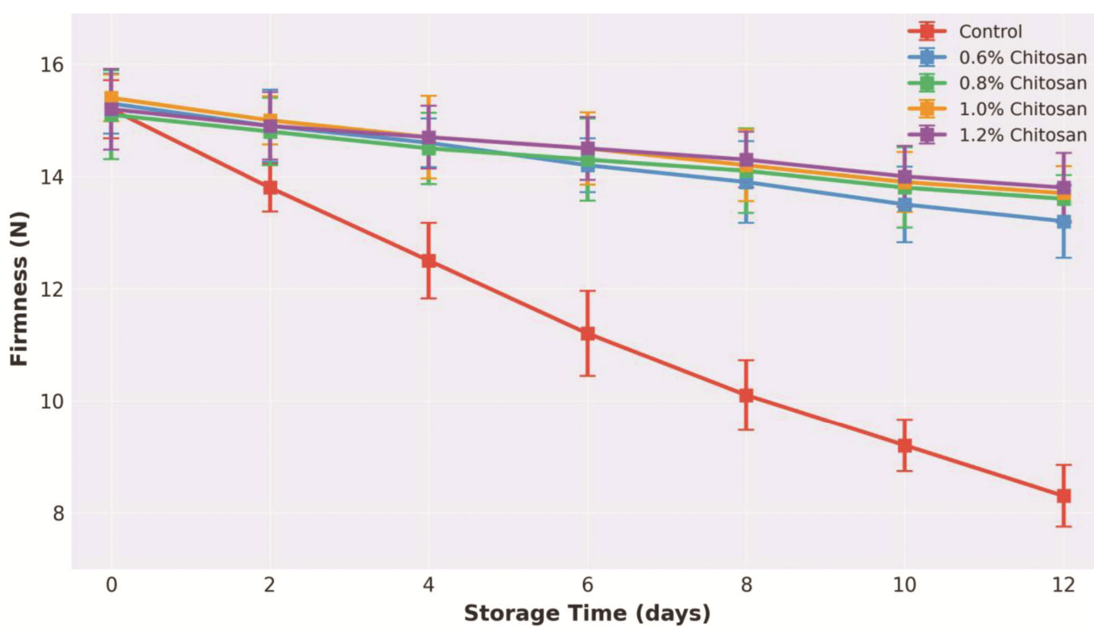

Fig. 3 — Firmness (N) in apple slices during 12-day storage at 4 °C. Error bars represent standard deviation (n=3). Different letters indicate significant differences ($p<0.05$)

