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EDITED BY

Shubham Mandliya,
University of Reading, United Kingdom

REVIEWED BY

Duong Duc La,
University of Science and Technology of
Hanoi, Vietnam
Janejira Phakawan,
Rajamangala University of Technology
Thanyaburi, Thailand

*CORRESPONDENCE

Marianela Inga
✉ marianelainga@lamolina.edu.pe

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Sustainable postharvest quality enhancement of Kent mangoes using alginate coating enriched with mango seed by-product extract

Clara Silva-Espíritu^{1,2}, Marianela Inga^{2*}, Jesaya Rios-Mendoza^{1,3},
Jorge Vivar-Méndez^{1,4} and Miguel Malnati-Ramos^{1,2}

¹Department of Biotechnology, SSF Innovation Center, Bio Natural Solutions S.A.C., Lima, Peru,

²Facultad de Industrias Alimentarias, Universidad Nacional Agraria La Molina, Lima, Peru, ³Facultad de Ciencias y Filosofía, Universidad Peruana Cayetano Heredia, Lima, Peru, ⁴Escuela de Ciencia de los Alimentos. Facultad de Farmacia y Bioquímica de la Universidad Nacional Mayor de San Marcos, Lima, Peru

Natural edible coatings enriched with bioactive compounds offer a promising approach to enhancing the postharvest quality of mangoes (*Mangifera indica* L.). These fruits are prone to rapid physiological and biochemical deterioration and diseases such as anthracnose caused by *Colletotrichum gloeosporioides*. This study investigated the efficacy of a natural alginate-based coating, enriched with mango seed extract, in improving the postharvest quality of fresh Kent mangoes. The mango seed extract was characterized for its total phenolic content, flavonoid levels, and antioxidant capacity using DPPH, ABTS, and FRAP assays. Mangoes were treated with various formulations and stored at a refrigerated temperature of 10 ± 2 °C for 25 days, during which quality parameters such as weight loss, firmness, respiration rate, internal color, total soluble solids, pH, titratable acidity, and antifungal activity were assessed. Results indicated that the alginate-based coating with 1% mango seed extract significantly enhanced the preservation of mango quality attributes, demonstrating reduced weight loss, improved firmness, and effective antifungal activity. This approach not only supports the sustainable postharvest management of export-quality mangoes but also promotes the valorization of agro-industrial waste and the development of environmentally friendly postharvest technologies.

KEYWORDS

antifungal activity, eco-friendly practices, harvesting techniques, sustainable, tropical fruit

1 Introduction

The mango (*Mangifera indica* L.) is one of the most significant tropical fruit crops worldwide, prized for its taste, aroma, and high nutritional value. It is a rich source of vitamin C and carotenoids (Rocha-Ribeiro and Schieber, 2010). Despite its popularity, mangoes are classified as climacteric and perishable fruits, meaning they undergo rapid ripening after harvest, which is characterized by increased respiration and ethylene production (Majeed et al., 2024; Rastegar et al., 2019). This swift deterioration makes mangoes highly susceptible to various diseases, notably anthracnose, primarily caused by the fungus *Colletotrichum gloeosporioides* (Sefu et al., 2015). Anthracnose leads to tissue

rot and significantly diminishes the commercial quality of the fruit (Law et al., 2025). Furthermore, this vulnerability, coupled with inadequate handling practices, results in substantial post-harvest losses, accounting for 30–40% of the total production within the supply chain (Gomes et al., 2021).

Traditionally, the control of anthracnose has relied on synthetic fungicides. However, concerns have arisen regarding chemical toxicity, the development of pathogen resistance, and environmental contamination (Fang et al., 2025; Souza et al., 2025). Consequently, there is an increasing demand for natural and environmentally friendly alternatives to preserve fruit quality and extend shelf life during storage (Ebrahimi and Rastegar, 2020).

The efficacy of these natural systems is increasingly supported by advanced extraction and bioprocessing strategies. Research into medicinal plants such as *Ginkgo biloba* has demonstrated that specialized extraction methods can maximize the yield of functional polysaccharides while preserving their biological activities (Zhang et al., 2024). Furthermore, biotechnological approaches like microbial fermentation have proven highly effective in significantly enriching the phenolic and flavonoid content of plant materials, thereby enhancing the overall antioxidant capacity of the resulting extracts (Lang et al., 2025).

Ibrahim et al. (2025) and Jafarzadeh et al. (2020) highlight that mango industrialization produces substantial amounts of agri-food waste, often discarded as trash. This waste can constitute up to 60% of the fruit's weight, amounting to approximately 75,000 tons annually. The agro-industrial sector's inadequate handling of these by-products, stemming from a lack of environmental awareness, technological capacity, and resources, results in their disposal through landfills, sanitary landfills, and combustion. This process generates significant emissions of methane, carbon dioxide, and other particles, contributing to environmental and social pollution (Venkatramanan et al., 2021).

This environmental challenge presents a clear opportunity for the revalorization of fruit remnants. Recent studies on species such as *Alpinia zerumbet* have shown that discarded plant tissues can be converted into purified polysaccharides with potent biological value (Hou et al., 2024). These extracts have demonstrated the capacity to inhibit oxidative stress and modulate cellular signaling pathways, providing a strong precedent for using similar agro-industrial residues as functional ingredients in post-harvest technologies.

Despite these challenges, agro-industrial waste, such as mango seeds, is recognized as an exceptional source of phenolic compounds, flavonoids, and carotenoids. These compounds exhibit potent antimicrobial properties that inhibit phytopathogens and possess antioxidant capacities that stabilize lipid oxidation (Jafarzadeh et al., 2020).

In this context, natural coatings have emerged as an innovative technology to prolong the shelf life of fruits. These coatings create a protective layer that limits vapor and oxygen exchange, thereby reducing water loss, respiration, and oxidation rates (Kalita et al., 2025; Jafarzadeh et al., 2020).

Polysaccharide-based coatings have gained popularity due to their stability and high solubility (Panahirad et al., 2019). Among these biopolymeric materials, sodium alginate stands out as a widely used coating agent (Such et al., 2023). Extracted from brown algae, sodium alginate is favored for its natural, sustainable, and biosafe properties. It is chemically inert, easy to handle, cost-effective,

non-toxic, and recognized as safe (GRAS) by the FDA (Kalita et al., 2025). This biopolymer exhibits viscoelastic qualities and an excellent ability to form gels, allowing for uniform coating on irregular surfaces. This is crucial in food preservation, particularly for fruits, as it reduces moisture loss and gas exchange, thereby delaying ripening and maintaining fruit firmness (Singh et al., 2020; Nair et al., 2018). To enhance the effectiveness of these coatings, current trends focus on incorporating bioactive compounds that offer antimicrobial and antioxidant properties (Fang et al., 2025).

Fang et al. (2025) report that incorporating mango seed-based extracts into alginate matrices enables the development of a coating that not only mechanically protects the fruit, preserving its quality and extending its shelf life, but also aligns with circular economy principles. By valorizing agro-industrial waste, this approach adds value by creating an innovative and sustainable matrix for mango preservation, effectively transforming what was once considered waste into a valuable resource and closing the production cycle.

Considering the importance of the Kent variety mango in international markets, it is crucial to establish post-harvest protocols that preserve fruit quality and extend shelf life during long-distance transportation (Vega-García et al., 2025). Therefore, this study aimed to evaluate a natural alginate-based coating, enhanced with bioactive compounds derived from mango seeds, to prolong the commercial life of Kent variety mangoes. This approach offers an eco-friendly alternative that reduces food waste.

2 Materials and methods

2.1 Material

Mango seeds were obtained from fresh Kent mango fruits sourced from Chulucanas, Piura, Peru. For the coating evaluation tests, fresh Kent mango fruits were collected at physiological maturity from Tambogrande, Piura, Peru. The fruits were selected based on homogeneous characteristics in color, size, and weight, as well as the absence of visible physical damage.

2.2 Methods

2.2.1 Preparation of mango seed extract

The preparation of the mango seed extract was conducted using the methodology proposed by Gómez-Maldonado et al. (2020), with several modifications. Fresh mangoes were disinfected by immersion in a solution of water and sodium hypochlorite at 50 ppm for 5 min. The seeds were extracted from the mangoes and dried in a hot air dryer (Excalibur, California, USA) at 40 °C for 48 h. The dried mango seeds were ground using a grinder (Bosch, Munich, Germany) until a fine powder was obtained. This powder was then mixed with an ethanol-water solution (50:50 v/v) at a material-to-solvent ratio of 1:20 g/mL. The mixture was subjected to high-power ultrasound (Biobase, Jinan, China) at a frequency of 20 kHz, with 50% amplitude, at room temperature (25 °C) for 30 min under dark conditions. The resulting mixture was macerated using a magnetic stirrer (DLAB, Beijing, China) at 1,500 rpm for 30 min at room temperature (25 °C) in darkness.

