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Development and evaluation of layer-by-layer polysaccharide based edible coatings for quality improvement of fresh-cut 'Totapuri' mango

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ABSTRACT

Purpose: The study examined the effectiveness of polysaccharide-based edible coatings enriched with citral microencapsulated in β-cyclodextrin for extending shelf-life and maintaining the quality of fresh-cut 'Totapuri' mango. **Research Method:** The sodium alginate (AG), carrageenan (CG), pectin (PT), and polycationic chitosan (CH) were applied as layer-by-layer through electrostatic deposition and single layer. The changes in quality properties of coated and uncoated fresh-cut 'Totapuri' mango were evaluated during 18 days of storage period at 5°C. Physicochemical properties like colour change, firmness, weight loss, carotenoids, vitamin C and phenolics were measured. Sensory characteristics such as color, taste, texture and odor were evaluated. Additionally, enzymatic activities of polygalacturonase, peroxidase, polyphenol oxidase and phenylalanine ammonia-lyase were evaluated and microbial growth was examined to check for contamination during storage. **Findings:** The application of AG and CH as single layer and layer-by-layer coatings especially AG+CH and CG+CH better maintained chroma (C), hue angle (h°), and lightness (L*), slowed down firmness and weight loss, retained carotenoids, vitamin C and phenolics as compared to single-layered and uncoated fresh-cut mango. Furthermore, layer-by-layer coatings of CH+AG and CH+CG reduced enzymatic activities of polygalacturonase (PG), peroxidase (POX), polyphenol oxidase (PPO) and phenylalanine ammonia-lyase (PAL) and prevented microbial growth during 18 days of storage at 5°C. The application of alginate and chitosan as single-layered and layer-by-layer on fresh-cut 'Totapuri' scored the highest overall consumer acceptability when compared to other coating treatments. **Research limitations:** There were no limitations. **Originality/Value:** The study suggest that application of AG and CH as single layer and layer-by-layer polysaccharide-based edible coating of CH+AG and CH+CG are effective and safe method of preserving the quality and extending the shelf-life of fresh-cut 'Totapuri' mango for 18 days at 5°C.

Keywords:
Antimicrobial, Microencapsulated, Polysaccharide, Shelf life, Storage

INTRODUCTION

Mango (*Mangifera indica* L.), widely regarded as 'King of fruit', is cultivated across tropical and subtropical regions worldwide owing to its distinctive flavor and high nutritional value. In recent years, as lifestyle becomes busier, consumers' strived for a healthier diet that is rich in antioxidants and ready-to-use. Minimally processed products of fruits and vegetables are value-added commodities that offer convenience and versatility. However, the fresh-cut products of mangoes undergo the rapid loss of water and flavor, surface browning, softening, and microbial growth on account of minimal processing during storage as shown in multiple studies (Sharma & Rao, 2017; Ullah et al., 2025).

Edible coatings can modulate gaseous and moisture exchange by forming a semipermeable barrier on cut fruits thereby delaying the deterioration. Layer-by-layer (LbL) electrodeposition is gaining considerable importance; fresh-cut fruits are alternately dipped in coating formulation with oppositely charged polyelectrolytes followed by drying steps after every dipping. The electrostatic force created due to charge alteration help to develop a thin multilayer coating over the cut fruit (McClements et al., 2009). Common polysaccharides used in such coatings include, the applications of starch, alginate, pectin, cellulose, pullulan, carrageenan, gellan gum, xanthan gum and chitosan (Salehi, 2020). These materials, especially Alginate, carrageenan, and pectin are anionic polymers and can form strong gels or insoluble polymers through cross-linking with a cationic chitosan solution.

Layer-by-layer edible coatings have preserved the quality attributes of fresh-cut fruits; fresh-cut melon (Poverenov et al., 2014) and pineapple using combination of chitosan, pullulan, and mucilage (Trevino-Garza et al., 2017). To further ensure microbial safety, the development of multifunctional edible coating formulation in terms of antimicrobial and antioxidant properties is one of the most advanced methods to be employed for extending the commercial shelf-life of minimally processed fruits.

