JOURNAL OF HORTICULTURE AND POSTHARVEST RESEARCH
2026, VOL. 9(1), 209-224

Journal of Horticulture and Postharvest Research

Journal homepage: www.jhpr.birjand.ac.ir

University of Birjand

Characterization of edible polysaccharide-beeswax coatings and their effects on marian plum (*Bouea burmanica* Griff) postharvest quality

Anussara Chopsri[1,*] and Nanthaya Kengkhetkit[2]

[1] *Department of Plant Science, Faculty of Sciences and Agricultural Technology, Rajamangala University of Technology Lanna Phitsanulok, Phitsanulok, Thailand*
[2] *Department of Science, Faculty of Sciences and Agricultural Technology, Rajamangala University of Technology Lanna Phitsanulok, Phitsanulok, Thailand*

ARTICLE INFO

Original Article

Article history:
Received 12 September 2025
Revised 4 December 2025
Accepted 8 December 2025

Keywords:
Carboxymethyl cellulose
Chitosan
Coating technology
Starch
Tropical fruit

DOI: 10.22077/jhpr.2025.10055.1579
P-ISSN: 2588-4883
E-ISSN: 2588-6169

***Corresponding author:**
Department of Plant Science, Faculty of Sciences and Agricultural Technology, Rajamangala University of Technology Lanna Phitsanulok, Phitsanulok, Thailand.

Email: anussara@rmutl.ac.th

ABSTRACT

Purpose: Marian plum deteriorates rapidly after harvest, causing significant postharvest losses. This study aimed to develop polysaccharide-based edible coatings combined with beeswax and evaluate their effects on marian plum (*Bouea burmanica* Griff) quality during cold storage. **Research Method:** The experiment used a completely randomized design. Three edible polysaccharide coatings (chitosan, starch, carboxymethyl cellulose) with varying beeswax concentrations (0-2%) were developed and characterized. Coated fruits were stored at 10°C for 16 days with quality assessments conducted every 4 days. **Findings:** Beeswax incorporation systematically increased film hydrophobicity across all polysaccharide types, with chitosan at 2% beeswax concentration achieving the highest contact angles (109.38°), though still below the natural fruit surface (115.70°). SEM analysis revealed that beeswax addition transformed smooth film surfaces into rougher morphologies while reducing moisture content. Most coated treatments showed higher weight loss (6.38-10.65%) than uncoated control (5.39%), while chitosan without beeswax has no significant different in weight loss compared to the uncoated control. Carboxymethyl cellulose with 1% beeswax showed significantly higher firmness than uncoated fruit at day 12. Total soluble solids slightly increased (14.5-16.5 °Brix) across treatments, while titratable acidity showed treatment-specific variations throughout the 16-day storage period. **Research limitations:** The study was conducted under controlled laboratory conditions over 16 days, requiring validation under commercial storage conditions. **Originality/Value:** This represents the first systematic evaluation of edible coatings for marian plum, providing practical guidance on effective postharvest treatments. The findings identify chitosan without beeswax maintains fruit quality without increasing weight loss, while demonstrating that complex formulations may reduce storage performance.

INTRODUCTION

Marian plum (*Bouea burmanica* Griff) is an economically important tropical fruit cultivated primarily in Southeast Asia, particularly in Malaysia, Indonesia, and Thailand (Subhadrabandhu, 2001). The fruit is characterized by its distinctive yellowish-orange peel and pulp, ovoid shape, and unique sweet-acid flavor profile. This fruit represents a significant agricultural commodity with growing international demand, particularly in the UK, Malaysia, and Japan (Watanadumrong & Chemsripong, 2021). In Thailand's northern provinces, where it is locally known as mayongchid, successful cultivation requires nighttime temperatures to drop to 18°C followed by warm daytime conditions that promote flower development from December to February (Mavuso & Yapwattanaphun, 2017). However, marian plum faces substantial postharvest challenges that limit its commercial potential. As a non-climacteric fruit, it exhibits continuous respiration decline during storage but deteriorates rapidly under ambient conditions, losing marketable quality within ten days (Wattanakeeboot & Chanasut, 2019). The fruit's high moisture content (approximately 85%) and thin epicarp make it particularly susceptible to water loss and mechanical damage during handling and transport. Optimal harvest timing is critical, as fully mature fruits that have developed for 85 days provide the best quality but deteriorate rapidly after harvest due to their highly perishable nature. This rapid deterioration severely limits shelf life and marketability, creating significant economic losses for producers and limiting market expansion opportunities. Global postharvest losses in fruits reach 28-55% of production, representing not only economic waste but also threats to food security and sustainability (Ali et al., 2025). For minor tropical fruits, these losses severely constrain market development and export potential, making postharvest technologies critically important for commercialization.

Edible coatings have emerged as a promising sustainable technology for extending fruit shelf life while addressing consumer demands for environmentally friendly preservation methods (Dhall, 2013; Singh et al., 2023). These biopolymer-based systems function as selective semipermeable barriers that regulate gas exchange, reduce moisture loss, and can incorporate active compounds for enhanced preservation effects (Kocira et al., 2021). Polysaccharide-based coatings have demonstrated effectiveness due to their ability to form continuous, flexible films with excellent barrier properties (Moradinezhad et al., 2025). Chitosan has demonstrated triple-action properties through eliciting effects that stimulate plant defense responses, antimicrobial activity against postharvest pathogens, and film-forming capabilities that create protective barriers (Romanazzi et al., 2018), while hydroxypropyl methylcellulose-beeswax formulations have proven effective for fruit protection applications (Fagundes et al., 2015). The incorporation of lipid components such as beeswax can further enhance barrier properties and improve coating performance through the formation of composite structures with improved water resistance (Pérez-Gago & Rhim, 2013). Nevertheless, the effectiveness of edible coatings depends on fruit-specific characteristics including physiology and surface properties. Studies have shown that coatings may occasionally have adverse effects on postharvest quality, particularly when they disrupt natural protective barriers or create unfavorable internal atmospheres (Park, 1999; Fernández-Catalán et al., 2021). Despite 40 years of global research in edible coatings and films, with annual postharvest losses estimated at 28-55%, comprehensive reviews continue to emphasize ongoing challenges in achieving consistent quality maintenance across diverse species (Ali et al., 2025). This variability in coating effectiveness stems primarily from species-specific differences in fruit physiology that have been extensively studied in major commercial fruits but remain largely unexplored in underutilized tropical species.

Marian plum exhibits distinctive surface characteristics and rapid postharvest deterioration patterns that may differ significantly from well-studied commercial fruits such as apples, citrus, or stone fruits. Most coating research has focused on a limited range of commercial fruits (Maringgal et al., 2020). Understanding how different polysaccharide-lipid combinations interact with marian plum's natural protective barriers is essential for developing targeted preservation strategies. Therefore, the objectives of this study were to develop and characterize polysaccharide-beeswax composite coatings and to evaluate their effectiveness in maintaining postharvest quality of marian plum during refrigerated storage.

MATERIALS AND METHODS

Experimental design

The experiment followed a completely randomized design. Three edible coating types (chitosan, starch, carboxymethyl cellulose) with varying beeswax concentrations (0%, 0.5%, 1%, 2% w/w) were developed, as preliminary trials showed beeswax above 2% caused phase separation and non-uniform films. This resulted in 12 coating treatments plus one uncoated control (13 treatments total). Individual fruits served as biological replicates, with sampling and measurement procedures detailed in the section of quality measurement. Fruits were randomly assigned to treatments.