The macerated extract was filtered using Whatman No. 3 paper to remove residues. The solvent in the extract was evaporated using a rotary evaporator at 55 °C for 5 h, followed by freeze-drying in a vertical freeze dryer (Biobase, Jinan, China) to obtain the concentrated mango seed extract (MSE). Finally, the extract was weighed and stored in a freezer at −18 °C until further use.

2.2.2 Determination of total phenolic content and total flavonoid content

The analysis of total phenolic content (TPC) was conducted using the Folin-Ciocalteu method, as described by Singleton and Rossi (1965), with slight modifications. An aliquot of 500 µL of the sample, diluted in distilled water (1:400), was transferred to a test tube containing 125 µL of 1 M Folin-Ciocalteu reagent and 125 µL of distilled water. The mixture was then vortexed for 20 s. After 5 min, 1,250 µL of Na₂CO₃ (7.5% w/v) was added. The solution was allowed to rest in the dark for 30 min, after which the absorbance was measured using a UV/VIS spectrophotometer (ThermoFisher Scientific, Beijing, China) at 755 nm. Total phenolic content was calculated based on a calibration curve using gallic acid as the standard. The results were expressed in milligrams of gallic acid equivalents per gram of mango seed flour on a dry weight basis (mg GAE/g dw).

The total flavonoid content (TFC) of the extract was determined using the method proposed by Zhishen et al. (1999), with slight modifications. An aliquot of 500 µL of the sample, diluted in distilled water, was mixed with 1,000 µL of distilled water. Subsequently, 75 µL of 5% NaNO₂ was added, and the mixture was allowed to rest for 5 min. Then, 150 µL of 10% AlCl₃ was added, followed by another 5-min resting period, after which 500 µL of 1 M NaOH was added. Finally, the absorbance was measured using a UV/VIS spectrophotometer at 510 nm. Total flavonoid content was calculated based on a catechin calibration curve and expressed in milligrams of catechin equivalents per gram of mango seed flour on a dry weight basis (mg QE/g dw).

2.2.3 Determination of antioxidant capacity using DPPH, ABTS, and FRAP

The antioxidant capacity was assessed using spectrophotometric methods, specifically DPPH, ABTS, and FRAP. The DPPH analysis was conducted based on the methodology proposed by Brand-Williams et al. (1995), with slight modifications. The stock DPPH solution was diluted with methanol to create a working solution with an absorbance of 0.9 ± 0.02 at a wavelength of 515 nm. Subsequently, 150 µL of the sample, diluted in distilled water, was placed in test tubes, and 2,850 µL of the DPPH solution was added. The mixture was allowed to rest at room temperature in the dark for 35 min, after which the absorbance was measured using a UV/VIS spectrophotometer at 510 nm. A Trolox calibration curve was used, and the results were expressed in µmol TE/g dw, similarly for the ABTS and FRAP methods.

The methodology for determining antioxidant capacity using the ABTS method was based on the approach proposed by Re et al.

(1999), with slight modifications. An ABTS solution (7 mM) was mixed with potassium persulfate (2.45 mM) in a 1:1 ratio and maintained at room temperature in the dark for 16 h to allow the formation of the ABTS radical cation (ABTS⁺). The resulting solution was diluted with methanol to achieve an absorbance of 0.70 ± 0.02 at 734 nm. Subsequently, 2,850 µL of the ABTS solution was added to 150 µL of the extract, allowed to rest for 30 min, and the absorbance was measured at 734 nm.

The FRAP method for determining antioxidant capacity was carried out according to the methodology proposed by Benzie and Strain (1996), with some modifications. The FRAP solution was prepared by combining 50 mL of an acetate buffer solution (0.3 M, pH 3.6), a 10 mM TPTZ solution in 40 mM HCl, and a 20 mM FeCl₃·6H₂O solution. A total of 290 µL of the FRAP solution was added to 20 µL of the extract, allowed to rest for 30 min, and the absorbance was measured at 593 nm.

2.2.4 Preparation of the coating solution and application to fruits

The formulation of the natural coating composed of alginate and ethanolic extract of mango seed was prepared following the methodology proposed by Najafi et al. (2021), with slight modifications. Initially, alginate was diluted to a concentration of 1% (w/v) in distilled water preheated to 85 °C using a magnetic stirrer set at 1,500 rpm for 5 min. The alginate solution was then combined with glycerol at a concentration of 0.5%, with stirring conducted at ambient temperature (25 °C) for an additional 5 min. Finally, the mixture was blended with mango seed extract (MSE) at concentrations of 0.5% and 1% using a homogenizer set at 2,500 rpm for 5 min until a stable coating solution was obtained. The selection of these MSE concentrations was based on preliminary trials and previous studies on the incorporation of bioactive extracts into polymeric matrices, where two representative levels are commonly evaluated to assess dose-dependent effects on quality parameters. Preliminary observations indicated that concentrations below 0.5% did not produce noticeable differences compared with the alginate-only treatment, suggesting that this value approximates the minimum effective concentration. In contrast, concentrations above 1% resulted in perceptible changes in the color of the coating, which could negatively affect the visual quality and commercial acceptability of the fruit. Therefore, the selected concentrations (0.5% and 1%) were considered an appropriate functional range to evaluate the effect of the extract on coating performance while maintaining acceptable sensory characteristics.

For the application process, fresh Kent variety mangoes were washed and disinfected by immersion in a solution of water and sodium hypochlorite at a concentration of 50 ppm for 5 min.

A total of 270 mangoes were used in the experiment and were randomly assigned to the five established treatments. Each treatment consisted of 54 fruits, which were distributed across six storage times (0, 5, 10, 15, 20, and 25 days), with nine fruits evaluated at each sampling time. Each evaluation time was composed of three independent replicates, with three fruits per replicate, ensuring experimental reproducibility and statistical reliability of the measurements.

The treatments were applied via spraying, followed by a resting period of 15 min. Subsequently, the treated mangoes were placed in plastic containers and stored at a temperature of $10 \pm 2^\circ\text{C}$ with a relative humidity of 85–90% for 25 days. This temperature was selected to simulate typical refrigerated conditions used during postharvest storage and export of mangoes. For many commercial cultivars, including “Kent,” storage temperatures between 10 and 13°C are commonly recommended to slow respiration and ripening processes while minimizing the risk of chilling injury that may occur at lower temperatures. These conditions are widely applied during refrigerated storage and maritime transport in international mango supply chains (Singh et al., 2013; Sivakumar et al., 2011).

Five treatments were evaluated: T1: control (No application), T2: commercial [Application of 18% oxidized polyethylene wax (E-914) + 0.2% Fludioxonil], T3: 1% Alginate, T4: 1% Alginate + 0.5% Mango Seed Extract, and T5: 1% Alginate + 1% Mango Seed Extract.

2.3 Evaluation of postharvest fruit quality during the storage period

2.3.1 Percentage of weight loss

The percentage of weight loss (WL) of the fruit was determined following the methodology outlined by Liu et al. (2021), with minor modifications. The weight loss ratio was calculated in relation to the initial weight of the samples, using an electronic balance (Biobase, Jinan, China). This calculation was performed using Equation 1:

$$WL(\%) = \frac{(W_i - W_f)}{W_i} * 100 \quad (1)$$

Where:

WL(%): Percentage of weight loss, W_i : Initial weight, W_f : Final weight.

2.3.2 Firmness

The assessment of fruit firmness was conducted in accordance with the methodology proposed by Jung and Choi (2021), with slight modifications. In this analysis, firmness was measured using a digital penetrometer (Lutron, Taipei, Taiwan) equipped with a 3 mm diameter probe. The values were expressed as the force (N) required to penetrate the tissue at a speed of 8 mm s^{-1} .

2.3.3 Respiration rate

The respiratory rate was evaluated following the methodology proposed by Ghosh and Dash (2020), with some modifications. The fruit was placed in a 3,000 mL hermetically sealed glass container, fitted with a rubber septum in the center of the metal lid, and incubated for 2 h under ambient conditions. The headspace gas volume (Vv) was determined as the difference between the total container volume (3,000 mL) and the volume occupied by the fruit. The fruit volume was estimated based on its mass and an average density of 0.96 kg L^{-1} .