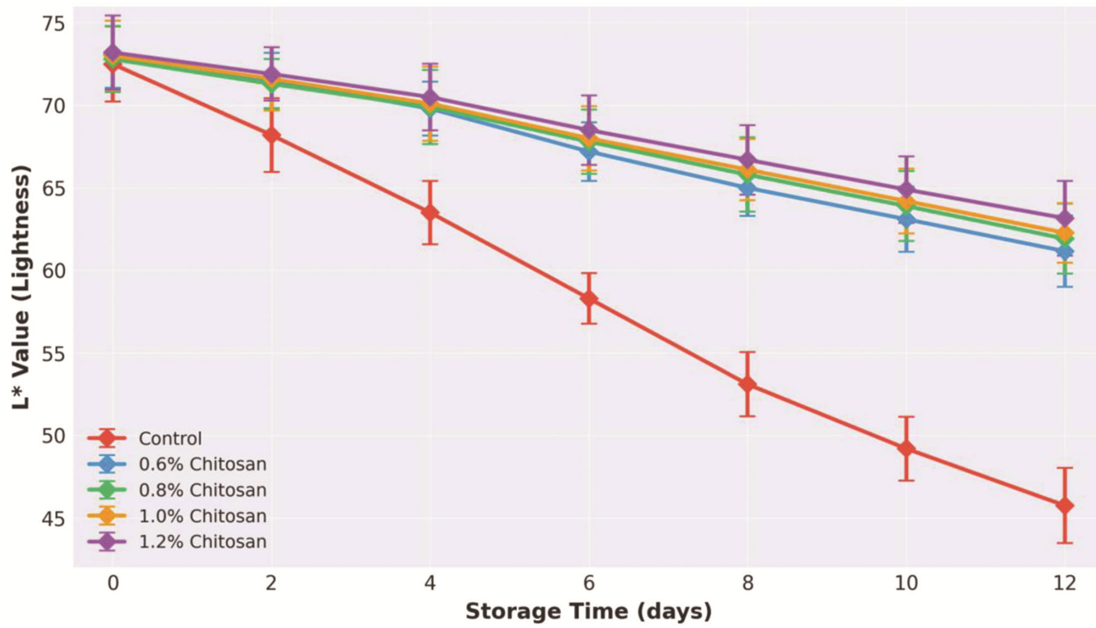

Fig. 4 — L* value of apple slices during 12-day storage at 4 °C. Error bars represent standard deviation (n=3). Different letters indicate significant differences ($p<0.05$)

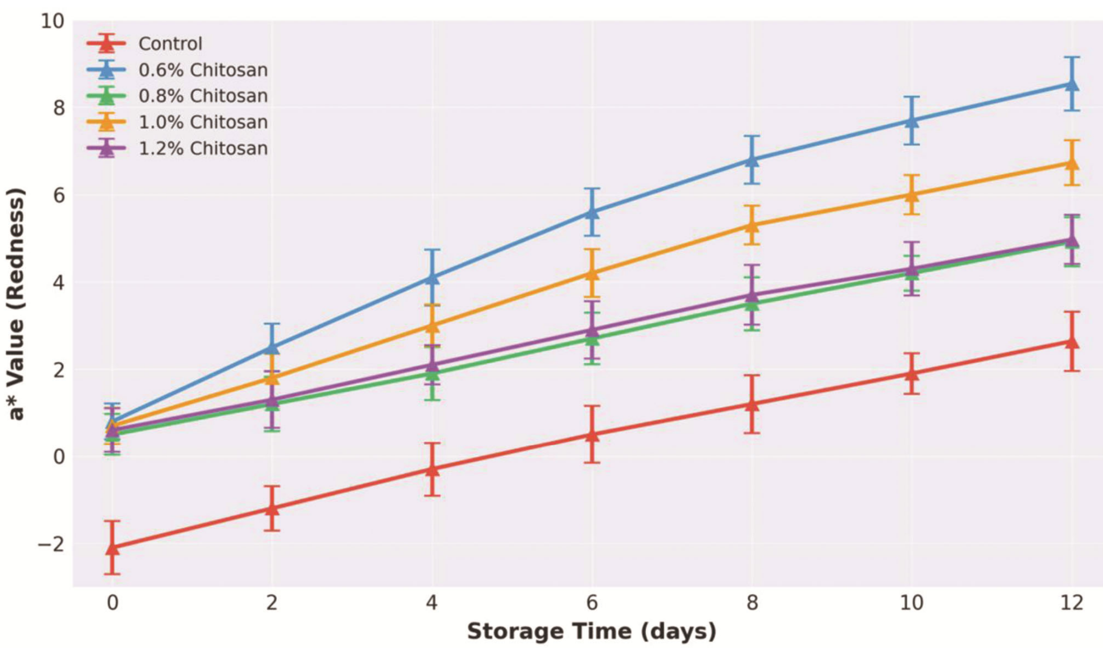

Fig. 5 — a* value of apple slices during 12-day storage at 4°C. Error bars represent standard deviation (n=3). Different letters indicate significant differences ($p<0.05$)

for control, 0.6%, 0.8%, 1.0%, and 1.2% chitosan, respectively. The elevated a* value for the 0.6% chitosan treatment merits discussion. While the L* value for this treatment (61.16) confirms overall lightness retention superior to the control, the higher a* suggests a degree of red-brown discolouration on certain sample surfaces. At low coating concentrations, the barrier effect may be insufficient to fully inhibit localized PPO activity, resulting in partial surface browning that preferentially elevates a* without substantially decreasing L*. This interpretation is consistent with the known threshold-dependency of chitosan's antimicrobial and antioxidative barrier properties. The a* trend across