Preparation of edible coatings

Beeswax-based emulsions were prepared at four concentrations: 0% (control), 0.5%, 1%, and 2% (w/v), with the lipid phase comprising beeswax and coconut oil at a 2:1 weight ratio (e.g., 1 g beeswax + 0.5 g coconut oil). Surfactants (Tween 80 and Span 80) were added according to Hydrophilic-Lipophilic Balance principles to achieve optimal emulsion stability (Griffin, 1949). Glycerol (1%) and distilled water (100 mL) were added to each mixture, followed by microwave heating (1300 watts, 60 seconds) and homogenization using a high-speed blender (14,500 rpm, 60 seconds). Subsequently, natural polymer solutions were prepared separately: 2% carboxymethyl cellulose, 6% starch, and 1.5% chitosan (540 kDa, >91% deacetylation) dissolved in 1.5% acetic acid. Preliminary testing showed these concentrations provided similar viscosity for uniform fruit dipping. Each polymer solution (100 mL) was combined with the respective beeswax-based emulsion (100 mL) at a 1:1 volume ratio using a high-speed blender (14,500 rpm, 60 seconds) to ensure uniform distribution. The resulting solutions were then cast into films for characterization and application studies. All chemicals used were of food-grade quality.

Evaluation of film properties

To visualize surface texture and structural features of each coating, films were examined using Scanning Electron Microscopy (SEM) (Prisma E, Thermo Fisher Scientific, Waltham, MA, USA) at 2.000 × magnification. The hydrophilic and hydrophobic properties of each coating film were evaluated by measuring water contact angles using a contact angle analyzer (OCA20, Dataphysics, Filderstadt, Germany). Five measurements per sample were taken and averaged. A 5 µL water droplet was placed on the film surface and contact angle measured within 10 seconds. Moisture content was determined by casting 10 mL of each coating solution into Petri dishes (100 mm diameter). Films were air-dried at room temperature (25 ± 2°C) under ambient humidity conditions for 48 hours until constant weight was achieved. Dried films were weighed before and after oven-drying (105°C, 24 hours). The moisture content percentage was calculated by comparing the weight difference before and after oven drying, with results expressed as a percentage of the original film weight.

Fresh fruit preparation and coating application

Fruits were obtained from an orchard situated at 16°51'46.2" N latitude and 100°41'03.5" E longitude in Phitsanulok province, northern Thailand. The tree grows naturally without irrigation and produces fruit in March. Fruits that had attained commercial maturity at 85% yellowness were meticulously handpicked in the morning and subsequently transported to the laboratory by car. Fruits with similar size, weight, color, and no defects were selected and prepared prior to coating. Whole fruits, including calyx, were dipped in coating solutions for one minute with gentle agitation. Excess coating was allowed to drain for 30 seconds. Uncoated fruits served as controls. All fruits were air-dried under controlled conditions (20 ± 2°C, 65 ± 5% relative humidity) by hanging them on crimped wire mesh. After drying, fruits were stored in a commercial refrigerator (Model DVV-02-110, V.J. Cool Stainless Co., Ltd., Bangkok, Thailand) equipped with forced air circulation maintained at 10 ± 2°C with atmospheric monitoring using a data logger (model RC-4HC, Elitech Technology Inc., San Jose, CA, USA). All fruits from each treatment were placed together in plastic trays with adequate spacing to ensure uniform air circulation. Trays were positioned on separate shelves within the refrigerator to ensure consistent environmental conditions. At each sampling date, six fruits per treatment were randomly selected from each tray, with three fruits used for non-destructive measurements (weight loss) and three for destructive measurements (firmness, total soluble solids, titratable acidity). The natural fruit's surface before and after coating was characterized using SEM and contact angle measurements as described in the section of evaluation of film properties.

Quality measurements

Measurements were conducted at day 0 (initial day after coating) and every 4 days for 16 days of storage. Storage was terminated at day 16 when visual inspection revealed pronounced wrinkling in uncoated control fruits, indicating loss of marketable quality.

Weight loss was measured at the initial day after coating (day 0), representing the initial weight. After storage at 4-day intervals, weight changes were recorded. Calculations were made by comparing the initial weight to the recorded weight, expressed as a percentage. Firmness of pulp was measured using a texture analyzer (TA.XT plus, Stable Micro Systems, Godalming, UK) with a 2 mm cylindrical probe (P/2N). The probe was calibrated before each use and operated at 1 mm/s penetration speed to a depth of 5 mm. Maximum force required for penetration was presented as Newton. Three measurements per fruit were taken and averaged. Total soluble solids (TSS) content was determined by extracting fruit juice and measuring using a digital refractometer (PAL-3, Atago Co., Ltd., Tokyo, Japan) calibrated with distilled water. Results were expressed as °Brix. Titratable acidity was determined following AOAC official method 942.15 (AOAC, 2019). One milliliter of fruit juice was diluted with distilled water and titrated with 0.1 N NaOH solution using 2 drops of 1% phenolphthalein indicator. The endpoint was reached when pink color persisted for 30 seconds. Results were expressed as percentage citric acid equivalent.

Statistical analysis

Data were analyzed using R software (R Core Team, 2025). One-way ANOVA was performed with Duncan's Multiple Range Test ($\alpha = 0.05$). Results are presented as means ± standard deviation.

RESULTS

Film characterization

This study characterized edible polysaccharide-beeswax coatings and evaluated their effects on marian plum postharvest quality. SEM analysis and contact angle measurements revealed significant differences among edible films (Fig. 1). All three film systems at 0% beeswax addition showed smooth and uniform surfaces, with carboxymethyl cellulose-based films having the lowest contact angle (28.85 ± 2.26°) whereas chitosan-based films had naturally high contact angles (85.02 ± 3.16°) (Fig. 1). Beeswax addition from 0.5% to 2% systematically created increasingly rough surface structures and improved water resistance. Chitosan-beeswax films consistently achieved the highest water resistance (109.38 ± 2.67°). Carboxymethyl cellulose films showed the greatest improvement in hydrophobicity with beeswax addition, increasing from 28.85 ± 2.26° to 72.17 ± 1.30° (150% increase). The moisture content of polysaccharide-based edible films is shown in Figure 2. Chitosan without beeswax exhibited highest moisture content (57.78 ± 3.34%), followed by carboxymethyl cellulose (41.81 ± 1.41%) and starch (24.30 ± 1.17%) (Fig. 2). Beeswax incorporation significantly reduced moisture content across all polysaccharide types in a concentration-dependent manner. Overall, chitosan consistently maintained higher water retention properties than carboxymethyl cellulose and starch at all beeswax concentrations.