The CO_2 concentration was measured at the beginning and at the end of the incubation period using a gas analyzer (WITT-Gas, Witten, Germany). Measurements were conducted at 25°C under atmospheric pressure, ensuring consistent experimental conditions during gas accumulation. The respiratory rate was calculated from the increase in CO_2 concentration within the headspace, and the values were normalized by the headspace gas volume (Vv), fruit mass, and incubation time, as described in Equation 2.

$$\text{Respiratory rate (ml de CO}_2 \text{ kg}^{-1} \text{ h}^{-1}) = \frac{\Delta\% \text{CO}_2 \times V_v}{W \times \Delta T} \quad (2)$$

Where:

$\Delta\% \text{CO}_2$: Difference in carbon dioxide concentration between the initial and final measurements, expressed as percentage (%), V_v : Headspace gas volume of the container (mL), W : Sample weight (Kg), ΔT : Time difference between the two measurements (h).

2.3.4 Internal color

The color determination of the fruit's internal pulp was measured using a colorimeter (Konica Minolta, Tokyo, Japan), following the methodology outlined by Nga and Bac (2021), with slight modifications. Both sides of the mango were cut near the seed without exposing it, and the device was then used to measure the L^* (lightness or brightness), a^* (redness or greenness), and b^* (yellowness or blueness) values of the fruit. Prior to measurement, the equipment was calibrated with a white standard. The total color difference (ΔE) was calculated using Equation 3:

$$\Delta E = \sqrt{(L_f^* - L_i^*)^2 + (a_f^* - a_i^*)^2 + (b_f^* - b_i^*)^2} \quad (3)$$

Where: L_f^* : Final lightness, L_i^* : Initial lightness, a_f^* : Final redness (+) or greenness (−), a_i^* : Initial redness (+) or greenness (−), b_f^* : Final yellowness (+) or blueness (−), b_i^* : Initial yellowness (+) or blueness (−).

2.3.5 Total soluble solids

The determination of total soluble solids (TSS) in the fruit was conducted according to the methodology proposed by Association of Official Analytical Collaboration: AOAC (2000), with slight modifications. A specific amount of juice was extracted from the fruit, and 3 to 4 drops were placed on the prism of a refractometer (Biobase, Jinan, China). The reading was performed at an ambient temperature of 25°C . The equipment was previously calibrated with distilled water, and the obtained values were expressed in $^\circ\text{Brix}$.

2.3.6 pH

The pH of the mangoes was determined following the methodology established by Association of Official Analytical Collaboration: AOAC (2000), with slight modifications. A 150 mL sample of fruit juice, previously homogenized using a blender, was

placed in a beaker. The electrode of a potentiometer (Hanna, Rhode Island, United States), which had been previously calibrated, was immersed in the solution to measure the pH at a temperature of 25 °C.

2.3.7 Titratable acidity

The titratable acidity (TA) of mango fruit was determined following the [Association of Official Analytical Collaboration: AOAC \(2000\)](#) method, with slight modifications. A sample of fruit juice was diluted in distilled water at a ratio of 1:5 and homogenized using a blender. It was then titrated using a 0.1 N sodium hydroxide solution until reaching a pH of 8.1 ± 0.2 . The volume of NaOH consumed was recorded and reported as a percentage of the predominant acid in mango, which is citric acid. The calculation of titratable acidity was performed using [Equation 4](#):

$$TA (\%) = \frac{K \cdot N \cdot G}{V} \cdot 100 \quad (4)$$

Where:

TA (%): Percentage of titratable acidity, k: Acidity constant (Citric acid = 0.064), N: Normality of NaOH, G: Volume of NaOH used in titration, V: Total volume of the sample.

2.3.8 In vivo antifungal activity

The *in vivo* antifungal activity was evaluated following the methodology described by [Zhang et al. \(2013\)](#), with slight modifications. Mango fruits were selected based on uniform ripeness, moderate size, and the absence of visible diseases or mechanical damage. The fruits were washed with tap water, air-dried, and surface-disinfected with 100 ppm sodium hypochlorite for 5 min. Subsequently, they were rinsed with sterile distilled water and allowed to air-dry.

Two wounds (3 mm in depth and 3 mm in diameter) were made on the lateral sides of each fruit using a sterile needle. A 5 µL aliquot of a conidial suspension of *Colletotrichum gloeosporioides* (1×10^6 spores mL⁻¹) was inoculated into each wound. After inoculation, the fruits were kept at room temperature for 2 h to allow the inoculum to dry and establish infection. The different treatments were then applied by spraying, and the fruits were air-dried at room temperature for 24 h.

Each treatment consisted of nine fruits distributed in three independent plastic containers (three fruits per container). Fruits were randomly assigned to each container. The experimental unit corresponded to a single fruit, and lesion diameter was calculated as the average of the two inoculated wounds per fruit.

Finally, the mangoes were stored at room temperature, and disease development was evaluated at 3-day intervals for 12 days by measuring lesion diameter (mm).

2.3.9 Statistical analysis

Data were expressed as mean $\pm$ standard deviation from three replicates. An analysis of variance (ANOVA) was conducted to

compare means; if significant differences between treatments were detected, Tukey's test for mean comparison was performed with a significance level of 5 percent ($p < 0.05$). The statistical software R-2024 [4.4.0 (64-bit)] was used for the analysis.

3 Results and discussion

3.1 Analysis of total phenolic content, total flavonoid content, and antioxidant capacity of mango seed extracts

[Table 1](#) illustrates the total phenolic content (TPC) identified in the extract from Kent variety mango seeds, measured at 40.08 mg GAE/ dry weight (dw). This value surpasses those reported by [El-Kady et al. \(2017\)](#), who documented a TPC of 21.29 mg GAE/g dw in Kernel variety mango seeds extracted with 80% ethanol, and by [Lim et al. \(2019\)](#), who reported 38.05 mg GAE/g dw for Carabao variety mango seeds extracted with 90% ethanol. Nonetheless, variations were observed in the TPC reported by [Alañón et al. \(2021\)](#), who found 78.0 mg GAE/g dw in Kent variety extracted with 80% methanol, and by [Choudhary et al. \(2026\)](#), who obtained 110.02 mg GAE/g dw from mango seeds extracted with 50% ethanol. [Abdel-Aty et al. \(2018\)](#) indicated that TPC values in mango seeds can fluctuate between 21.97 and 148.4 mg GAE/g dw, contingent upon the fruit variety. According to [Hazrati et al. \(2024\)](#), discrepancies in TPC values reported in the literature can be primarily attributed to the interaction of multiple intrinsic factors (such as the solvent used, solvent concentration, extraction conditions, etc.) and extrinsic factors (including mango variety, region of fruit production, and fruit maturity).

The type and concentration of the solvent play a crucial role in extraction efficiency, given the diverse chemical structures and affinities of phenolic compounds ([Rebollo-Hernanz et al., 2021](#)). Similarly, extraction conditions, including the method applied, duration, and temperature, significantly affect the release or degradation of phenolic compounds, thereby contributing to the variability in phenolic content observed by [Alcántara et al. \(2020\)](#). Furthermore, [Lebaka et al. \(2021\)](#) emphasize that variations among crop varieties, such as mango, significantly impact the biosynthesis and accumulation of phenolic compounds in the seed. Additionally, [Hazrati et al. \(2024\)](#) highlight that agronomic factors, such as the fruit's maturity at harvest and the production region, directly

TABLE 1 Total phenolic content (TPC), total flavonoid content (TFC), and antioxidant capacity (ABTS, DPPH, and FRAP) of mango seed extract from the Kent variety.

Compound	Value
Total phenolic content (mg GAE/g dw)	40.08 $\pm$ 0.18
Total flavonoid content (mg QE/g dw)	105.65 $\pm$ 0.67
ABTS (µmol TE/g dw)	1,431.40 $\pm$ 1.69
DPPH (µmol TE/g dw)	1,106.56 $\pm$ 2.98
FRAP (µmol TE/g dw)	1,234.14 $\pm$ 2.07

The results were presented as mean $\pm$ standard deviation.

influence the content of secondary metabolites and, consequently, the concentration of phenolic compounds.

The total flavonoid content (TFC) obtained from mango seed extract, measured at 105.65 mg QE/ dry weight (dw), as shown in Table 1, exceeded the values reported by Bernal-Mercado et al. (2018), who found 78.68 mg QE/g dw in Haden variety seeds, and Abdel-Aty et al. (2018), who documented 33.25 mg QE/g dw in Hindi variety seeds. Similar values were reported by Vega-Vega et al. (2013), who obtained 107 mg QE/g dw for the Ataulfo variety. While the total polyphenol content of the extract was moderate compared to other reported varieties, the substantial amount of flavonoids suggests that this proportion represents a significant component of the phenolic compounds present in mango seeds. This finding aligns with studies indicating the abundance of total flavonoids in mango seeds (Tirado-Kulieva et al., 2021).