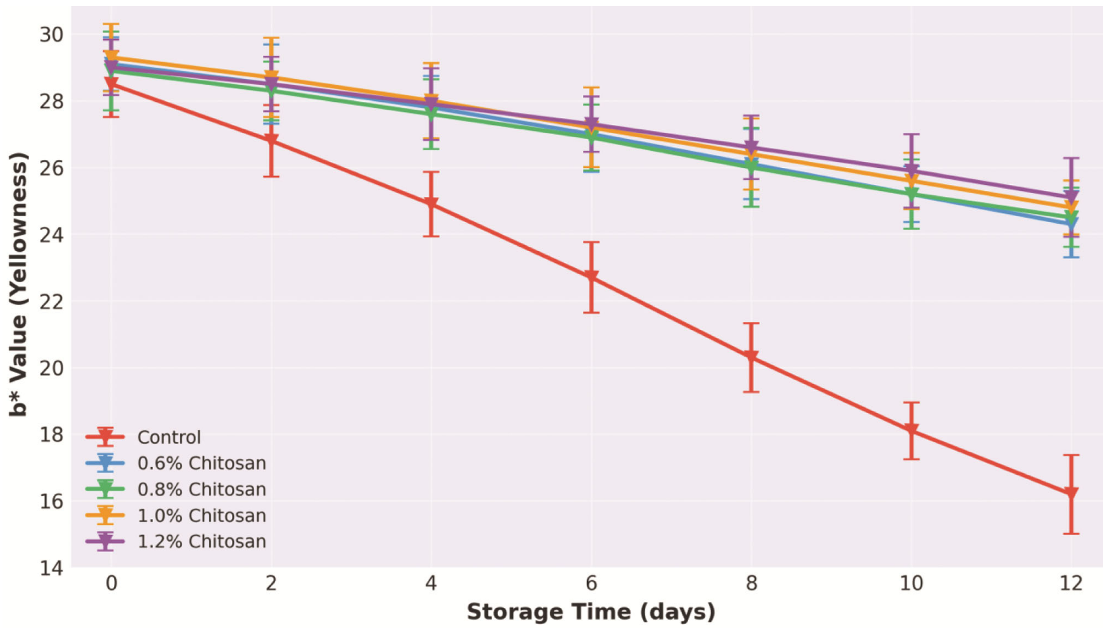

Fig. 6 — b* value of apple slices during 12-day storage at 4°C. Error bars represent standard deviation (n=3). Different letters indicate significant differences ($p<0.05$)