Citral, chemically known as 3, 7-dimethyl-2, 6-octadienal, is a key constituent of lemongrass **(***Cymbopogon citrates***)** oil**.** The application of edible coatings enriched with citral has demonstrated its ability in the quality retention of citrus fruit **(**Fan et al**.,** 2014**)** and raspberry (Guerreiro et al., 2015). However, citral's volatility and low water solubility limit its direct use. Microencapsulation—such as entrapping citral in β-cyclodextrin—helps stabilize and control the release of such hydrophobic compounds (Gonzalez-Aguilar et al., 2010). Encapsulation enhances their stability and simplifies maintenance, thus preventing them from direct exposure to the atmospheric adverse conditions like high moisture, temperature, etc. β-Cyclodextrin is a naturally occurring cyclic oligosaccharide consisting of seven glucopyranose units. Its torus-shaped ring structure characterized by hydrophobic cavity and hydrophilic outer shell makes it a unique molecule to incorporate hydrophobic components into its cavity. The inclusion complexes develop through host-guest interaction enhances solubility and diffusivity of guest molecules. Multilayered edible coatings enriched with microencapsulated antimicrobial complex prevent the decay of fresh-cut fruit and enhance the efficacy of active agents through their control release (Ghidelli & Perez-Gago, 2018). Due to their ability to act multi-functionally, previous studies have documented the influence of multilayer antimicrobial edible coatings on many fresh-cut fruits. Multilayer coatings developed by chitosan with β-cyclodextrin + transcinnamldehyde complex and pectin were effective on fresh-cut cantaloupe up to 9 days at 4°C (Martinon et al., 2014). Similarly, multilayer coatings made up of alginate, chitosan, pectin, and β-cyclodextrin + transcinnamldehyde complex were also contributed to maintain the quality of fresh-cut pineapple (Mantilla et al., 2013) and fresh-cut papaya (Brasil et al., 2012).

Due to increased demand for fresh-cut fruits and vegetables among consumers, identifying cost-effective, sustainable preservation methods is essential. Our earlier work demonstrated that the fresh-cut 'Totapuri' mango shelf-life was extended up to 8 and 4 days at 5°C and 10°C respectively, as compared to the fresh-cut products of the other mango cultivars tested. The current study aims to decipher single and multilayer polysaccharide-based edible coatings incorporating citral microencapsulated complex (citral in β-cyclodextrin) for their ability to enhance the quality and storability of the fresh-cut 'Totapuri' mango.

MATERIALS AND METHODS

Procurement of Fruit

The fruit of mango (cv. Totapuri) were harvested from a farm in Karamsad of District Anand, Gujarat, India during their growing season. Fruits were brought to the laboratory within 2 h and washed under running tap water, then sanitized by immersion in 0.2 mL L^{-1} sodium hypochlorite solution (pH 6.5) at 25°C for 10-15 min and rinsed with distilled water. The mangoes were precooled to 20±2°C and held until further processing.

Preparation of microcapsules

An inclusion complex of citral encapsulated in β-cyclodextrin (β-CD) was produced using a modified version of the precipitation technique of Bhandari et al. (1998). β-cyclodextrin (25 g) was dissolved in 250 mL of an ethanol/water (1:2) mixture by stirring on a magnetic stirrer at 55°C until a clear solution was obtained. Meanwhile 10mL of Citral was dissolved in ethanol (10% w/v) and gradually introduced in to the warm β-cyclodextrin solution. Afterward the mixture was stirred for the next 4 h at room temperature. The final solution was refrigerated overnight at 4°C to induce precipitation. The cold precipitated citral: β-CD microcapsules were then centrifuged at 12,500 g for 30 min at 4°C. The precipitate was dried in a desiccator for 24 h and stored in airtight at 4°C.

Preparation of edible coating formulations

Sodium alginate-based edible coating **(**AG**)** was prepared according to the method described by Azarakhsh et al. (2012). Sodium alginate powder **(**1**.**29%, w/v**)** was dissolved at 70°C in distilled water, adding Glycerol **(**1.18%, w/v**)** and olive oil **(**0.1%, v/v**)** and stirred on magnetic stirrer**.** To prepare a chitosan-based coating solution **(**CH**)** Chitosan powder with 90% deacetylation was added at the concentration of 1% **(**w/v**)** in an aqueous solution of acetic acid **(**pH 5**)** at 45°C. Carrageenan coating solution **(**CG**) (**1%, w/v**)** was prepared in distilled water and glycerol was added at the concentration of 0.75 g/g carrageenan. Pectin-based edible coating solution **(**PT**)** (1%, w/v) was prepared by dissolving 5 g of citrus pectin in 500 mL of warm distilled water until the solution cleaned. To impart antimicrobial properties citral**:** β-CD microcapsules **(**0.1%, w/v**)** were added to each coating solutions**.** Calcium propionate (2%) was used as a firming agent**.**

Edible coating application

Minimal processing of 'Totapuri' fruits was started on the second day of harvesting by manual peeling with sterilized sharp stainless steel peeler and cut longitudinally into a 4-6 finger-let like fashion of 1.0-1.5 cm thick from each half of fruit following the flat side of the seed. Edible coating treatments were given by dipping method of fresh-cut 'Totapuri' into each solution for 2 min followed by drip off step for 2 min before submerging these pre-coated cut fruits into subsequent coating solutions. Single layered of edible coatings were

created by first dipping into 2% calcium propionate solution and then into AG, CH, CG, and PT coating solutions enriched with antimicrobial citral : β-CD microcapsules. For, layer-by-layer coating application, similar steps as taken for single layer edible coating application was followed by second dipping in CH coating solution. Samples dipped into sterile distilled water for the same duration were set as control. After proper drying of edible coatings, 250 g finger-lets were packaged into food-grade clamshell and stored at 5±1°C. The physiological and biochemical analysis was performed at the interval of 6 days up to 18 days of storage time.