According to Edo et al. (2023), flavonoids constitute one of the major subclasses of phenolic compounds, recognized for their antioxidant and antimicrobial properties. These characteristics are primarily attributed to their polyphenolic structure, which is rich in hydroxyl groups. These groups enhance their antioxidant capacity by facilitating electron transfer and neutralizing reactive oxygen species. Additionally, flavonoids can interact with cell membranes, nucleic acids, and proteins, thereby disrupting essential processes vital for microbial survival (De Rossi et al., 2025).

The determination of the antioxidant capacity of Kent variety mango seeds using three techniques—ABTS, DPPH, and FRAP—is presented in Table 1. The values obtained from the Kent variety mango seed extract were 1,431.40, 1,106.56, and 1,234.14 $\mu\text{mol TE/g dw}$ for ABTS, DPPH, and FRAP methods, respectively. These values exceed those reported by Sogi et al. (2013), who found 1,233 $\mu\text{mol TE/g dw}$ for ABTS and 766 $\mu\text{mol TE/g dw}$ for FRAP in Tommy Atkins variety mango seed extract. Similarly, studies by Gómez-Maldonado et al. (2020) reported a DPPH determination value of 1,024.8 $\mu\text{mol TE/g dw}$ in Manila variety mango seeds. Furthermore, Pinsirodom et al. (2018) reported that Kaew Dum variety mango seed extract exhibited greater antioxidant capacity compared to the fruit's peel and pulp, with values ranging from 686 $\mu\text{mol TE/g dw}$ to 1,666 $\mu\text{mol TE/g dw}$ using the DPPH method, and from 597 to 705.6 $\mu\text{mol TE/g dw}$ for the FRAP method. These findings confirm that mango seed, obtained as an agro-industrial by-product, is a valuable and promising source of phenolic compounds, flavonoids, and antioxidants.

3.2 Percentage of fruit weight loss

The determination of weight loss (WL) is a critical indicator for assessing the quality and shelf life of mango fruit, as it directly reflects the intensity of transpiration and respiration, processes that lead to dehydration and loss of firmness over the storage period. Figure 1 illustrates the progression of the percentage of weight loss (WL) in Kent variety mangoes subjected to various treatments over 25 days of storage. All treatments exhibited a gradual increase in WL as the storage period progressed, consistent with the physiological behavior of climacteric fruits such as mango (Kuldeep Singh et al., 2025). However, significant

differences between treatments ($p < 0.05$) were observed starting from day 15 of storage, indicating a differentiated effect of the coatings applied in controlling WL. At the end of the storage period, treatment T5 demonstrated the lowest WL (4.67%) compared to treatment T2 (5.57%) and the control treatment T1 (8.43%).

These results suggest that the use of alginate as a coating serves as an effective moisture barrier. By forming a semipermeable layer over the fruit, it ensures that moisture loss initially occurs from the coating rather than from the fruit itself (Kocira et al., 2021). Furthermore, Bonilla et al. (2012) indicate that sodium alginate also provides an excellent barrier against oxygen due to its low permeability to this gas, thereby reducing oxygen diffusion into the fruit and consequently lowering the respiratory rate, which is associated with reduced weight loss. According to Chen et al. (2023), alginate facilitates the incorporation of bioactive compounds, such as extracts, which promotes a synergistic effect favoring the formation of a denser and more cohesive polymeric network. This is the result of physicochemical interactions between alginate chains and the functional groups of phenolic compounds present in the extracts, reducing the mobility of alginate chains and consequently decreasing water vapor permeability, thus delaying fruit dehydration.

These physicochemical interactions are supported by experimental evidence in alginate-based composite films enriched with phenolic compounds. FTIR analyses of such films show shifts in absorption bands corresponding to $-\text{OH}$ and $-\text{COO}^-$ groups, confirming the formation of hydrogen bonds between the hydroxyl groups of phenolic molecules and the carboxylate or hydroxyl groups of the alginate chains (Luo et al., 2019; Li et al., 2022). These intermolecular interactions create a denser and more cohesive polymer network, which increases the tortuosity of water diffusion pathways and effectively lowers water vapor permeability (Asiri et al., 2024). This structural reinforcement also contributes to improved mechanical stability and cohesion of the film, providing a mechanistic explanation for the observed delay in fruit dehydration when alginate coatings are enriched with phenolic compounds.

Similar results were reported by Vilchez et al. (2023), who applied a coating based on chitosan and 1% orange peel residues to fresh mangoes stored at 5 °C for 8 days, successfully reducing weight loss from 2.03% in the control to 1.47% in the treated fruits. Similarly, Elsayed et al. (2022) observed that a coating formulated with whey protein concentrate and 1% mango residue extract significantly reduced weight loss in broccoli stored at 5 °C for 28 days, compared to samples without coating. Additionally, Zam (2019) reported that the combination of alginate with olive leaf extract in sweet cherries reduced weight loss to 5.35%, compared to 9.63% in the control, highlighting the positive effect of incorporating plant extracts on postharvest preservation.

3.3 Effect of treatments on fruit firmness

Firmness is one of the most crucial quality attributes of mango, as it is closely linked to consumer acceptance and the commercial value of the fruit (Amir et al., 2021). As depicted in Figure 2, all evaluated treatments exhibited a progressive reduction in firmness during the storage period. The results demonstrated

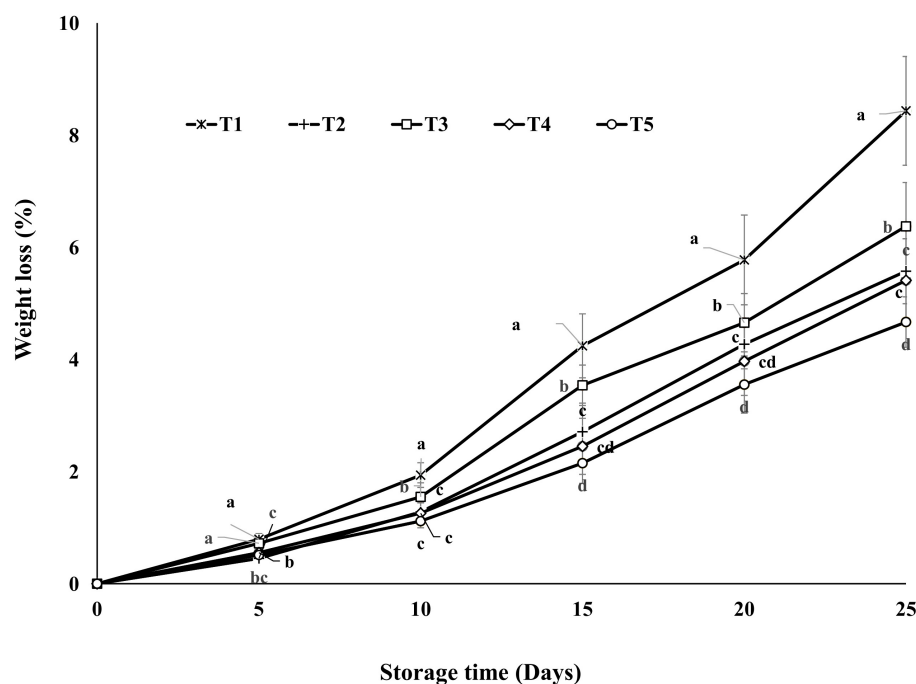


FIGURE 1

Percentage weight loss of mangoes under different treatments during 25 days of storage at 10 °C. Different letters within the same day indicate significant differences among treatments ($p < 0.05$). Treatments were defined as: T1 (control), T2 (commercial coating), T3 (alginate), T4 (alginate + 0.5% MSE), and T5 (alginate + 1% MSE). Vertical bars represent the standard deviation.

a significant effect of the interaction between treatment type and storage duration ($p < 0.05$) on the reduction of fruit firmness. At the conclusion of the study (day 25), fruits treated with T5 maintained the highest firmness values, with a value of 37.74 N, followed by T2 with a value of 30.38 N. In contrast, fruits subjected to the control treatment (T1) showed a pronounced loss of firmness (16.87 N), which is primarily associated with physiological changes linked to the ripening of climacteric fruits like mango. These changes involve the action of hydrolytic enzymes responsible for the degradation of pectin, a key component of the surface tissue that imparts firmness to the mango's cell walls, and its degradation facilitates softening (Ebrahimi and Rastegar, 2020).