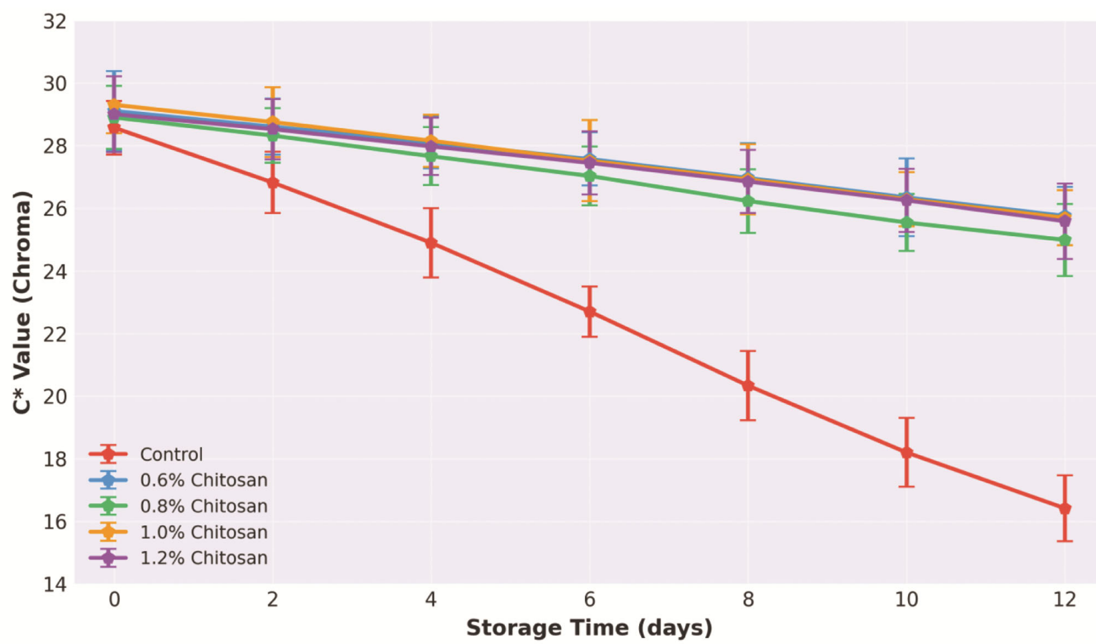

Fig. 7 — C* value of apple slices during 12-day storage at 4°C. Error bars represent standard deviation (n=3). Different letters indicate significant differences ($p<0.05$)

concentrations was non-monotonic (0.6 > 1.0 > 1.2 ≈ 0.8 > control), which we attribute to the interplay between coating thickness, ascorbic acid distribution within the matrix, and surface coverage uniformity at different viscosities. Future work using confocal microscopy to assess coating uniformity at different concentrations is recommended.

Total soluble solids (TSS)

TSS of fresh-cut apples decreased gradually during 12 days of storage at 4°C. The lowest TSS value was shown by the control (11.2 ± 0.6 Brix), followed by 0.6% (11.8 ± 0.4 Brix), 0.8% (12.1 ± 0.5 Brix), 1.0% (12.3 ± 0.4 Brix), and 1.2% (12.4 ± 0.5 Brix) chitosan coating on day 12 (Fig. 8). The positive relationship

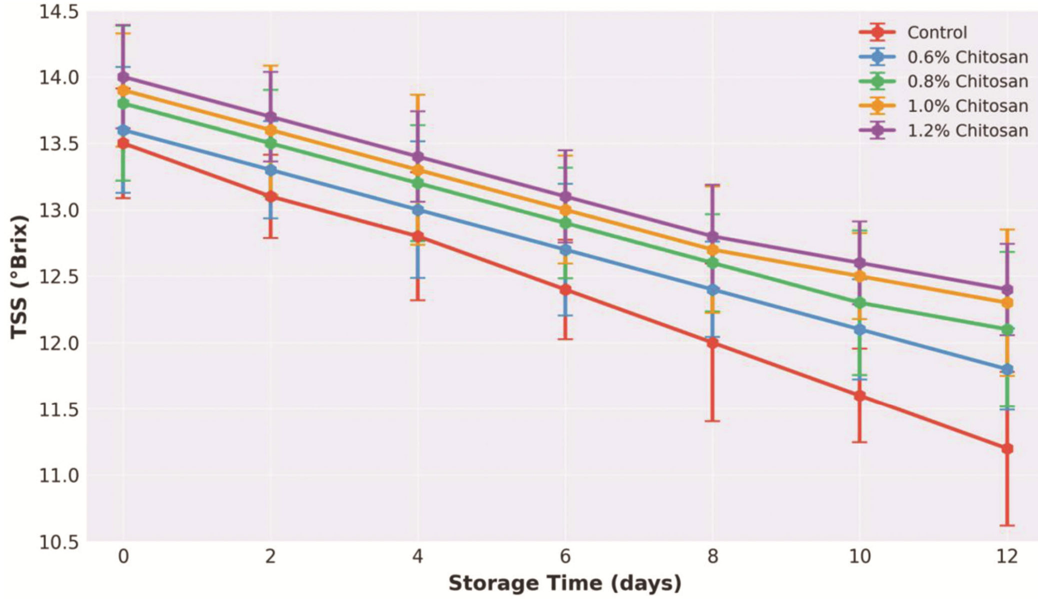

Fig. 8 — TSS (Brix) value of apple slices during 12-day storage at 4 °C. Error bars represent standard deviation (n=3)