Determination of quality attributes

Color

The changes in color of fresh-cut mango slices during storage were evaluated following the procedure of Papadakis et al. (2000) using a digital camera **(**FinePix S2950, FUJIFILM, Japan**)** and Adobe Photoshop CS 8.0 software **(**Adobe System, Inc**.** San Jose, CA, USA**).** Specifically, the L* (lightness), a* (green–red axis), and b* (blue–yellow axis) values were sampled at multiple points across each fruit image. From these, hue (h°) and chroma (C*) were calculated using the standard transformations according to the formula (1) and (2), respectively.

$$\text{Hue angle}(h°) = \tan^{-1} b*/a* \quad (1)$$

$$\text{Chroma } (C) = \sqrt{a^{*2} + b^{*2}} \quad (2)$$

Firmness

Fruit firmness was assessed using pressure tester **(**FT-327, FACCHINI Srl, Alfonsine, Italy**)** fitted with a flat-bottomed probe of 11 mm diameter. The probe was inserted 5 mm into the mango flesh and the force required to achieve penetration was expressed in terms of Newton **(**N**).**

Weight loss percentage (WLP)

Mango slices **(**50 g**)** from each replicate were placed in previously tarred petri-dish. They were then dried in an oven at 70°C for 48 h. After cooling down in a desiccator to room temperature, the weight was recorded using an analytical balance **(**Shimadzu BW 380 H, Tokyo, Japan). Weight loss was calculated using the formula (3):

$$\text{Weight loss } (\%) = \{(\text{Initial Weight} - \text{Final Weight})/\text{ Initial Weight}\} \times 100 \quad (3)$$

Total soluble solids (TSS), pH, and titratable acidity (TA)

TSS and pH of the fruit were measured at 25°C using a digital refractometer (Atago, Japan) and a pH meter (Elico LI 120 pH Meter), respectively (Moradinezhad et al., 2008). TA was determined by using titration with 0.1 N NaOH up to pH of 8.1 using 10 mL of diluted juice prepared from homogenizing 1 gm tissue in 10 mL distilled water (Ranjbari et al., 2018). TA as expressed as % citric acid per gm fresh weight.

Ascorbic acid (AA)

Ascorbic acid was determined according to the procedure of Roe and Oesterling (1944). Fruit tissue was extracted with (5%) metaphosphoric acid in glacial acetic acid, and then centrifuged for 10 min at 5000 rpm. The resulting supernatant was reacted with 0.2 g L^{-1} 2, 4-dinitrophenyl hydrazine, and 10 µL of 100 g L^{-1}thiourea for 3 h at 37°C to form orange-red osazone crystals. After adding 5 mL of 85% sulphuric acid, the absorbance was measured at 540 nm. Concentrations were calculated against a calibration curve and expressed in a gram of ascorbic acid per kilogram of fresh weight (g kg^{-1}).

Carotenoids

Carotenoids were determined as per the procedure given by Wang et al. (2005). Two g of sample was extracted with 5 ml of hexane: acetone mixture (60:40) on ice. The upper organic layer was transferred into a tube and residual was re-extracted with until the aqueous layer becomes colourless. The extract was filtered and absorbance was measured using spectrophotometer at 450 nm.

Phenolic

Five grams of fruit tissue was homogenized in 50 mL of methanol and centrifuged at 10,621 ×g for 15 min at 4°C**.** Phenolic was determined by Lim et al. (2006). 0**.**2 mL of supernatant was mixed with 10 fold diluted 1**.**5 mL of Folin-Ciocalteu**'**s reagent and 1**.**2 mL of sodium carbonate **(**7**.**5**%**, w/v**).** After vortexing, samples were incubated in dark for 30 min at room temperature**.** Absorbance at 765 nm was measured and results were expressed as grams of gallic acid equivalents **(**GAE**)** per kilogram of fresh weight**.**

Malondialdehyde (MDA) and Hydrogen peroxide content (H_2O_2)

One gram of fresh cut mango was homogenized in a 10 mL of chilled 0.1% TCA for determination of MDA and H_2O_2 content, according to the method described by Velikova et al**. (**2000**).** The homogenate was centrifuged at 12,000 × g for 15 min at 4 °C. For MDA, 0.5 mL of the supernatant was mixed to 1 mL of 0.5% TBA prepared in 20% TCA, boiled for 30 min, and the reaction stopped at 0 °C for 10 min. Absorbance at 532 nm was measured using a UV–visible spectrophotometer (Shimadzu, UV-160A). MDA levels were calculated from the extinction coefficient 1.55 mmol L^{-1} m^{-1}.