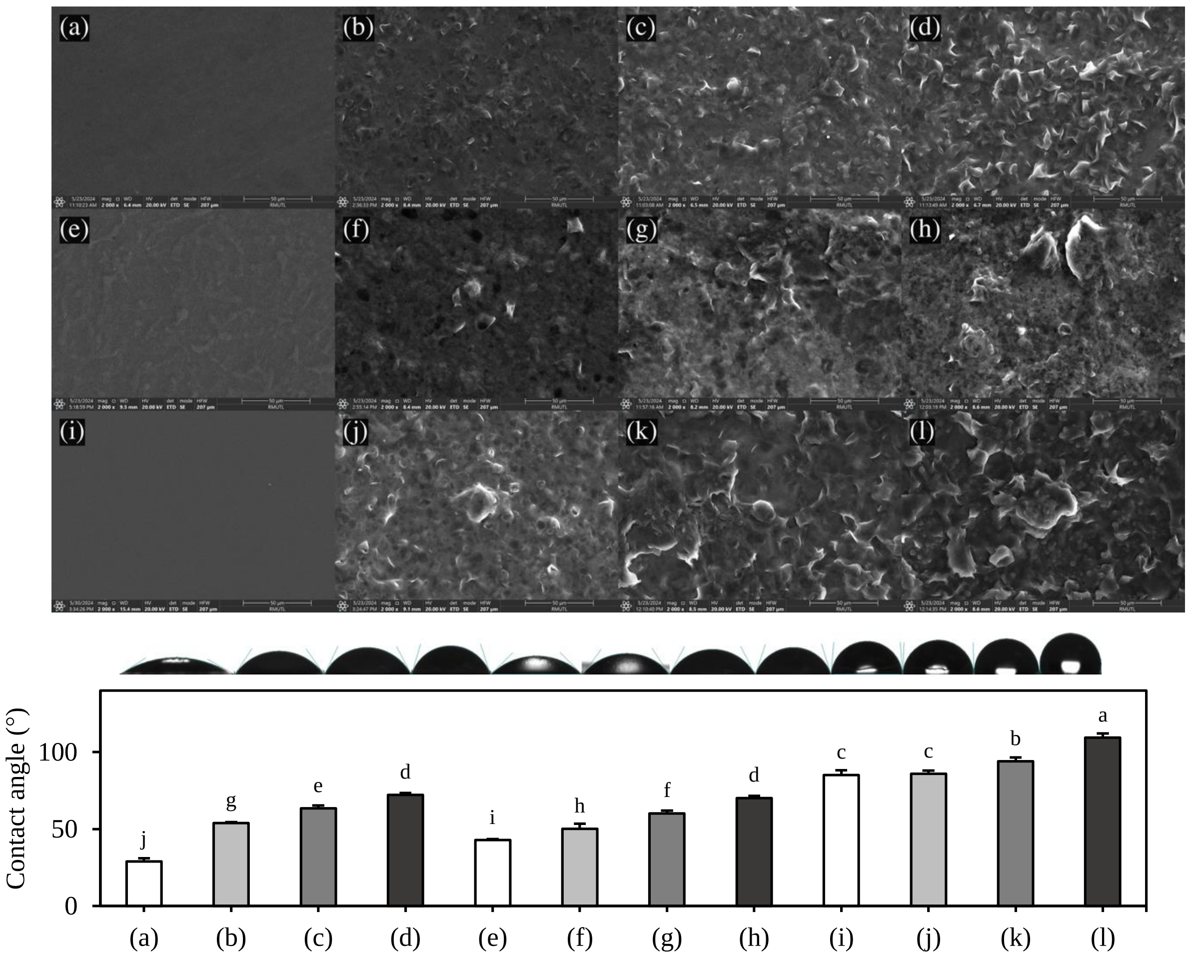

Fig. 1. SEM images (2000× magnification) and contact angle measurements of edible films at varying beeswax concentrations (0%, 0.5%, 1%, 2% w/w): (a-d) carboxymethyl cellulose-beeswax films, (e-h) starch-beeswax films, (i-l) chitosan-beeswax films. Contact angles shown as mean ± SD; different letters indicate significant differences (P < 0.05).

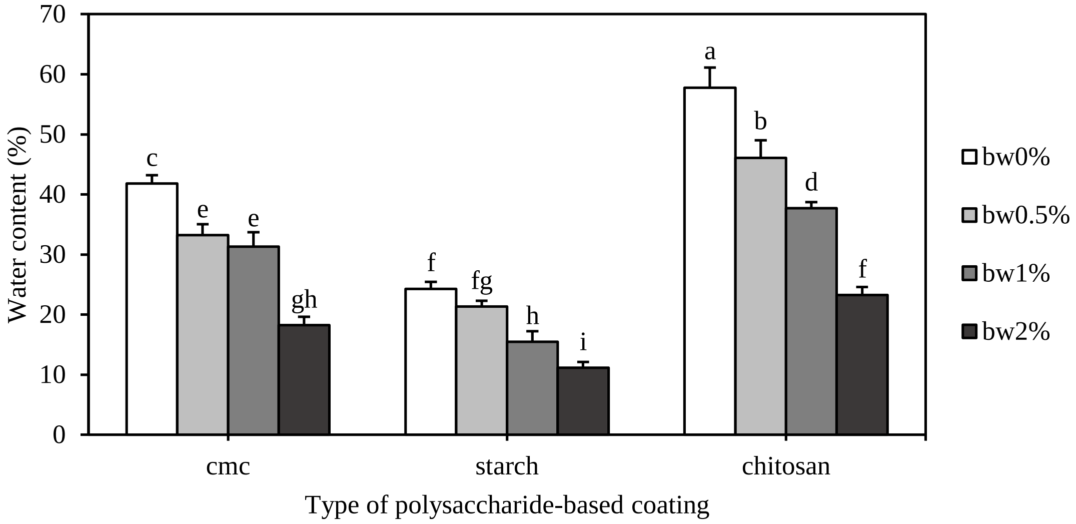

Fig. 2. Moisture content of edible films formulated with cmc (carboxymethyl cellulose), starch, and chitosan at varying beeswax concentrations (0%, 0.5%, 1%, 2%). Error bars represent ± SD. Columns with different letters indicate significant differences (P < 0.05).

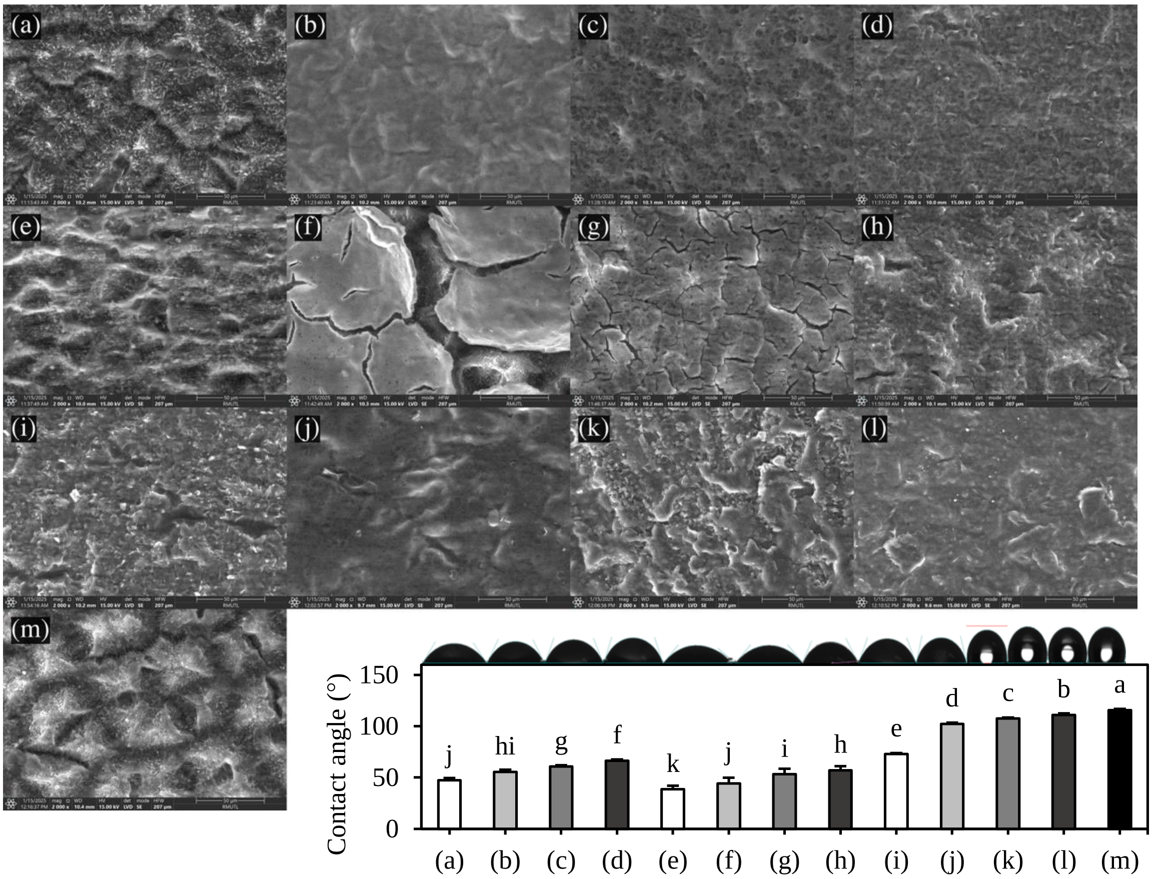

Fig. 3. SEM images (2000× magnification) and contact angle measurements of marian plum fruits coated with edible coatings at varying beeswax concentrations (0%, 0.5%, 1%, 2% w/w): (a-d) carboxymethyl cellulose-beeswax coatings, (e-h) starch-beeswax coatings, (i-l) chitosan-beeswax coatings, comparing with uncoated fruit (m). Contact angles shown as mean ± SD; different letters indicate significant differences (P < 0.05).