Liguori et al. (2020) indicate that for mango fruits to achieve acceptable consumer quality in terms of firmness, they must exhibit values greater than 17 N, which places the control treatment outside the acceptance range. Similarly, as previously demonstrated, the use of alginate coatings enhanced with mango seed extracts (T4 and T5) effectively preserved fruit firmness. According to Shan et al. (2023), the inclusion of extracts rich in bioactive compounds within alginate matrices allows for direct or indirect interaction with pectinolytic enzymes. This occurs through the formation of phenol-polysaccharide complexes with pectin, reducing enzyme accessibility to the substrate and delaying the degradation of the cell wall (Pan et al., 2024).

It is also important to emphasize that the results presented are consistent with the negative correlation between firmness and weight loss parameters observed in fruits during postharvest storage, as moisture loss and dehydration directly contribute to fruit softening (Paniagua et al., 2013). In the current study, treatment T5 exhibited both higher firmness (33.88 N) and lower weight loss

(4.67%) after 25 days of storage, whereas the control treatment (T1) showed the greatest weight loss (8.43%) and the lowest firmness (16.87 N).

3.4 Effect of treatments on fruit respiration rate

The progression of the respiration rate of fresh mangoes during storage is depicted in Figure 3. This parameter serves as a crucial physiological indicator in the ripening process, as it reflects the intensity of the fruit's metabolic activity and its response to storage conditions and applied treatments (Kuldeep Singh et al., 2025). The results demonstrated that during the first 10 days of storage, there was an increase in the respiration rate across all evaluated treatments, a typical behavior at the onset of the climacteric phase in mangoes. However, 5 days later, a differentiated response among treatments was observed. Specifically, fruits subjected to treatments T4 and T5 exhibited a temporary decrease in respiration rate, whereas the other treatments showed an increase, following the order: T2 < T3 < T1. This divergence suggests that the application of a coating enhanced with mango seed extract exerted a modulatory effect on respiratory activity during the intermediate stages of storage (Kumar et al., 2024). By day 25 of storage (the final day), all samples exhibited an increase in respiration rate, a typical behavior in climacteric fruits such as mangoes. However, significant differences were observed among treatments ($p < 0.05$), with fruits treated with T4 and T5 recording the lowest respiration rates, at 53.24 and 50.38 ml CO₂ kg⁻¹ h⁻¹, respectively. In contrast,

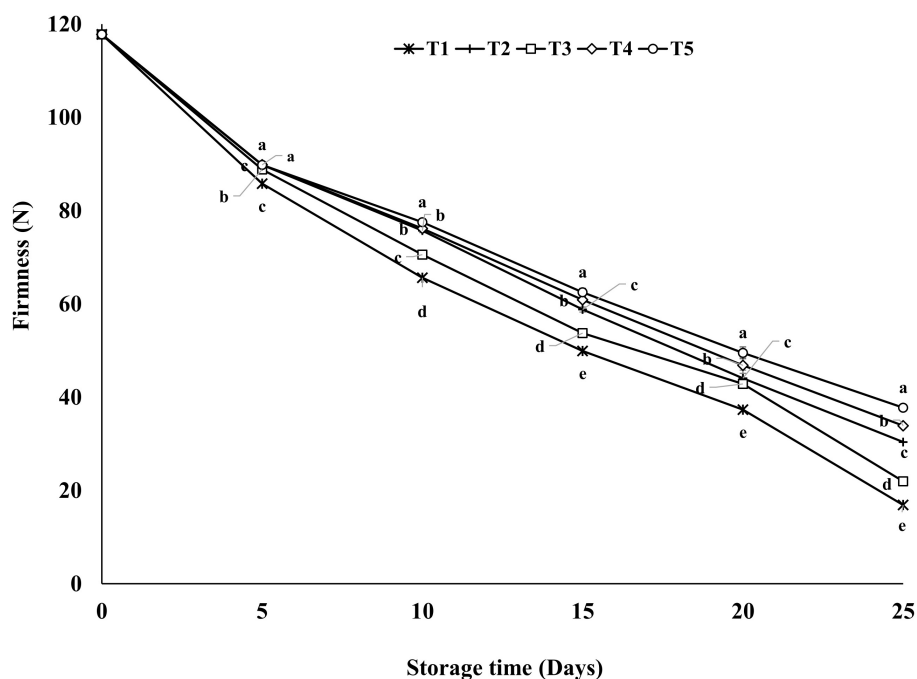


FIGURE 2

Changes in mango firmness under different treatments during 25 days of storage at 10 °C. Different letters within the same day indicate significant differences among treatments ($p < 0.05$). Treatments were defined as: T1 (control), T2 (commercial coating), T3 (alginate), T4 (alginate + 0.5% MSE), and T5 (alginate + 1% MSE). Vertical bars represent the standard deviation.

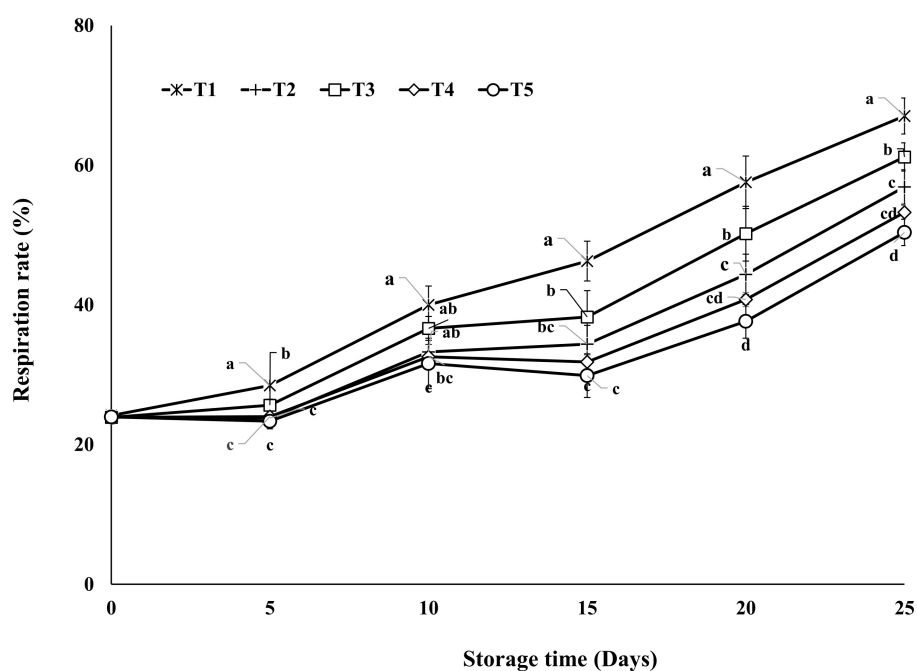


FIGURE 3

Changes in the respiration rate of mangoes under different treatments during 25 days of storage at 10 °C. Different letters within the same day indicate significant differences among treatments ($p < 0.05$). Treatments were defined as: T1 (control), T2 (commercial coating), T3 (alginate), T4 (alginate + 0.5% MSE), and T5 (alginate + 1% MSE). Vertical bars represent the standard deviation.

the control treatment exhibited the highest respiration rate, with a value of $67.04 \text{ ml CO}_2 \text{ kg}^{-1} \text{ h}^{-1}$.

The reduced respiratory activity observed in treatments T4 and T5 aligns with the findings of Medina-Jaramillo et al. (2020),

who reported that films based on polysaccharides and polyphenolic extracts enhance the skin's resistance to gas diffusion. This is attributed to the formation of denser polymeric networks, stabilized through hydrogen bonding, which results in coatings with lower

gas permeability. This reduced permeability facilitates the creation of a modified internal atmosphere, characterized by relatively high concentrations of carbon dioxide and low levels of oxygen, thereby decreasing the intensity of respiratory processes (Alemu et al., 2025).

Similarly, Vázquez-Ovando et al. (2022) highlighted that the antioxidant capacity of extracts such as mango seed extract mitigates oxidative stress and modulates respiratory metabolism in climacteric fruits, thereby reducing the respiration rate in fruits like mangoes. Collectively, these findings demonstrate that the alginate coating enhanced with mango seed extract not only acts as a physical barrier to gas exchange but also contributes to the physiological modulation of fruit respiration. This dual function is crucial for delaying the progression of ripening and preserving the quality of mangoes.