For the H_2O_2 assay, 0.5 mL of supernatant was combined with 0.5 mL of 10 mmol L^{-1} potassium phosphate buffers **(**pH 7.0**)** and 1**.**0 mL of 1**.**0 mol L^{-1} KI, incubation for 30 min at room temperature. Absorbance was measured at 390 nm using a UV–visible spectrophotometer (Shimadzu, UV-160A) was used to calibration curve obtained with H_2O_2 standard solutions, and the results was expressed in terms of micrograms per kilograms of fresh weight**.**

Enzymes activity

Polygalacturonase (PG) activity

5 g of fruit tissue was extracted in 20 mL 0.1mol L^{-1} sodium citrate, pH 4.6, containing 1mol L^{-1} sodium chloride (NaCl), 13mmol L^{-1} ethylene diamine tetra acetic acid (EDTA), 10 mM β-mercaptoethanol, and 2% (w/v) soluble polyvinyl pyrrolidone (PVP-40), incubated for 30 min with occasional stirring and finally centrifuged at 15000 × *g* for 30 minutes at 4°C.

Enzyme activity was assayed in a 1 mL reaction containing 0.2 mL acetate buffer (0.2 mol L^{-1}, pH 4.5), 0.1 mL NaCl (0.2 mol L^{-1}), 0.3 mL polygalacturonic acid (1% solution, pH 4.5), and 50 µL enzyme extract. After 1 hour at 37 °C, the reaction was stopped by boiling, and the amount of reducing sugars released (as galacturonic acid) was measured. One unit of PG activity corresponds to the release of 1 µmol reducing group per minute at 37 °C (Srivastava & Dwivedi, 2000).

Polyphenol oxidase (PPO) and Peroxidase (POX) activity

Two grams of the mango was homogenized with 25 mL of 0.1 mol L^{-1} sodium phosphate buffer (pH 6.5) and centrifuged for 30 min at 20,627 × g for PPO and 29,703 × g for POX at 4 °C. PPO activity was assayed according to the method of Zhu and Zhan **(**2010**)**, for which 0.1 mL enzyme extract was reacted with 2.5 mL of catechol (0.5 mol L^{-1}), and change in

absorbance was recorded at 420 nm at the interval of 30 s. Activity was expressed in katals per kilogram of protein.

POX activity was assayed by the method described by Mazumdar and Majumder **(**2003**).** Ortho-dianisidine and hydrogen peroxide were incubated at 30 °C for 5 min and the reaction was stopped by addition of sulphuric acid, absorbance was measured at 430 nm and expressed in katals per kilogram of protein.

Phenylalanine ammonia-lyase (PAL) activity

The PAL activity was determined as described by Malik and Singh **(**1980**)**. Briefly, one gr of tissue was extracted in 0.1 mol L^{-1} sodium borate buffer (pH 8.8), centrifuged at 19,250 × g for 20 min at 4°C. Enzyme assay comprises 0.2 mL L-phenylalanine (0.1 mol L^{-1}) and 3.2 mL of sodium borate buffer (0.1 mol L^{-1}, pH 8.8), and 0.2 mL enzyme extract at 37 °C for 2 h. Activity was measured at 290 nm and the result was expressed in katals per kilogram of protein.

Sensory evaluation

At the end of storage samples of fresh-cut mango were allowed to equilibrate at room temperature before sensory testing by method described by Rocha et al. (2007). All the samples were randomly presented to twenty non-trained panelists consisting of laboratory research scholars and graduate students. All the attributes were judged and a rating using a 9 points hedonic scale: (9 = excellent and 1 = poor).

Microbiological analysis

Microbial growth was assessed at 0, 12, and 18 days of storage period. Mango slices (10 g) were vigorously washed with 90 mL of aseptic sterile buffered peptone water (1 g L^{-1}) under aseptic conditions. Serial dilutions were prepared and plated using spread plating method. Total aerobic mesophilic bacteria were counted on Plate Count Agar, incubated at 35 °C for 48 hours; yeasts and molds were enumerated on Potato Dextrose Agar (PDA) with 0.05 g L^{-1} chloramphenicol, incubated at 21 °C for 5–7 days, following International Commission on Microbiological Specifications for Foods (1978). Results were expressed as log CFU g^{-1} FW.

Statistical analysis

A completely randomized design with three replications was employed sampling three clamshells per treatment at each time point. Statistical analysis was performed using GraphPad Prism software version 3 (GraphPad Software, Inc, San Diego, USA). Values are expressed as mean ± standard deviation. Analysis of Variance (ANOVA) followed by Turkey's multiple comparisons posthoc tests was employed to assess the statistical differences among means at the level of 0.05.