Coating-fruit surface interactions

Assessment of coating performance on marian plum surfaces revealed complex interactions between applied coatings and natural fruit characteristics. The uncoated plum exhibited a naturally rough surface and a highly hydrophobic contact angle of 115.70 ± 1.30° (Fig. 3). When coatings were applied, starch-beeswax coatings showed the most hydrophilic properties (< 90°) with heterogeneous surface structures showing distributed wax particles (Fig. 3). Contact angles increased progressively with beeswax incorporation: carboxymethyl cellulose coatings increased from 47.43 ± 2.13° (0% beeswax) to 66.32 ± 1.42° (2% beeswax), starch-beeswax coatings from 38.47 ± 3.64° to 57.13 ± 4.02°, and chitosan coatings from 73.02 ± 0.85° to 111.07 ± 1.28°. Chitosan demonstrated the most dramatic response, with the highest beeswax formulation approaching but not matching the natural fruit surface based on Duncan's Multiple Range Test results. Visual appearance evaluation provided additional insights into coating-fruit interactions. At day 0, all treatments showed uniform bright yellow color and smooth skin appearance (Fig. 4a). However, after 16 days of storage at 10°C, clear visual differences emerged between treatments (Fig. 4b). The uncoated control fruit exhibited a dull, wrinkled appearance. In contrast, chitosan-beeswax treatments maintained superior visual quality with glossy, vibrant surfaces. Carboxymethyl cellulose-beeswax treatments also retained good visual appeal with minimal surface changes. Starch-beeswax treatments showed more variable results, with starch at 1% and 2% beeswax displaying visible white residues on fruit surfaces.

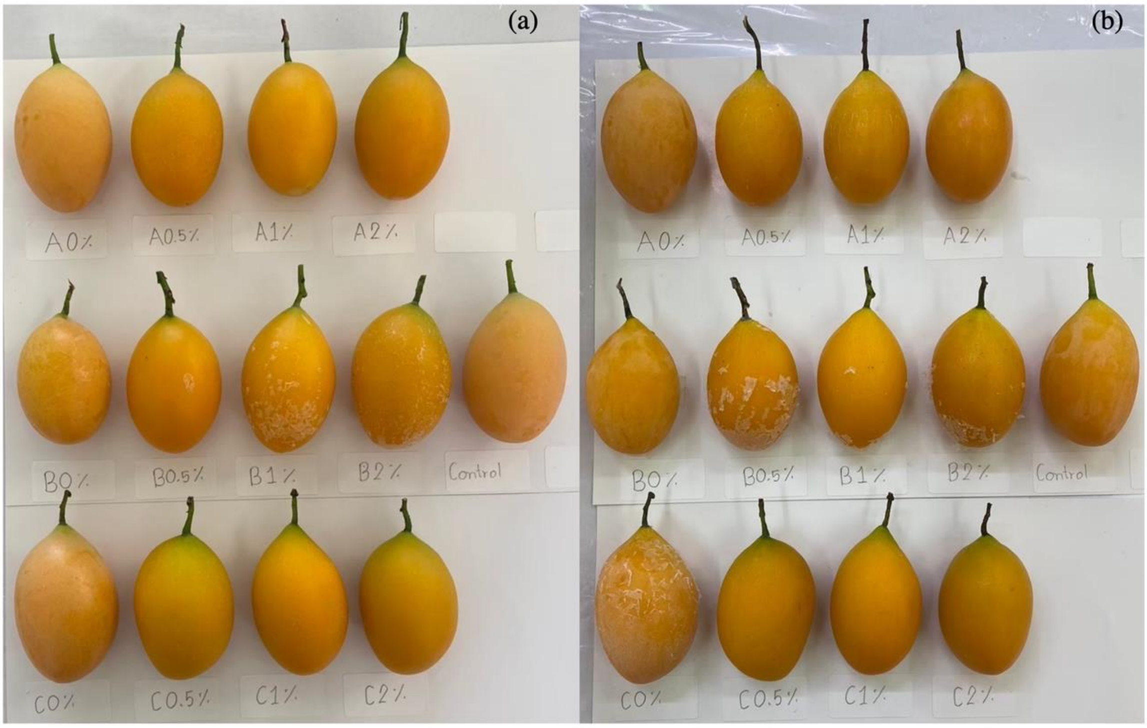

Fig. 4. Appearance of marian plums alone (control) or treated with edible coatings at varying beeswax concentrations (0%, 0.5%, 1%, 2%); A: carboxymethyl cellulose-beeswax coatings, B: starch-beeswax coatings, and C: chitosan-beeswax coatings. The fruit were stored at 10°C at day 0 (a) and after 16 days of storage (b).

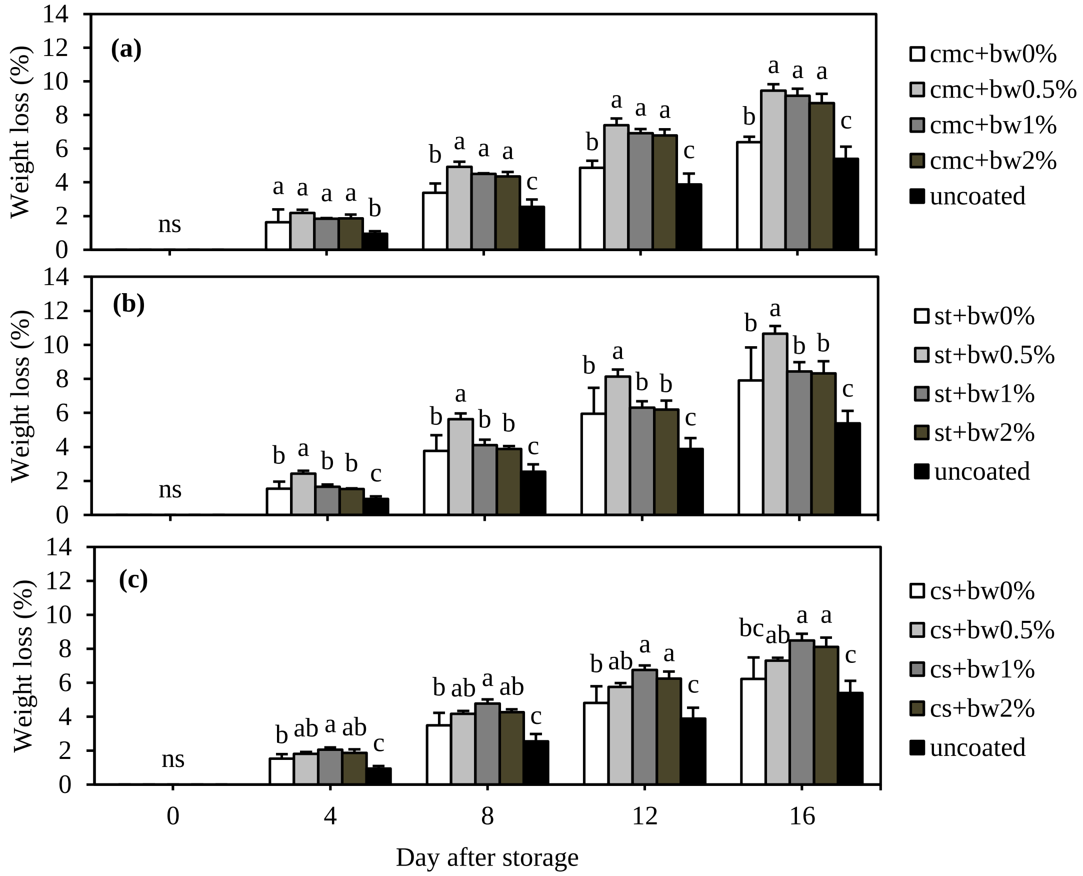

Fig. 5. Weight loss of marian plum coated with different edible coatings. Carboxymethyl cellulose-beeswax coatings: cmc+bw (a), starch-beeswax coatings: st+bw (b), and chitosan-beeswax coatings: cs+bw (c) during storage at 10 ± 2 °C and 68 ± 5% RH. Error bars represent ± SD. Different letters indicate significant differences within treatment on the same day (P < 0.05); ns = not significant (P > 0.05).