3.5 Changes in physicochemical parameters during storage

All treatments presented the same initial physicochemical characteristics at day 0, including total soluble solids (8.21 ± 0.06 °Brix), pH (3.34 ± 0.012), titratable acidity (1.44 ± 0.010), color change, and color parameters (L^* : 42.71 ± 0.03 , a^* : -4.96 ± 0.09 , b^* : 22.67 ± 0.07). Therefore, these values are not shown in Table 2 to avoid redundancy.

3.5.1 Effect of total soluble solids in fruits

The increase in total soluble solids (TSS) content during the fruit ripening stage is primarily attributed to hydrolytic processes that lead to the degradation of complex polysaccharides into soluble simple sugars. These sugars are the main components measured in the determination of TSS, making it a key parameter in the study of the ripening of climacteric fruits such as mangoes (Hernández-Guerrero et al., 2020). The results obtained for TSS determination showed a significant difference ($p < 0.05$) among treatments after 25 days of storage, as presented in Table 2. According to these results, the control treatment T1 exhibited a higher TSS content of 18.78 ± 0.10 °Brix, indicating more accelerated ripening due to the absence of a barrier to reduce the fruit's respiration rate.

In contrast, treatment T5 exhibited the lowest TSS content (16.51 ± 0.18 °Brix), underscoring its effectiveness in reducing the respiration rate. This is attributed to the alginate matrix acting as a semipermeable barrier, combined with the phenolic compounds from mango seed extract, which help regulate oxidative metabolism. Moqbeli et al. (2025) demonstrated that coatings with chitosan and plant extracts showed a TSS content of 16.08 °Brix compared to the control, which had a value of 19.63 °Brix. Similar results have been found in natural edible coatings made with plant extracts rich in polyphenolic compounds.

The commercial treatment T2 also exhibited a lower total soluble solids (TSS) content compared to T1, albeit with less efficacy than T5. This outcome aligns with various studies that have investigated edible coatings composed solely of impermeable

matrices. For instance, the findings of Daisy et al. (2020) utilized gum arabic as a matrix, which reduced TSS in mangoes compared to the control but did not demonstrate additional bioactive effects that can occur in synergy with plant extracts. Although T2 shows a lower TSS value than the control T1, T5 stands out for its efficacy and potential in natural edible coatings due to its inclusion of mango seed extract as a source of polyphenolic compounds. It also demonstrates an extended preservation period for mangoes with reduced total soluble solids (TSS), indicating a lower ripening stage and consequently a prolonged postharvest phase. This finding is consistent with studies conducted by Kumar et al. (2024), in which control mangoes exhibited an increase in TSS (14.02 °Brix) compared to the xanthan gum treatment with pomegranate peel extract, which showed a lower TSS value (10.48 °Brix).

3.5.2 Effect of treatments on pH

The pH levels among the applied treatments exhibited a significant difference ($p < 0.05$), as shown in Table 2. Treatment T5 displayed the lowest pH values (4.11), which can be attributed to the combined action of the alginate polysaccharide matrix and the 1% mango seed phenolic extract. Treatment T2 achieved the second lowest pH at 4.16, likely due to its polyethylene wax composition that reduces the respiration rate. However, it is not as effective as T5, which contains a phenolic extract that resulted in a pH of 4.11, compared to the control T1, which had a higher pH value (4.61), associated with accelerated ripening in the absence of the coating. These findings are consistent with those reported by El-Ashaal et al. (2025), who evaluated the effect of a chitosan matrix with mango seed extract applied to strawberries stored at 4°C for 21 days, and found that the coated fruits exhibited the lowest pH values (3.74 and 3.84).

Conversely, Daisy et al. (2020) investigated the effect of an arabic gum matrix (0, 10, 15, and 20%) applied to mangoes, which successfully reduced the increase in pH and enhanced titratable acidity. This outcome is attributed to the matrix's ability to modify the atmosphere surrounding the fruit, forming a semipermeable barrier that regulates gas and moisture transport. This regulation effectively slows the early development of organic acids, resulting in fruit with a lower pH. From a physiological perspective, there is a significant relationship between pH and titratable acidity, as an increase in pH and a progressive decrease in titratable acidity are characteristic processes of postharvest ripening (Liu et al., 2023). This relationship has been demonstrated in the present study.

3.5.3 Effect of treatments on titratable acidity

The determination of titratable acidity in fruits is primarily attributed to citric acid content, as it is considered the dominant acid in mangoes (Maldonado-Celis et al., 2019). According to Anthon et al. (2011), acidity is a crucial factor during the storage process, as its preservation is essential for enhancing fruit quality in the postharvest stage. Table 2 shows a progressive decrease in all treatments during storage, a characteristic behavior of the ripening process in climacteric fruits like mangoes, primarily due to the consumption of organic acids as respiratory substrates

TABLE 2 Determination of total soluble solids (TSS), pH, titratable acidity (TA, %), and total color difference (ΔE) in mangoes stored for 25 days at 10 °C.

Treatment	Storage time (days)				
	5	10	15	20	25
	Total soluble solids (°Brix)				
T1	9.80 ± 0.09 ^a	12.14 ± 0.07 ^a	15.17 ± 0.15 ^a	17.83 ± 0.21 ^a	18.78 ± 0.10 ^a
T2	9.20 ± 0.09 ^c	10.47 ± 0.15 ^c	12.70 ± 0.08 ^c	15.12 ± 0.20 ^c	17.56 ± 0.13 ^c
T3	9.44 ± 0.05 ^b	11.03 ± 0.08 ^b	13.89 ± 0.13 ^b	16.02 ± 0.12 ^b	18.11 ± 0.11 ^b
T4	9.27 ± 0.10 ^c	10.60 ± 0.07 ^c	12.47 ± 0.11 ^d	14.57 ± 0.27 ^d	17.21 ± 0.06 ^d
T5	9.22 ± 0.08 ^c	10.26 ± 0.11 ^d	12.12 ± 0.14 ^e	14.33 ± 0.19 ^d	16.51 ± 0.18 ^e
	pH				
T1	3.51 ± 0.01 ^a	3.80 ± 0.01 ^a	3.93 ± 0.01 ^a	4.16 ± 0.02 ^a	4.61 ± 0.01 ^a
T2	3.42 ± 0.01 ^b	3.51 ± 0.01 ^d	3.61 ± 0.01 ^d	3.78 ± 0.01 ^e	4.16 ± 0.01 ^e
T3	3.44 ± 0.01 ^a	3.64 ± 0.01 ^b	3.75 ± 0.02 ^b	3.93 ± 0.01 ^b	4.36 ± 0.01 ^b
T4	3.42 ± 0.01 ^b	3.52 ± 0.01 ^c	3.62 ± 0.02 ^{cd}	3.84 ± 0.01 ^d	4.22 ± 0.01 ^c
T5	3.41 ± 0.01 ^b	3.51 ± 0.01 ^{cd}	3.59 ± 0.02 ^c	3.72 ± 0.01 ^c	4.11 ± 0.01 ^d
	Titratable acidity (%)				
T1	1.10 ± 0.01 ^d	0.90 ± 0.01 ^e	0.71 ± 0.02 ^c	0.48 ± 0.01 ^d	0.29 ± 0.01 ^d
T2	1.26 ± 0.01 ^a	1.14 ± 0.01 ^a	0.96 ± 0.02 ^a	0.85 ± 0.02 ^a	0.68 ± 0.02 ^a
T3	1.15 ± 0.01 ^c	0.98 ± 0.01 ^d	0.77 ± 0.02 ^b	0.69 ± 0.02 ^c	0.46 ± 0.01 ^c
T4	1.25 ± 0.01 ^{ab}	1.09 ± 0.01 ^c	0.95 ± 0.01 ^a	0.80 ± 0.03 ^b	0.62 ± 0.02 ^b
T5	1.25 ± 0.01 ^a	1.11 ± 0.01 ^b	0.95 ± 0.01 ^a	0.84 ± 0.02 ^a	0.67 ± 0.01 ^a
	Lightness (L*)				
T1	48.33 ± 0.45 ^a	55.60 ± 0.41 ^a	62.35 ± 0.48 ^a	69.89 ± 0.36 ^a	74.70 ± 0.60 ^a
T2	45.59 ± 0.30 ^d	50.32 ± 0.38 ^d	54.79 ± 0.26 ^e	63.00 ± 0.20 ^e	66.10 ± 0.65 ^d
T3	46.71 ± 0.57 ^b	52.20 ± 0.47 ^b	58.86 ± 0.27 ^b	66.40 ± 0.44 ^b	70.44 ± 0.39 ^b
T4	45.11 ± 0.37 ^{cd}	50.63 ± 0.43 ^c	55.01 ± 0.31 ^d	64.01 ± 0.20 ^d	67.95 ± 0.38 ^c
T5	45.00 ± 0.41 ^c	49.00 ± 0.85 ^c	54.59 ± 0.38 ^c	61.91 ± 0.40 ^c	65.02 ± 0.51 ^e
	a*				
T1	−1.29 ± 0.02 ^a	3.57 ± 0.06 ^a	6.97 ± 0.069 ^a	11.73 ± 0.15 ^a	15.84 ± 0.34 ^a
T2	−2.97 ± 0.05 ^d	1.31 ± 0.04 ^d	4.08 ± 0.051 ^d	7.83 ± 0.21 ^d	11.02 ± 0.26 ^d
T3	−2.22 ± 0.04 ^b	2.24 ± 0.07 ^b	5.62 ± 0.043 ^b	10.17 ± 0.13 ^b	13.06 ± 0.20 ^b
T4	−3.00 ± 0.06 ^c	1.80 ± 0.02 ^c	4.89 ± 0.043 ^c	8.82 ± 0.17 ^c	11.88 ± 0.18 ^c
T5	−3.48 ± 0.05 ^c	0.84 ± 0.03 ^e	3.07 ± 0.03 ^e	6.61 ± 0.32 ^e	10.73 ± 0.37 ^d
	b*				
T1	24.92 ± 0.07 ^a	29.83 ± 0.16 ^a	31.86 ± 0.21 ^a	36.89 ± 0.18 ^a	40.68 ± 0.84 ^a
T2	24.13 ± 0.09 ^d	26.92 ± 0.12 ^d	30.50 ± 0.10 ^b	34.66 ± 0.19 ^c	38.01 ± 0.88 ^c
T3	24.45 ± 0.12 ^c	28.65 ± 0.20 ^b	31.81 ± 0.16 ^a	35.96 ± 0.12 ^b	39.30 ± 1.16 ^b
T4	24.36 ± 0.09 ^c	26.98 ± 0.09 ^d	29.98 ± 0.10 ^c	34.39 ± 0.27 ^c	37.05 ± 0.87 ^{cd}
T5	24.52 ± 0.11 ^b	27.22 ± 0.11 ^c	28.81 ± 0.19 ^d	32.87 ± 0.20 ^d	36.08 ± 0.76 ^d
	Total color difference (ΔE)				
T1	7.07 ± 0.36 ^a	10.23 ± 0.13 ^a	17.87 ± 0.47 ^a	28.06 ± 0.29 ^a	35.36 ± 0.54 ^a
T2	3.79 ± 0.27 ^c	3.97 ± 0.14 ^d	10.93 ± 0.20 ^d	20.01 ± 0.20 ^d	25.46 ± 0.56 ^b
T3	5.17 ± 0.45 ^b	6.49 ± 0.19 ^b	14.53 ± 0.28 ^b	24.25 ± 0.38 ^b	30.23 ± 0.63 ^c
T4	3.54 ± 0.23 ^{cd}	4.49 ± 0.19 ^c	11.97 ± 0.25 ^c	21.1 ± 0.17 ^c	26.68 ± 0.34 ^d
T5	3.31 ± 0.31 ^d	3.48 ± 0.12 ^e	8.75 ± 0.29 ^e	17.79 ± 0.36 ^e	23.59 ± 0.62 ^e