RESULTS AND DISCUSSION

Changes in Color

The effect of given treatments on the color attributes of fresh-cut mango is summarized in Figure 1. The color parameters *L**, *h*° and C of fresh-cut mangoes at 0 days were 62.00±0.98, 88.54±0.25, and 46.01±4.25 units. Over 18 days, uncoated slices experienced a ~15-unit drop in L*, compared to a more limited 3–11-point decline in coated samples (Fig. 1a). Since lower L* indicates browning—linked to pigment changes—coatings, especially AG and AG+CH, effectively slowed lightness loss ($p < 0.05$). The decline of *L** value is an indication of flesh browning in fresh-cut mangoes. The result regarding the change in *h*° decreased from 88.54 to

73.41 units for uncoated fresh-cut mango while it ranged from 76.60 – 83.33 units for coated samples after 18 days of storage. A decline in L* is associated with enzymatic browning, primarily due to PPO and POX-mediated oxidation of phenolics to brown melanins (Hssaini, 2025). Coated mangoes have greater *h*° than the control samples, though significant variation ($p<0.05$) existed among various coatings. In mango, the rise in *a** reflects that the flesh turning more red/orange and higher *b** more yellow (Gonzalez-Aguilar et al., 2000). Thus, a decline in *h*° value indicates the turning of flesh yellowness to orange or red for both treated and control fruits. This rise in the redness may be the consequence of high rate of respiration and metabolic activity in control samples. A decline in h° reflects chlorophyll degradation and carotenoid accumulation. Lower rates of decline in coated fruits suggest delayed pigment degradation due to reduced respiration and ethylene action. Among the studied treatments, CH+CG coated mangoes have better retained the *h*° value (83.33 units) at end of storage time (Fig. 1b). Chroma (C) values, exhibited a decreasing trend with the advance of storage time (Fig. 1c). The uncoated samples displayed the least *C* (19.84±0.73), whereas AG+CH and CG+CH samples have maintained the highest *C* (~33) by 18 days of storage. The color attributes of mangoes is an important quality determining traits to the consumers, the result reveals that the layer-by-layer antimicrobial edible coatings did not effects the original color and able to maintain *L**, *h*°, and chroma *C* during 18 days of storage period.

Changes in firmness and weight loss percentage (WLP)

Fruit firmness is an important quality and ripening index and therefore can be a shelf-life determinant of fresh-cut fruit and a crucial parameter that influences the consumer acceptability of fresh produce (Nguyen & Nguyen, 2021). Table 1 represented the significant ($p<0.05$) decline ($p<0.05$) in firmness of coated and uncoated fresh-cut mango during the storage period of 18 days. The loss of firmness (~91%) which is a higher value for uncoated samples in contrast with that of its initial value. However, the extent of firmness loss was found varied among coated samples. The least decline (~35%) in firmness was recorded in AG, CH and CH+AG coated mangoes up to 12 days of storage. On 18 days, it values enhanced significantly ($p<0.05$) in control fruits, whereas coated samples retained approx. 10 - 30% higher firmness. In contrast, multilayer coatings, particularly CH+AG and CH+CG, significantly delayed texture softening and moisture loss throughout the storage period of 18 days as compared to uncoated fruits. The results reflect the gas and moisture barrier capability of single-layer and multilayer edible coating considerably reduces firmness, weight loss and decay percentage (Wani et al., 2021).

Firmness is directly affected by weight loss and metabolic processes. Throughout 18 days, WLP of uncoated samples was greater than that of coated samples (Table 1). Among coated samples, WLP was varied during the entire storage period. The control samples had the highest WLP (37%), whereas edible coated fruits showed delayed weight loss and therefore WLP ranged from 11.67% - 23.33% during 18 days of storage. The least WLP (11.67%) was exhibited by CH+CG coated samples. The edible coating reduced weight loss in fresh-cut mango than that reported for the monolayer treated samples for 18 days. This protective effect can be attributed to the barrier properties of CH and AG, which reduce moisture migration and limit enzymatic degradation. Edible coatings are known to form semi-permeable films that modulate gas exchange and reduce transpiration (Gupta et al., 2024), thereby preserving tissue turgidity.