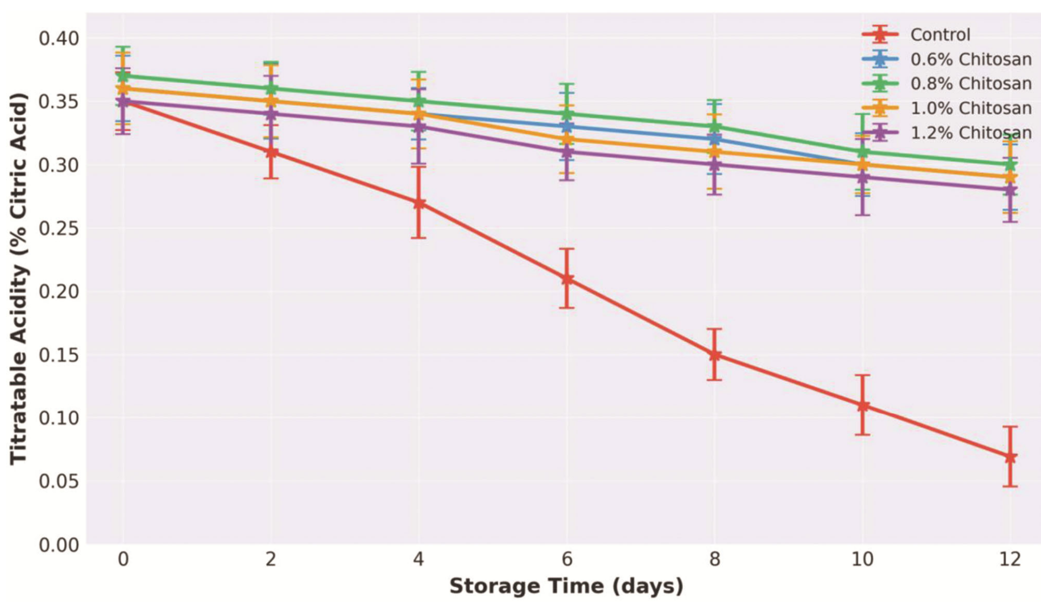

Fig. 9 — Titratable acidity (% citric acid) of apple slices during 12-day storage at 4 °C. Error bars represent standard deviation (n=3)

between coating concentration and TSS retention is consistent with the enhanced gas barrier properties of thicker chitosan matrices, which create a modified atmosphere around the fruit tissue and suppress aerobic respiration, thereby conserving soluble solids[25]. This pattern supports the dose-dependent barrier effect of the coating.

Titratable acidity and pH

Titratable acidity (TA) decreased with increasing storage period. TA at the end of storage was 0.29 ± 0.03%, 0.30 ± 0.02%, 0.29 ± 0.03%, 0.28 ± 0.02%, and 0.069 ± 0.01% for 0.6%, 0.8%, 1.0%, 1.2% chitosan coating and control samples, respectively (Fig. 9). During storage, pH increased (Fig. 10) from initial values of 3.8 ± 0.1 to final values of 4.3 ± 0.2 for coated samples and 4.8 ± 0.3 for control samples, indicating decreasing acidity. The decrease in titratable acidity is attributable to the oxidative catabolism of organic acids (primarily malic acid) during respiration and fruit metabolism, as previously reported for apple and other climacteric fruits[26].