Results were presented as mean ± standard deviation. Mean values in the same column followed by different letters indicate significant differences ($p < 0.05$) from lowest to highest in alphabetical order.

Treatments were defined as: T1 (control), T2 (commercial coating), T3 (alginate), T4 (alginate + 0.5% MSE), and T5 (alginate + 1% MSE).

The symbol * refers to the CIE L*a*b* color space.

(Bashir et al., 2023). However, a significant difference was observed between treatments ($p < 0.05$), particularly on the 25th day of storage. Treatments T5 and T2 exhibited considerably higher titratable acidity levels, at 0.67% and 0.68%, respectively. This indicates that treatment T5 performs similarly to T2, reflecting better efficacy in preserving organic acids compared to the other treatments.

The preservation of titratable acidity through the use of a natural coating enhanced with mango seed can be primarily explained by its physical and metabolic actions. These coatings act as semipermeable barriers, reducing respiratory metabolism and, consequently, the degradation or consumption of organic acids as energy substrates. The results presented are consistent with the findings of Ehteshami et al. (2022), who demonstrated that the application of an alginate coating enhanced with phenolic extracts can improve the preservation of quality parameters, such as titratable acidity, in mangoes during storage. This contributes to maintaining higher acidity levels compared to untreated controls.

Similarly, a study conducted by Silva et al. (2018) reported that polysaccharide-based coatings, such as those made from alginate and pectin enhanced with citric acid, modulate changes in titratable acidity in fruits like mango, maintaining stable values compared to other treatments. In contrast, Parvin et al. (2023) demonstrated that the use of a chitosan-based coating resulted in higher titratable acidity levels than untreated samples across various storage conditions. These findings suggest that the titratable acidity results confirm that T5 represents a natural alternative comparable to commercial coatings (T2), with potential applications in the post-harvest preservation of Kent variety mangoes.

3.5.4 Effect of treatments on total color difference (ΔE) of fruit

The pulp color is one of the most critical indicators in assessing the maturity and internal quality of mangoes, as it is closely linked to their sensory and chemical properties (Vu et al., 2023). During ripening, the pulp develops yellow-orange hues, which allows for a more objective and reliable estimation of the fruit's maturity and suitability for consumption. However, changes in the skin color of Kent variety mangoes do not always correlate with physiological maturity or internal quality. Therefore, determining the pulp color serves as a more objective and reliable indicator (Liang et al., 2020).

Table 2 presents total color difference (ΔE) of mango pulp, showing a gradual increase across all treatments throughout the storage period. From day 10 of storage, a significant difference between treatments was observed ($p < 0.05$), with treatment T5 consistently exhibiting the lowest values, reaching a value of 23.59 by day 25 of storage, compared to 35.36 for the control T1 and other treatments. The superior performance of T5 can be attributed to the synergistic effect between the polysaccharide matrix of alginate and the phenolic compounds in mango seed extract. Numerous studies have indicated that phenol-rich extracts incorporated into coatings not only enhance barrier properties but also impart antioxidant capacity. This contributes to the protection of pulp pigments,

such as carotenoids, against oxidation and enzymatic degradation processes inherent to ripening (Joseph et al., 2024).

Tacias-Pascacio et al. (2022) demonstrated that phenolic compounds in mango, such as gallic acid and chlorogenic acid, are correlated with the antioxidant activity of the pulp. This finding underscores the importance of preventing the oxidation of natural pulp pigments, such as carotenoids. This behavior explains why T5 exhibited significantly lower values than T4, indicating that an increased concentration of the extract influences the stability of the fruit's internal color. Similarly, in the case of T2, although it showed a considerable reduction in color variation, it suggests that commercial waxes based on petroleum derivatives, while delaying certain quality characteristics, do not offer an equivalent or superior level of protection in terms of color preservation (Kaushik et al., 2014).

The results presented here are similar to those reported by Nair et al. (2018), who observed that the use of an alginate-based coating enriched with pomegranate peel extract significantly reduced color variation in guavas due to the antioxidant protection of the pigments, compared to the control over a period of 20 days at 10 °C.

3.6 Effect of *in vivo* antifungal activity against *Colletotrichum gloeosporioides* in fruits

Figure 4 provides a representative depiction of the antifungal activity, illustrating the visual progression of damage caused by the phytopathogen *Colletotrichum gloeosporioides* in Kent mangoes subjected to different treatments over a 12-day incubation period. The lesion diameter caused by the phytopathogen progressively increased across all treatments as the evaluation period advanced, consistent with the infectious behavior of the fungus in climacteric fruits such as mango (Table 3). The results, evaluated on specific days, showed significant differences between treatments ($p < 0.05$), particularly from day 6 and more pronounced by day 12 of incubation. Treatments T2 and T5 exhibited the smallest lesion diameters, measuring 2.82 mm and 3.22 mm, respectively, with no statistical difference between them, demonstrating comparable efficacy in inhibiting pathogen development and significantly outperforming the control T1 (14.16 mm), T3 (11.76 mm), and T4 (7.74 mm).

The commercial control (T2) contained fludioxonil, a synthetic fungicide widely recognized for its high efficacy against postharvest fungal pathogens in mango, including stem-end rot and soft brown rot (Swart et al., 2009). Its antifungal activity is based on a specific biochemical mode of action that directly inhibits fungal growth.