Postharvest quality parameters

Evaluation of fruit preservation during 16 days of cold storage revealed significant treatment effects on multiple quality parameters, demonstrating complex relationships between coating formulations and fruit quality responses. Significant treatment effects were observed in weight loss of the fruit throughout storage (Fig. 5). Uncoated fruits exhibited the lowest weight loss (5.39 ± 0.72%) by day 16. Carboxymethyl cellulose-beeswax coatings resulted in weight loss ranging from 6.38 ± 0.91% (0% beeswax) to 9.45 ± 1.23% (0.5% beeswax) at the end of storage (Fig. 5a). Starch-beeswax coatings showed weight loss between 7.91 ± 1.15% (0% beeswax) and 10.65 ± 1.47% (0.5% beeswax) (Fig. 5b). Chitosan-beeswax coatings resulted in weight loss ranging from 6.23 ± 0.98% (0% beeswax) to 8.49 ± 1.34% (1% beeswax) (Fig. 5c). Among coated treatments, chitosan without beeswax showed the lowest weight loss (6.23 ± 0.98%) with no significant difference from uncoated (P > 0.05). Pulp firmness declined from initial values of 0.62-0.83 N to 0.39-0.69 N by day 16 across all treatments (Fig. 6). Carboxymethyl cellulose with 1% beeswax demonstrated the highest firmness (0.87 ± 0.15 N) compared to uncoated (0.65 ± 0.18 N) at day 12 (P < 0.05) (Fig. 6a). At day 16, carboxymethyl cellulose with 0.5% beeswax achieved the highest firmness (0.69 ± 0.09 N) compared to uncoated (0.57 ± 0.04 N), though this difference was not statistically significant (P> 0.05). Chitosan-beeswax and starch-beeswax treatments showed no significant differences from uncoated throughout the storage period (P> 0.05) (Fig. 6c).

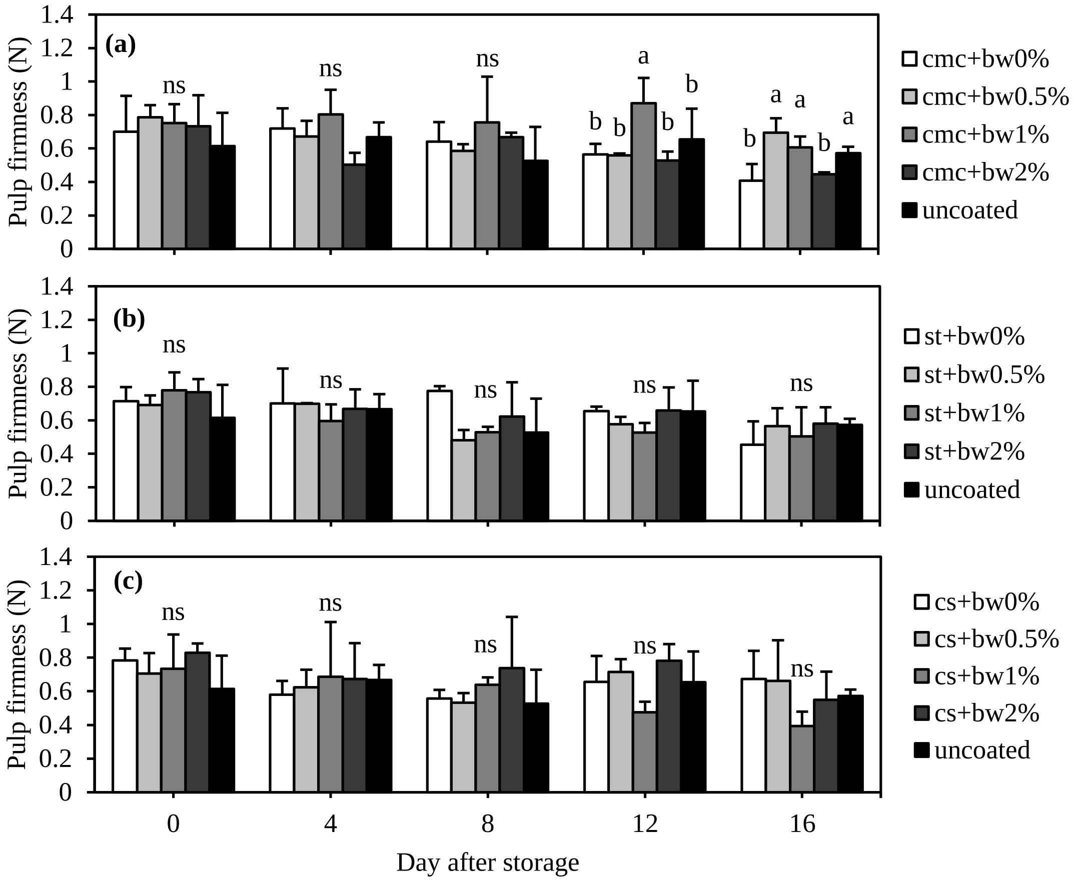

Fig. 6. Pulp firmness of marian plum coated with different edible coatings. Carboxymethyl cellulose-beeswax coatings: cmc+bw (a), starch-beeswax coatings: st+bw (b), and chitosan-beeswax coatings: cs+bw (c) during storage at 10 ± 2 °C and 68 ± 5% RH. Error bars represent ± SD. Different letters indicate significant differences within treatment on the same day ($P < 0.05$); ns = not significant ($P > 0.05$).

Total soluble solids values showed gradual increases during storage, rising from initial values of 14.5-15.7 to 16.0-16.5 °Brix by day 16, with no significant treatment effects observed between coating formulations (Fig. 7). Values of titratable acidity ranged from 0.68-1.33% across treatments during storage. Treatment effects varied by sampling date (Fig. 8). For chitosan treatments, significant differences ($P < 0.05$) occurred at day 12, with chitosan with 1% beeswax showing significantly higher acidity (1.19%) than chitosan alone (0.91%). Starch-beeswax treatments showed no significant differences throughout storage. Carboxymethyl cellulose treatments exhibited significant differences ($P < 0.05$) at days 8 and 16, with carboxymethyl cellulose with 0.5% beeswax showing significantly higher acidity compared to carboxymethyl cellulose alone and other carboxymethyl cellulose-beeswax formulations at both timepoints.