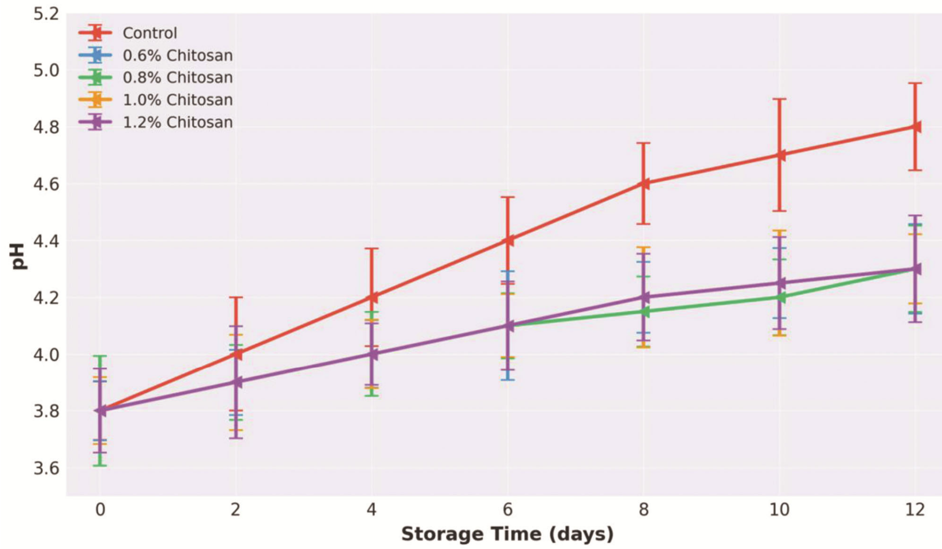

Fig. 10 — pH value of apple slices during 12-day storage at 4 °C. Error bars represent standard deviation (n=3)

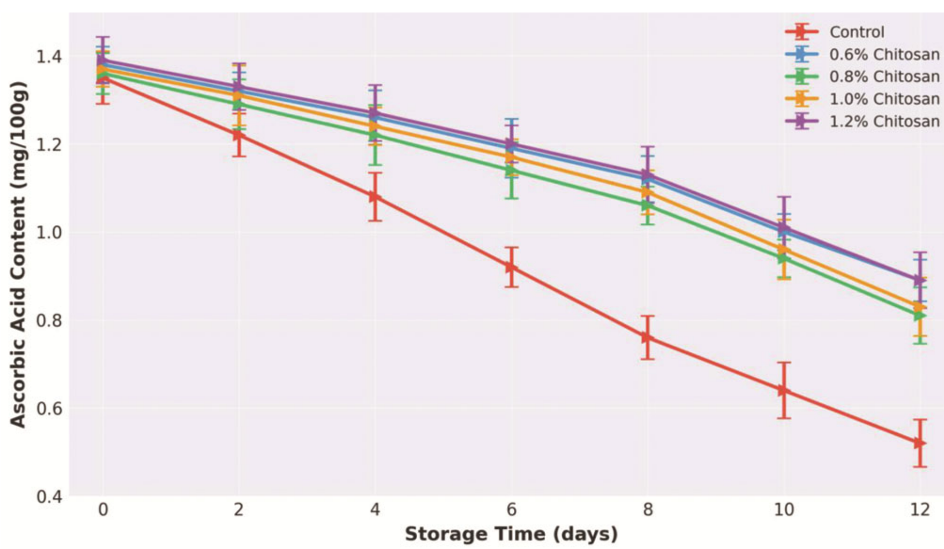

Fig. 11 — Ascorbic acid content (mg/100 g) in apple slices during 12-day storage at 4 °C. Error bars represent standard deviation (n=3)