In contrast, alginate-based coatings primarily function as semi-permeable barriers that regulate gas exchange and moisture loss, thereby creating conditions that may limit microbial development (Dhall, 2013). When supplemented with plant-derived extracts, these coatings may also provide additional antimicrobial effects associated with bioactive compounds such as phenolics and essential oils (Valdés et al., 2017; Hassan et al., 2018). Therefore, comparisons between T2 and the experimental treatments should be interpreted considering these fundamental

T1



T2



T3



T4



T5



0 d

3 d

6 d

9 d

12 d

FIGURE 4

Visual evolution of the damage caused by the phytopathogen *Colletotrichum gloeosporioides* in mangoes subjected to different treatments during 12 days of incubation. Treatments were defined as: T1 (control), T2 (commercial coating), T3 (alginate), T4 (alginate + 0.5% MSE), and T5 (alginate + 1% MSE).

TABLE 3 Effect of different treatments on lesion diameter (mm) in Kent mangoes inoculated with *Colletotrichum*.

Treatment	Diameter of the lesion during storage time (days)				Inhibition (%) day 12
	3	6	9	12	
T1	3.56 ± 0.13 ^a	3.58 ± 0.14 ^a	10.83 ± 0.16 ^a	14.16 ± 0.19 ^a	0.00 ± 0.00 ^a
T2	1.51 ± 0.04 ^d	1.57 ± 0.07 ^d	1.72 ± 0.05 ^d	2.82 ± 0.13 ^d	80.08 ± 0.01 ^d
T3	3.03 ± 0.10 ^b	3.16 ± 0.16 ^b	10.23 ± 0.31 ^b	11.76 ± 0.23 ^b	16.95 ± 0.02 ^b
T4	2.89 ± 0.12 ^b	2.98 ± 0.09 ^b	4.92 ± 0.19 ^c	7.74 ± 0.07 ^c	45.34 ± 0.01 ^c
T5	1.77 ± 0.07 ^c	1.85 ± 0.06 ^c	1.88 ± 0.03 ^d	3.22 ± 0.14 ^d	77.27 ± 0.01 ^d

Results are presented as mean ± standard deviation. Mean values in the same column followed by different letters indicate significant differences ($p < 0.05$) from lowest to highest in alphabetical order.
Treatments were defined as: T1 (control), T2 (commercial coating), T3 (alginate), T4 (alginate + 0.5% MSE), and T5 (alginate + 1% MSE).

differences in mechanism and technological purpose. While fludioxonil-based formulations represent the current industry standard for postharvest disease control, natural coatings are increasingly explored as more sustainable alternatives in response to concerns about chemical residues and the potential development of pathogen resistance.

The comparison between Figure 4 and Table 3 reinforces the findings, as treatments T2 and T5 clearly demonstrate a reduction in lesion progression and tissue darkening caused by the phytopathogen. This effect is consistent with the high inhibition percentages observed at day 12, where T2 and T5 reached 80.08% and 77.27% inhibition, respectively. Furthermore, Figure 4 illustrates that fruits treated with T5 preserved the green coloration of the peel, in contrast to T2, which exhibited a marked advancement in ripening, characterized by a reddish-yellow surface coloration.

This visual distinction supports the previously obtained results from quality assessments, demonstrating that, in addition to effectively inhibiting the growth of *Colletotrichum gloeosporioides*, it more effectively contributes to the preservation of the fruit's physiological state. This intervention challenges the processes associated with fruit ripening, thereby maintaining fruit quality.

Artificial inoculation is widely used in postharvest pathology to evaluate the efficacy of antifungal treatments under controlled and reproducible conditions. This methodology allows precise control of inoculum concentration, infection site, and environmental factors, thereby reducing the variability commonly observed in natural field infections. In studies on mango anthracnose caused by *Colletotrichum gloeosporioides*, artificial wound inoculation followed by the application of a conidial suspension is commonly employed to ensure uniform infection and enable reliable comparisons among treatments (Konsue et al., 2020). This approach facilitates the development of measurable lesions and allows the quantitative assessment of disease severity under standardized conditions.

Moreover, studies on mango anthracnose have shown that disease development under natural conditions is strongly influenced by environmental factors and host susceptibility, which may lead to variable infection levels in the field (Grice et al., 2023). Therefore, although artificial inoculation does not fully reproduce the epidemiological complexity of natural infections, it provides a robust and reproducible experimental model for evaluating antifungal treatments against postharvest pathogens.

The results obtained under these controlled conditions provide valuable insight into the potential effectiveness of the treatments and may indicate their capacity to reduce disease development during postharvest storage; however, further studies under semi-commercial or field conditions are necessary to confirm their performance under natural infection scenarios.

Numerous studies, including those conducted by Alañón et al. (2021), have demonstrated that mango seed extracts are rich in phenolic compounds such as chlorogenic acid, gallic acid, quercetin, rutin, and caffeic acid. These compounds exhibit antioxidant and antifungal properties, with the latter conferring fungicidal and fungistatic effects against *Colletotrichum gloeosporioides*. Additionally, it has been reported that the extract from Kent variety mango seeds contains other bioactive polyphenols, such as ferulic acid, p-coumaric acid, and quercetin, which are well-documented for their antifungal activity (Davidova et al., 2024). These metabolites primarily function by disrupting the integrity of the fungal cell wall and membrane, leading to increased permeability, leakage of intracellular components, and structural disorganization of hyphae (Khanzada et al., 2021; Esmaeili et al., 2025). Specifically, flavonoids like quercetin interfere with the biosynthesis of ergosterol, a key component of the fungal membrane (Bitencourt et al., 2013), while phenolic acids can induce intracellular oxidative stress and affect the fungal energy metabolism, thereby inhibiting conidial germination and mycelial growth (Liu et al., 2025).

Similarly, studies such as the one reported by Dorta et al. (2016) have highlighted that plant extracts, including those derived from mango seeds, not only exhibit high antioxidant capacity and substantial polyphenolic and flavonoid content but also demonstrate strong antifungal activity against pathogens such as *Colletotrichum gloeosporioides*. According to Gómez-Maldonado et al. (2020), the extract from Manila variety mango seeds showed potent antifungal activity against *Colletotrichum* spp., completely suppressing mycelial growth for 9 days, in contrast to the commercial fungicide thiabendazole, which achieved only 67.6% inhibition of mycelial growth.

Additionally, Tirado-Kulieva et al. (2021) conducted a study on mango seeds and peels, revealing significant bioactive potential due to a diverse array of phenolic compounds, such as flavonoids (epicatechins, quercetin, kaempferol), which provide antimicrobial effects against *Colletotrichum gloeosporioides*,

Sclerotinia sclerotiorum, *Fusarium oxysporum*, and *Mucor* sp. These findings position alginate coatings enriched with mango seed extract as a natural, effective, and sustainable alternative for controlling *Colletotrichum gloeosporioides* in mangoes, with considerable potential for commercial application.

Future studies could investigate antioxidant enzyme activities, such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD), to further elucidate the physiological mechanisms underlying quality preservation and antifungal resistance in coated mangoes. Evaluating these biochemical markers would provide deeper insights into how natural alginate-phenolic coatings modulate oxidative stress and contribute to maintaining postharvest fruit quality.

4 Conclusions

The findings of this study demonstrate that a 1% mango seed extract-enhanced alginate coating effectively preserves the postharvest quality of Kent mangoes during 25 days of refrigerated storage. The coating maintained key quality attributes, including firmness and reduced weight loss, and exhibited antifungal efficacy comparable to commercial coatings containing synthetic fungicides. The study was conducted under controlled laboratory conditions using a single cultivar, which may limit the generalizability of the findings. Although all experiments were performed under cold storage, the results suggest that this natural coating could also contribute to improved postharvest preservation in regions with limited refrigeration, although further studies under such conditions are required to confirm its broader applicability. By utilizing agro-industrial by-products, this approach promotes environmental sustainability and advances postharvest technologies, providing benefits for both producers and consumers.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

CS-E: Formal analysis, Funding acquisition, Investigation, Methodology, Writing – original draft, Writing – review & editing. MI: Conceptualization, Funding acquisition, Supervision, Validation, Writing – original draft, Writing – review & editing. JR-M: Conceptualization, Funding acquisition, Validation, Writing – original draft, Writing – review & editing. JV-M: Investigation,

Methodology, Writing – review & editing. MM-R: Funding acquisition, Project administration, Writing – review & editing.

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Conflict of interest

CS-E, JR-M, JV-M, and MM-R are employees of Bio Natural Solutions (BNS). These authors provided materials and general guidance; however, the experimental design, data collection, analysis, and interpretation were conducted independently by the academic authors.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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