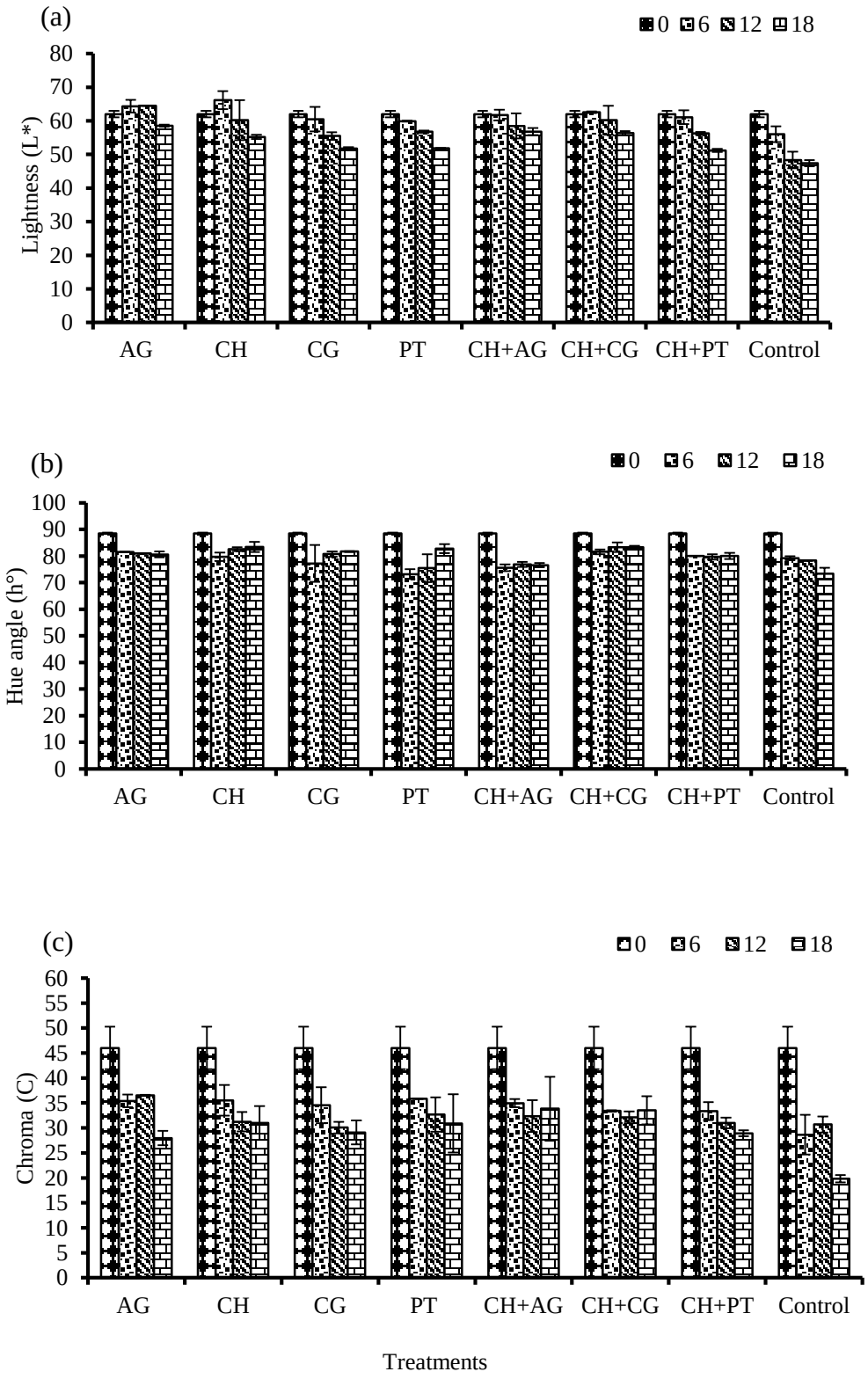


Fig. 1. Changes in (a) Lightness (L*), (b) Hue angle (h°), and (c) Chroma (C) in fresh-cut 'Totapuri' mango treated with polysaccharides-based antimicrobial single and multilayer edible coatings during 18 days of storage at 5±1°C.

Table 1. Changes in firmness and weight loss percentage (WLP) in fresh-cut 'Totapuri' mango treated with polysaccharide-based antimicrobial single and multilayer edible coatings during storage at 5±1°C.

Treatments	Storage period (Days)			
	0	6	12	18
Firmness (Newton)				
AG	29.51±0.99^{a}	24.59±1.09^{b}	19.59±0.97^{c}	14.41±3.16^{d}
CH	29.51±0.99^{a}	20.85±0.69^{b}	12.10±1.60^{c}	7.69±0.49^{d}
CG	29.51±0.99^{a}	26.33±0.64^{b}	11.37±1.26^{c}	5.24±0.01^{d}
PT	29.51±0.99^{a}	20.07±2.70^{b}	11.29±2.09^{c}	3.32±1.10^{d}
CH+AG	29.51±0.99^{a}	28.38±1.15^{b}	19.62±0.98^{c}	6.77±0.94^{d}
CH+CG	29.51±0.99^{a}	26.17±1.81^{b}	19.48±2.32^{c}	3.81±0.56^{d}
CH+PT	29.51±0.99^{a}	17.68±0.52^{b}	9.24±0.68^{c}	2.15±0.38^{d}
Control	29.51±0.99^{a}	4.55±0.29^{b}	2.36±0.67^{c}	1.68±0.26^{d}
Weight loss percentage (WLP)				
AG	0.00±0.00^{d}	10.00±0.00^{c}	13.67±0.32^{b}	18.67±0.15^{a}
CH	0.00±0.00^{d}	6.00±0.20^{c}	11.00±0.10^{b}	18.33±0.55^{a}
CG	0.00±0.00^{d}	3.67±0.21^{c}	10.33±0.25^{b}	20.00±0.15^{a}
PT	0.00±0.00^{d}	12.33±0.32^{c}	20.00±0.10^{b}	23.33±0.42^{a}
CH+AG	0.00±0.00^{d}	2.67±0.12^{c}	9.99±0.26^{b}	12.00±0.10^{a}
CH+CG	0.00±0.00^{d}	5.00±0.10^{c}	11.67±0.72^{b}	18.67±0.40^{a}
CH+PT	0.00±0.00^{d}	12.33±0.06^{c}	14.00±0.10^{b}	18.67±0.23^{a}
Control	0.00±0.00^{d}	23.00±0.30^{c}	29.67±0.84^{b}	36.67±1.15^{a}