Ascorbic acid content

The ascorbic acid content of fresh-cut apples gradually decreased with storage time in all treatments. Ascorbic acid values at day 0 were comparable across all treatments (mean: 4.82 ± 0.31 mg/100 g fresh weight), consistent with typical values for Malus domestica. By day 12, retention was: 1.2% chitosan: 0.89 ± 0.04 mg/100 g; 0.6% chitosan: 0.89 ± 0.05 mg/100 g; 1.0% chitosan: 0.83 ± 0.04 mg/100 g; 0.8% chitosan: 0.81 ± 0.06 mg/100 g; control: 0.52 ± 0.07 mg/100 g (Fig. 11). Values are expressed per 100 g fresh weight of apple flesh. The observed decline reflects oxidative destruction of ascorbic acid by polyphenol oxidase and peroxidase enzymes during storage[27]. The slightly lower retention in 0.8% coated samples relative to 0.6% and 1.2% may reflect greater initial ascorbic acid incorporation into enzymatic reactions given the intermediate coating density. The better overall retention in coated vs. uncoated samples is attributed to the reduced oxygen permeability of the chitosan film limiting oxidative degradation[22].

Sensory evaluation

Sensory evaluation of coated and uncoated samples was carried out at 0, 4, 8, and 12 days of storage (Fig. 12). It was found that incorporation of ascorbic acid, glycerol, and Tween-80 in coated samples was effective in maintaining texture and colour of the product over 12 days of storage. The slight acidic