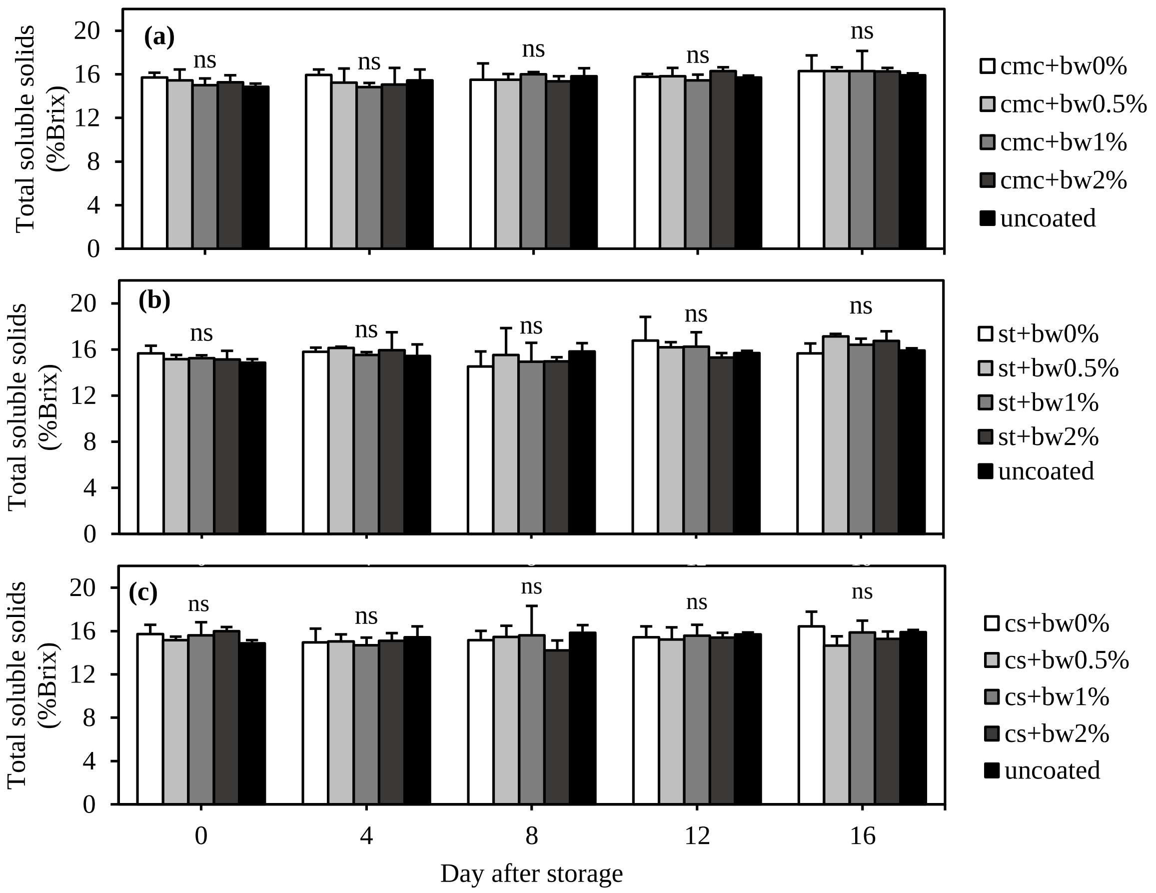

Fig. 7. Total soluble solids of marian plum coated with different edible coatings. Carboxymethyl cellulose-beeswax coatings: cmc+bw (a), starch-beeswax coatings: st+bw (b), and chitosan-beeswax coatings: cs+bw (c) during storage at 10 ± 2 °C and 68 ± 5% RH. Error bars represent ± SD. ns = not significant within treatment on the same day (P > 0.05).

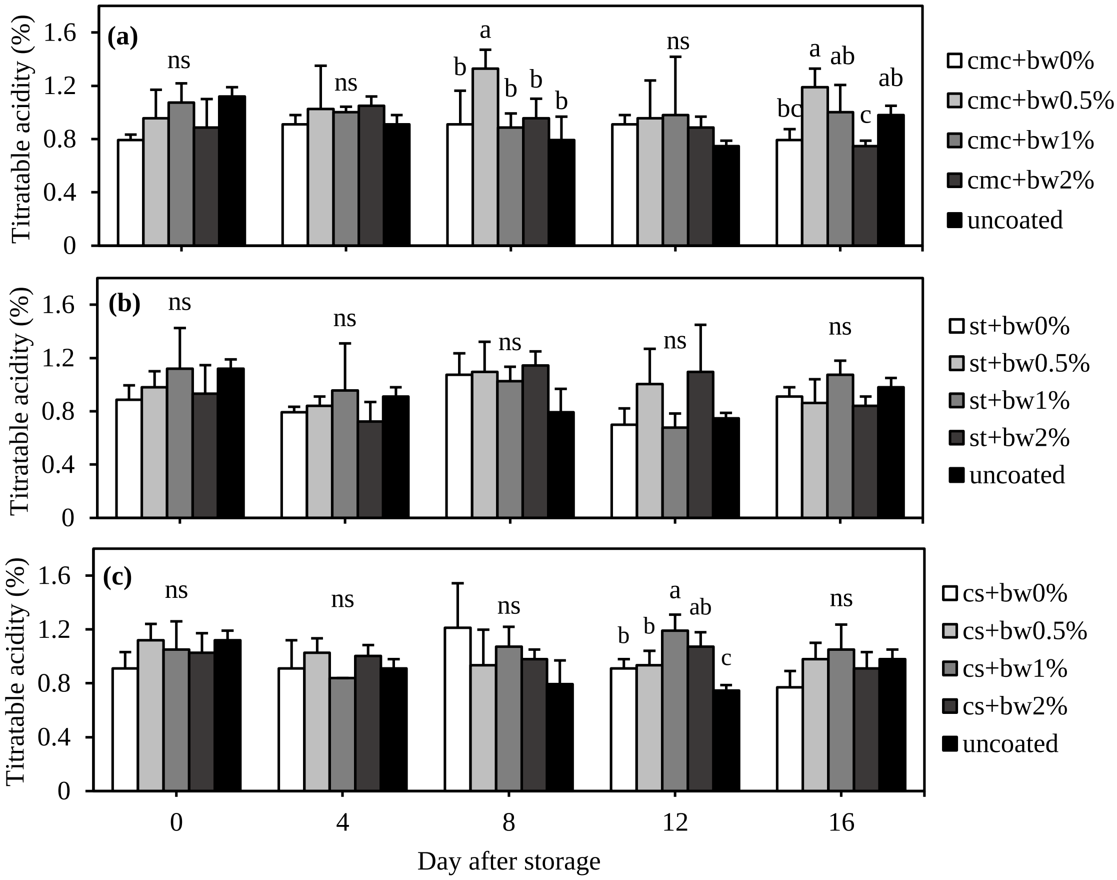

Fig. 8. Titratable acidity of marian plum coated with different edible coatings. Carboxymethyl cellulose-beeswax coatings: cmc+bw (a), starch-beeswax coatings: st+bw (b), and chitosan-beeswax coatings: cs+bw (c) during storage at 10 ± 2 °C and 68 ± 5% RH. Error bars represent ± SD. Different letters indicate significant differences within treatment on the same day ($P < 0.05$); ns = not significant ($P > 0.05$).

DISCUSSION

SEM confirmed successful incorporation of beeswax into all polysaccharide films, though interactions varied by type. The images show that adding beeswax transformed smooth film surfaces into rougher morphologies, consistent with Pérez-Gago and Rhim (2013) who attributed this to lipid dispersion during emulsion formation. This structural change of the films corresponds with improved water resistance, as demonstrated by the systematic increase in contact angles with beeswax addition. Beeswax enhances hydrophobicity due to its natural tendency to migrate to the surface during drying. Surface crystallites and bumps trap air pockets, consequently, reducing water–surface contact and promoting droplet rolling (Holloway, 1969). Both chemical hydrophobicity of beeswax and microscale surface roughness contributed synergistically to improved water resistance (Vijayan et al., 2023). Among the polysaccharide films, chitosan showed the greatest improvement, from 73.0° to 109.38°. Interestingly, chitosan exhibited dual behavior: despite hydrophobic surface layers, the bulk retained substantial internal moisture (57.78%). This phenomenon can be explained by chitosan's cationic amino groups forming hydrogen bonds with water, while molecular rearrangement during drying drives hydrophobic segments toward the air interface and retains hydrophilic domains within the matrix (Hubbe, 2019). This moisture retention challenge in chitosan films has been well-documented, with chitosan films showing significant water absorption and swelling when exposed to moisture (Cui et al., 2011). However, beeswax incorporation mitigated this moisture retention (Pérez-Vergara et al., 2020). Increasing beeswax concentration reduced internal water content, suggesting partial penetration into hydrophilic domains and disruption of hydrogen-bonded water. This trend was consistent across chitosan, carboxymethyl cellulose, and starch films, confirming a universal barrier-enhancing role for beeswax independent of polysaccharide chemistry. Overall, beeswax acts through a dual mechanism-chemical repellency and physical surface structuring-while simultaneously reducing bulk water retention. These combined effects establish beeswax as an effective natural modifier for improving the water barrier performance of polysaccharide-based coatings.