Means within the row represented by different superscript letters are significantly different at $p < 0.05$ using Tukey's Multiple Comparison Test. The values represented (a-d) in the results indicated the range from higher to lower rank. AG – Sodium alginate, CH- Chitosan, CG- Carrageenan, PT- Pectin.

Changes in total soluble solids (TSS), pH, and titratable acidity (TA)

Water-soluble components like organic acids, sugars, vitamin C, and some pectins constitute TSS (Maldonado-Celis et al., 2019). TSS at 0 days was 11°Brix, which tends to elevate in all the coated samples and uncoated samples with the storage (Table 2). Among coated samples single layer coated samples exhibited the least increment, while it was higher in samples that had multilayer edible coatings and pectin coated samples. The maximum increment was observed for control samples i.e., 11 °Brix at 0 days to 21.67 °Brix at 18 days of analysis. The coatings delayed the accumulation of TSS during 18 days of storage at 5ºC, maybe through lowering the respiration rate due to the creation of a partial barrier over the cut surface. In this context, Olivas and Barbosa-Canovas (2005), pointed out that the creation of a semipermeable barrier by the application of edible coatings leads to the modification of fruit's internal gaseous composition, thereby slowing down the metabolic processes. Kumar et al. (2021) correlated the rate of respiration with the changes in pH, TA, and TSS in mango fruit. Interestingly, the multilayer-coated fruits had higher TSS content than that single layer coated samples during storage, indicating the integrity of the applied multilayer coating might have changed with the increase of storage period. The study conducted by Poverenov et al. (2014), revealed that the CO_2 permeability of multilayer coating increases under high humidity due to swelling of chitosan layer applied over alginate coating in fresh-cut melon. A similar phenomenon might be the probable reason behind the compromised performance of multilayer edible coating at the end of storage and therefore leading to a significant rise of TSS in those samples after 12 days of storage.

Table 2. Changes in total soluble solids, pH and Titratable acidity in fresh-cut 'Totapuri' mango treated with polysaccharides based antimicrobial single and multilayer edible coatings during storage at 5±1°C.

Treatments	Storage time (Days)			
	0	6	12	18
Total Soluble solids (TSS) (°Brix)				
AG	11.00±0.00^{d}	12.00±0.0^{c}	13.33±0.58^{a}	13.00±0.10^{a}
CH	11.00±0.00^{b}	11.33±0.58^{b}	14.00±0.00^{a}	13.67±1.53^{a}
CG	11.00±0.00^{c}	11.67±0.58^{bc}	12.00±0.00^{b}	13.33±0.58^{a}
PT	11.00±0.00^{d}	13.00±0.00^{c}	15.00±0.00^{b}	19.33±1.15^{a}
CH+AG	11.00±0.00^{d}	14.00±0.00^{c}	15.33±0.58^{b}	16.33±1.53^{a}
CH+CG	11.00±0.00^{d}	13.00±0.00^{c}	16.00±0.00^{b}	18.33±1.15^{a}
CH+PT	11.00±0.00^{d}	12.00±0.00^{c}	14.00±0.00^{b}	19.00±1.00^{a}
Control	11.00±0.00^{c}	14.00±0.00^{b}	14.33±0.58^{b}	21.67±1.23^{a}
pH				
AG	2.79±0.014^{b}	3.35±0.007^{a}	2.97±0.00^{b}	3.27±0.099^{a}
CH	2.79±0.014^{b}	3.13±0.014^{a}	3.1±0.014^{a}	3.23±0.156^{a}
CG	2.79±0.014^{b}	3.19±0.007^{a}	3.19±0.00^{a}	3.55±0.007^{a}
PT	2.79±0.014^{b}	2.88±0.007^{b}	2.85±0.028^{b}	3.10±0.00^{a}
CH+AG	2.79±0.014^{b}	3.34±0.007^{a}	3.10±0.007^{a}	3.17±0.049^{a}
CH+CG	2.79±0.014^{b}	2.88±0.00^{b}	2.88±0.014^{b}	3.10±0.078^{a}
CH+PT	2.79±0.014^{b}	2.99±0.007^{b}	2.99±0.007^{b}	3.23±0.032^{a}
Control	2.79±0.014^{a}	2.89±0.007^{a}	2.89±0.00^{a}	3.78±0.00^{b}
Titratable acidity (TA) (% citric acid)				
AG	0.182±0.005^{a}	0.109±0.00^{b}	0.112±0.001^{b}	0.096±0.005^{c}
CH	0.182±0.005^{a}	0.085±0.00^{b}	0.085±0.001^{b}	0.077±0.002^{c}
CG	0.182±0.005^{a}	0.092±0.00^{b}	0.072±0.00^{c}	0.077±0.00^{c}
PT	0.182±0.005^{a}	0.101±0.00^{d}	0.143±0.009^{b}	0.138±0.014^{c}
CH+AG	0.182±0.005^{a}	0.147±0.005^{b}	0.089±0.001^{c}	0.074±0.002^{d}
CH+CG	0.182±0.005^{a}	0.142±0.00^{b}	0.128±0.001^{c}	0.102±0.009^{d}
CH+PT	0.182±0.005^{a}	0.138±0.001^{b}	0.109±0.001^{c}	0.077±0.00^{d}
Control	0.182±0.005^{a}	0.074±0.00^{b}	0.0729±0.00^{b}	0.046±0.005^{c}