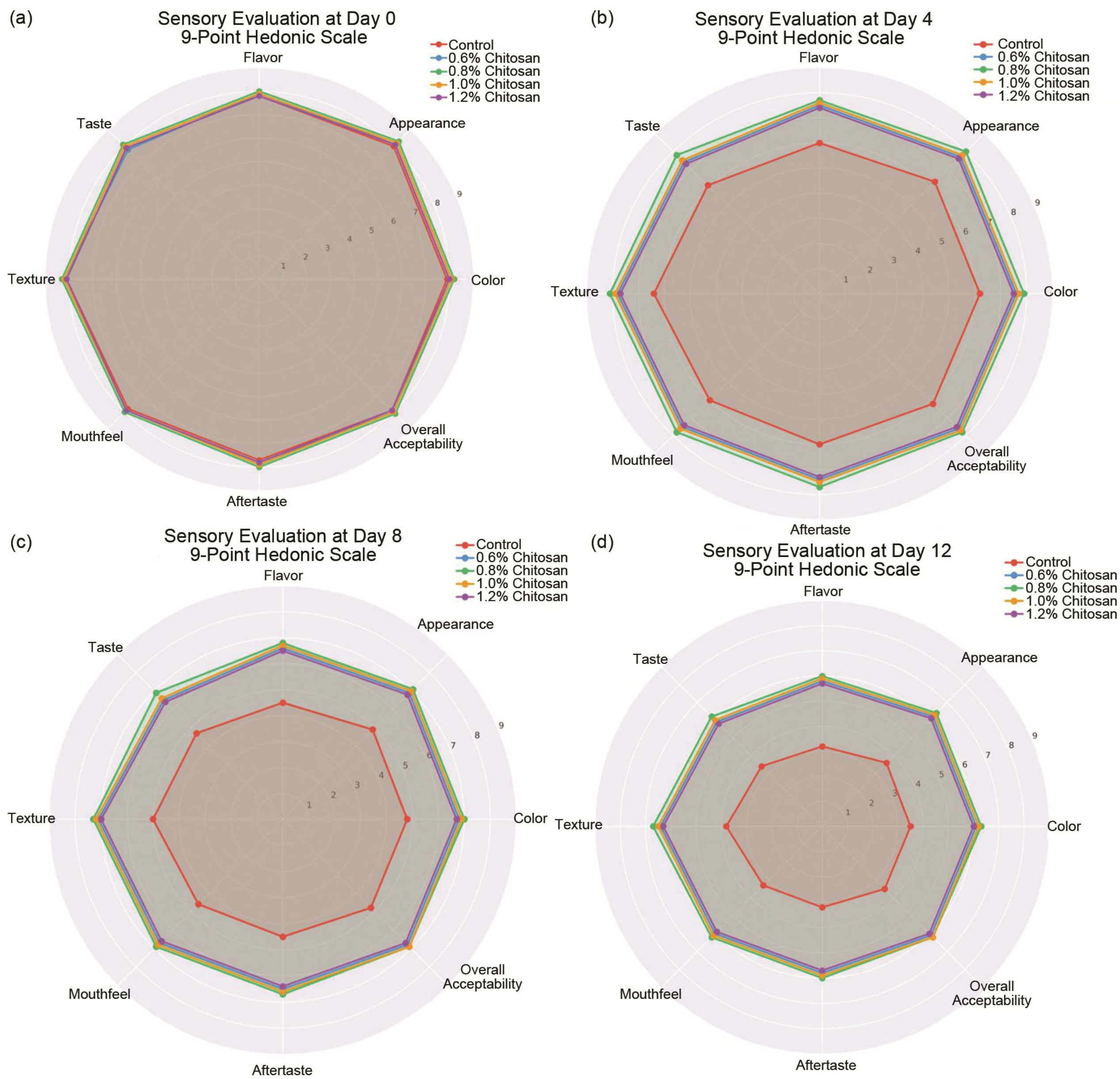

Fig. 12 — Sensory evaluation scores at day (a) 0, (b) 4, (c) 8 and (d) 12. Spider plot showing ratings for colour, appearance, flavor, taste, texture, mouthfeel, aftertaste, and overall acceptability

taste from the acetic acid solvent was generally well-accepted by the panelists and did not significantly detract from overall acceptability in the early storage period.

The 0.8% w/v chitosan formulation provided maximum overall acceptance during storage, with scores of 8.1 ± 0.6, 7.8 ± 0.7, 6.9 ± 0.8, and 6.2 ± 0.9 at days 0, 4, 8, and 12, respectively. Control samples received scores of 7.9 ± 0.5, 6.2 ± 0.9, 4.8 ± 1.1, and 3.5 ± 1.2. The threshold for commercial acceptability on the 9-point hedonic scale was set at ≥5.0, consistent with the definition provided by Civille *et al.*[28] By this criterion, coated samples remained acceptable through day 12 (scores ≥6.2), while control samples dropped below the acceptability threshold between days 8 and 12. The superior sensory performance of the 0.8% formulation over the 1.2% formulation despite lower performance on objective parameters is likely attributable to the higher coating concentration contributing to a slightly thicker texture and residual acetic acid note, which panelists perceived as less desirable at elevated concentrations.

Conclusion

Based on the results obtained from this study, chitosan-ascorbic acid-glycerol-Tween-80 edible coatings are very effective in extending the shelf life of fresh-cut apples stored at 4 °C. Chitosan-based coating treatments effectively retarded enzymatic browning and prevented tissue softening of apple slices up to 12 days of storage. Statistical analysis revealed significant differences ($p<0.05$) between coated and uncoated samples for all measured parameters. The 1.2% chitosan coating showed the best performance for weight loss reduction (24.2% vs. 27.9% for control) and colour retention ($L^* = 63.16$ vs. 45.75 for control). However, the 0.8% chitosan formulation demonstrated the best overall sensory acceptance, making it the most practical choice for commercial applications. The divergence between objective and sensory optima at 0.8% vs. 1.2% chitosan likely reflects the effect of coating concentration on mouthfeel and residual acidity, and warrants further investigation. Future research should focus on extending the use of chitosan-based edible coatings for minimal processing of various fruits and vegetables. Further investigation of physicochemical, microbial, and barrier parameters is recommended. In particular, microbial safety analysis (total aerobic plate count, yeast and mold) should be incorporated in future studies to fully validate the antimicrobial efficacy of the coating system. Additionally, studies on the economic feasibility and scale-up of this technology for commercial application would be valuable. Incorporating value-added bioactive components such as vitamins, minerals, or functional ingredients into the coating matrix to improve nutritional value and market acceptance warrants further investigation.

Conflict of Interest

The authors declare no conflict of interest.

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