Marian plum fruit surfaces exhibited hydrophobic characteristics with a contact angle of 115.70 ± 1.30°, attributed to a wax-like coating observed in SEM analysis. Koch and Barthlott (2009) reported that epicuticular waxes are characterized by composite three-dimensional wax structures, which often appear as white or bluish coloration on fruit surfaces, such as grapes and plums. Our visual assessment confirmed the presence of this distinctive white-bluish coloration on marian plum fruit surfaces. According to Koch and Barthlott (2009), hydrophobic surfaces are characterized by high contact angles (greater than 90° but less than 150°), where water droplets form semi-spherical shapes. This classification confirms that marian plum fruit surfaces are hydrophobic. The plant cuticle is an extracellular hydrophobic layer providing its primary function as a transpiration barrier (Yeats & Rose, 2013). The films were expected to modify surface permeability and reduce weight loss. SEM revealed full coverage with homogeneous surface structures, particularly for carboxymethyl cellulose coatings. However, unexpectedly, most coatings increased moisture loss compared to uncoated fruit. Early systematic research recognized that coating success depends highly on controlling internal gas composition. Park (1999) noted that in some cases, edible coatings resulted in worse fruit quality rather than preservation benefits. Coating technologies developed for one species may therefore disrupt the finely tuned surface properties of another. Given that contact angles were significantly reduced when all polysaccharide-beeswax coatings were applied to fruit surfaces, this phenomenon may be explained by the observations in other fruit systems where coating application disrupted natural barrier function (Fernández-Catalán et al., 2021; Martin & Rose, 2013). Baales et al. (2023) reported that plant surfaces can experience significant contact angle reductions immediately after surfactant application.

Chitosan without beeswax may be more compatible with marian plum's natural protective systems, achieving weight loss comparable to control fruit. While Arnon et al. (2014) reported that chitosan coatings were ineffective in preventing weight loss in citrus fruit, suggesting general limitations of chitosan barriers, this comparable performance represents the best outcome among all treatments tested, as all beeswax-containing formulations increased weight loss above control levels. Notably, chitosan films without beeswax retained the highest film moisture content among all treatments. In contrast, films with beeswax incorporation themselves had the lowest moisture content, which may have created a moisture gradient favoring water transfer from fruit to coating. The low water content of beeswax-containing films likely promoted transpiration via the epidermis through water vapor diffusion (Ben-Yehoshua & Rodov, 2002), with the hygroscopic coating matrix absorbing moisture from fruit tissue. Although Alemu et al. (2025) recommend lipid-based coatings with enhanced moisture barrier properties for high-moisture fruits, this reduced film moisture content appears to have been counterproductive for marian plum, creating conditions that promoted rather than prevented fruit moisture loss. Overall, this indicates that formulations incorporating multiple components like beeswax and surfactants may create interference with existing fruit barriers.

For commercial maturation, the postharvest quality changes observed in marian plum during this study align with similar trends reported previously by Wattanakeeboot and Chanasut (2019) and Posom et al. (2020). The findings demonstrated that coating applications provided beneficial effects through multiple mechanisms. Regarding firmness retention, treatment effects were evident throughout the storage duration. At day 12, carboxymethyl cellulose with 1% beeswax exhibited superior firmness compared to uncoated samples. By the end of storage, carboxymethyl cellulose with 0.5% beeswax displayed the highest firmness values, although there was no significant difference when compared to uncoated fruit. The maintenance of firmness values between 0.39-0.69 N through day 16 demonstrates that coating treatments, especially carboxymethyl cellulose with beeswax, delayed the natural fruit softening process. During storage, total soluble solids (TSS) content increased progressively from initial levels of 15.0-15.7 °Brix to final values of 16.0-16.5 °Brix by day 16 due to starch conversion and water loss concentration (Gidado et al., 2024). No significant differences were detected between coating formulations regarding TSS changes. Titratable acidity (TA) measurements ranged from 0.68-1.33% throughout the storage period across all treatments, with treatment effects showing variation depending on the sampling date. These significant TA variations observed in our experiment represent typical characteristics of marian plum. Posom et al. (2020) reported that marian plum at the commercial harvest stage (75 days after flower blooming) displayed the broadest range for titratable acidity (7.9 ±3.39%) alongside a moderate range for soluble solids content (16.45 ±1.39 °Brix).

The collective findings from film characterization, surface interactions, and quality outcomes reveal a critical insight. Coating performance depends not on individual component properties, but on their compatibility as a system. Enhanced film characteristics from beeswax incorporation, increased hydrophobicity (109.38°) and reduced moisture content, created a critical incompatibility when applied to marian plum's naturally hydrophobic surface (115.70°). The low moisture content of beeswax films established a gradient that promoted water transfer from fruit to coating via transpiration, while coating surfactants disrupted epicuticular waxes, collectively resulting in increased weight loss. However, these surface-level disruptions affected quality parameters differentially that weight loss increased, firmness was maintained or improved with CMC-beeswax treatments, and total soluble solids remained unaffected. This property-specific response indicates that coating effects operate through multiple independent mechanisms rather than a single pathway. The superior performance of chitosan without beeswax, despite having the poorest barrier properties, demonstrates that coating-fruit compatibility is more important than individual film characteristics. For commercial applications, these results establish that successful coating development for tropical fruits requires matching coating properties to existing fruit surface characteristics and moisture dynamics, rather than maximizing film barrier performance alone.

CONCLUSION

This study revealed a critical finding that beeswax incorporation into polysaccharide coatings increased marian plum weight loss, contradicting the traditional moisture barrier function of edible coatings. Despite successfully enhancing film hydrophobicity to 109.38°, these coatings disrupted the fruit's natural protective barrier because coating hydrophobicity remained lower than the fruit surface (115.70°), while surfactants and hygroscopic matrices further compromised the epicuticular wax layer. Chitosan without beeswax performed comparably to uncoated fruit, whereas carboxymethyl cellulose with beeswax provided firmness benefits. These findings demonstrate that coating-fruit surface compatibility is more critical than film hydrophobicity enhancement alone for commercial applications.

Understanding this incompatibility prevents similar failures in coating development for tropical fruits. Future research should optimize chitosan formulations and explore alternative treatments that complement natural fruit protection systems.

Conflict of interest

The authors declare that there is no conflict of interest.

Acknowledgments

The authors gratefully acknowledge the Fundamental Fund grant numbered 4695755 from Thailand Science Research and Innovation for financial support.

REFERENCES

Alemu, T. T., Intipunya, P., & Gebeyo, B. A. (2025). A comprehensive review of edible coatings for postharvest management of fruits and vegetables: Enhancing food and nutrition security. *Discover Agriculture*, *3*(1). https://doi.org/10.1007/s44279-025-00348-8

Ali, M., Ali, A., Ali, S., Chen, H., Wu, W., Liu, R., Chen, H., Ahmed, Z. F. R., & Gao, H. (2025). Global insights and advances in edible coatings or films toward quality maintenance and reduced postharvest losses of fruit and vegetables: an updated review. *Comprehensive Reviews in Food Science and Food Safety*, *24*(1), e70103. https://doi.org/10.1111/1541-4337.70103

AOAC. (2019). *Official methods of analysis of AOAC International* (21st ed.). AOAC International.

Arnon, H., Zaitsev, Y., Porat, R., & Poverenov, E. (2014). Effects of carboxymethyl cellulose and chitosan bilayer edible coating on postharvest quality of citrus fruit. *Postharvest Biology and Technology, 87,* 21–26. https://doi.org/10.1016/j.postharvbio.2013.08.007

Baales, J., Zeisler-Diehl, V. V., Narine, S., & Schreiber, L. (2023). Interaction of surfactants with *prunus laurocerasus* leaf surfaces: Time-dependent recovery of wetting contact angles depends on physico-chemical properties of surfactants. *Chemical and Biological Technologies in Agriculture*, *10*(1), 81. https://doi.org/10.1186/s40538-023-00455-y

Ben-Yehoshua, S., & Rodov, V. (2002). Transpiration and water stress. In *Postharvest Physiology and Pathology of Vegetables* (pp. 143-197). CRC Press. https://doi.org/10.1201/9780203910092.ch5

Cui, S., Zheng, X., & Beach, E. S. (2011). Modification of chitosan films with environmentally benign reagents for increased water resistance. *Green Chemistry Letters and Reviews*, *4*(1), 35-40. https://doi.org/10.1080/17518253.2010.500621

Dhall, R. K. (2013). Advances in edible coatings for fresh fruits and vegetables: A review. *Critical Reviews in Food Science and Nutrition*, *53*(5), 435-450. https://doi.org/10.1080/10408398.2010.541568

Fagundes, C., Palou, L., Monteiro, A. R., & Pérez-Gago, M. B. (2015). Hydroxypropyl methylcellulose-beeswax edible coatings formulated with antifungal food additives to reduce *Alternaria* black spot and maintain postharvest quality of cold-stored cherry tomatoes. *Scientia Horticulturae*, *193*, 249-257. https://doi.org/10.1016/j.scienta.2015.07.027

Fernández-Catalán, A., Palou, L., Taberner, V., Grimal, A., Argente-Sanchis, M., & Pérez-Gago, M. B. (2021). Hydroxypropyl methylcellulose-based edible coatings formulated with antifungal food additives to reduce alternaria black spot and maintain postharvest quality of cold-stored 'Rojo Brillante' persimmons. *Agronomy, 11*(4), 757. https://doi.org/10.3390/agronomy11040757

Gidado, M. J., Gunny, A. A. N., Gopinath, S. C. B., Ali, A., Wongs-Aree, C., & Salleh, N. H. M. (2024). Challenges of postharvest water loss in fruits: Mechanisms, influencing factors, and effective control strategies–A comprehensive review. *Journal of Agriculture and Food Research*, *17*, 101249. https://doi.org/10.1016/j.jafr.2024.101249

Griffin, W. C. (1949). Classification of surface-active agents by HLB. *Journal of the Society of Cosmetic Chemists*, *1*(5), 311-326.

Holloway, P. J. (1969). Chemistry of leaf waxes in relation to wetting. *Journal of the Science of Food and Agriculture*, *20*(2), 124-128. https://doi.org/10.1002/jsfa.2740200214

Hubbe, M. A. (2019). Why, after all, are chitosan films hydrophobic? *BioResources*, *14*(4), 7630-7631. https://doi.org/10.15376/biores.14.4.7630-7631

Koch, K., & Barthlott, W. (2009). Superhydrophobic and superhydrophilic plant surfaces: An inspiration for biomimetic materials. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 367*(1893), 1487–1509. https://doi.org/10.1098/rsta.2009.0022

Kocira, A., Kozłowicz, K., Panasiewicz, K., Staniak, M., Szpunar-Krok, E., & Hortyńska, P. (2021). Polysaccharides as edible films and coatings: Characteristics and influence on fruit and vegetable quality –A review. *Agronomy*, *11*(5), 813. https://doi.org/10.3390/agronomy11050813

Maringgal, B., Hashim, N., Mohamed Amin Tawakkal, I. S., & Muda Mohamed, M. T. (2020). Recent advance in edible coating and its effect on fresh/fresh-cut fruits quality. *Trends in Food Science & Technology*, *96*, 253–267. https://doi.org/10.1016/j.tifs.2019.12.024

Martin, L. B. B., & Rose, J. K. C. (2013). There's more than one way to skin a fruit: Formation and functions of fruit cuticles. *Journal of Experimental Botany, 65*(16), 4639–4651. https://doi.org/10.1093/jxb/eru301

Mavuso, V. L., & Yapwattanaphun, C. (2017). Effect of environmental conditions on flower induction of marian plum (*Bouea burmanica* Griff). *Agriculture and Natural Resources, 51*(4), 243–246. https://doi.org/10.1016/j.anres.2017.01.004

Moradinezhad, F., Adiba, A., Ranjbar, A., & Dorostkar, M. (2025). Edible coatings to prolong the shelf life and improve the quality of subtropical fresh/fresh-cut fruits: a review. *Horticulturae*, *11*(6), 577. https://doi.org/10.3390/horticulturae11060577

Park, H. J. (1999). Development of advanced edible coatings for fruits. *Trends in Food Science and Technology*, *10*(8), 254-260. https://doi.org/10.1016/S0924-2244(00)00003-0

Pérez-Gago, M. B., & Rhim, J. W. (2013). Edible coating and film materials: Lipid bilayers and lipid emulsions. In *Innovations in Food Packaging* (2nd ed., pp. 325-350). Academic Press. https://doi.org/10.1016/B978-0-12-394601-0.00013-8

Pérez-Vergara, L. D., Cifuentes, M. T., Franco, A. P., Pérez-Cervera, C. E., & Andrade-Pizarro, R. D. (2020). Development and characterization of edible films based on native cassava starch, beeswax, and propolis. *NFS Journal*, *21*, 39–49. https://doi.org/10.1016/j.nfs.2020.09.002

Posom, J., Klaprachan, J., Rattanasopa, K., Sirisomboon, P., Saengprachatanarug, K., & Wongpichet, S. (2020). Predicting marian plum fruit quality without environmental condition impact by handheld visible–near-infrared spectroscopy. *ACS Omega*, *5*(43), 27909-27921. https://doi.org/10.1021/acsomega.0c03203

R Core Team. (2025). R: A language and environment for statistical computing. *R Foundation for Statistical Computing*. https://www.R-project.org

Romanazzi, G., Feliziani, E., & Sivakumar, D. (2018). Chitosan, a biopolymer with triple action on postharvest decay of fruit and vegetables: Eliciting, antimicrobial and film-forming properties. *Frontiers in Microbiology*, 9, 2745. https://doi.org/10.3389/fmicb.2018.02745

Singh, S., Dubey, A., Gangwar, V., Kumar, A., Kumar, A., Kumar, M., & Wamiq, M. (2023). Edible coatings for improving the storability of fresh fruits and vegetables: A review. *Pharma Innovation Journal*, *12*(6), 3992-4002.

Subhadrabandhu, S. (2001). Under-utilized tropical fruits of Thailand. Food and Agriculture Organization of the United Nations.

Vijayan, S. P., Aparna, S., & Sahoo, S. K. (2023). Effect of beeswax on hydrophobicity, moisture resistance and transparency of UV curable linseed oil based coating for compostable paper packaging. *Industrial Crops and Products, 197,* 116645. https://doi.org/10.1016/j.indcrop.2023.116645

Watanadumrong, B., & Chemsripong, S. (2021). Supply chain analysis of the production and marketing of the marian plum in the case of San Khao farmers, Phitsanulok, Thailand. *Open Journal of Social Sciences*, *09*(03), 491–505. https://doi.org/10.4236/jss.2021.93032

Wattanakeeboot, P., & Chanasut, U. (2019). Effect of harvesting stages on jelly seed symptom of plango (*Bouae burmanica*) cv. Thunl Klao fruits. *International Journal of Geomate, 17*(61), 104-108. https://doi.org/10.21660/2019.61.4799

Yeats, T. H., & Rose, J. K. C. (2013). The formation and function of plant cuticles. *Plant Physiology, 163*(1), 5–20. https://doi.org/10.1104/pp.113.222737