Means within the row represented by different superscript letters are significantly different at $p < 0.05$ using Tukey's Multiple Comparison Test. The values represented (a-d) in the results indicated the range from higher to lower rank. AG – Sodium alginate, CH- Chitosan, CG- Carrageenan, PT- Pectin.

The pH of fresh-cut 'Totapuri' mango at 0 days was 2.79, which increases slightly over the storage period in all the coated samples, while in control TA declined approx. by 36% at the end of storage time (Table 2). Interestingly, the pH observed in samples coated with CG and CH+CG was comparatively higher i.e., 21%, and 17.82% respectively than that of other single layer and multilayer-coated samples. Overall results showed that though it was observed slight fluctuation but remained acidic till the end of storage. Maintaining the lower pH can contribute to microbial protection of fresh-cut fruits. Similar results were reported by Dea et al. (2010) in fresh-cut 'Kent' mangoes, who interpreted that the little change in pH was undetectable in terms of taste. Brasil et al. (2012) also reported that the pH remains unaffected in fresh-cut papaya by chitosan-pectin-based multilayer coating enriched with trans-cinnamaldehyde and β-cyclodextrin complex during 15 days of storage.

Table 3. Changes in Vitamin C, total carotenoids and phenolics in fresh-cut 'Totapuri' mango treated with polysaccharides-based antimicrobial single and multilayer edible coatings during storage at 5±1°C.

Treatments	Storage period (Days)			
	0	6	12	18
Vitamin C (mg.100 g^{-1})				
AG	43.06±3.66^{b}	53.82±1.50^{a}	41.15±3.17^{c}	37.50±0.52^{d}
CH	43.06±3.66^{c}	51.39±2.57^{b}	53.13±4.77^{a}	31.94±1.67^{d}
CG	43.06±3.66^{c}	50.17±3.17^{a}	48.44±5.22^{b}	29.69±1.38^{d}
PT	43.06±3.66^{a}	44.27±6.34^{a}	42.36±1.50^{b}	36.28±3.01^{c}
CH+AG	43.06±3.66^{c}	53.13±10.05^{a}	47.74±2.10^{b}	33.33±1.38^{d}
CH+CG	43.06±3.66^{c}	48.43±4.51^{a}	47.22±4.51^{b}	32.99±4.55^{d}
CH+PT	43.06±3.66^{c}	48.09±3.14^{a}	45.14±1.83^{b}	42.88±2.57^{c}
Control	43.06±3.66^{a}	40.63±3.39^{b}	35.07±2.10^{c}	13.19±1.67^{d}
Carotenoids (µg.g^{-1})				
AG	4.63±0.023^{d}	14.85±0.12^{c}	15.05±0.10^{b}	16.37±0.20^{a}
CH	4.63±0.023^{d}	12.21±0.14^{c}	19.97±0.23^{a}	13.36±0.14^{b}
CG	4.63±0.023^{c}	12.08±0.35^{b}	19.03±0.02^{a}	19.36±0.14^{a}
PT	4.63±0.023^{d}	9.29±0.18^{c}	16.23±0.24^{b}	17.73±0.13^{a}
CH+AG	4.63±0.023^{c}	10.64±0.14^{b}	18.88±0.28^{a}	18.39±0.66^{a}
CH+CG	4.63±0.023^{a}	10.60±0.14^{b}	11.28±0.23^{a}	11.55±0.10^{a}
CH+PT	4.63±0.023^{d}	15.07±0.14^{c}	25.64±0.26^{a}	18.03±0.19^{b}
Control	4.63±0.023^{a}	12.91±0.14^{b}	21.44±0.34^{a}	10.83±0.17^{c}
Phenolics (mg.g^{-1})				
AG	5.65±0.13^{a}	6.02±0.56^{a}	2.25±0.19^{b}	2.97±0.92^{b}
CH	5.65±0.13^{a}	5.15±0.30^{a}	2.19±0.21^{b}	1.77±0.45^{c}
CG	5.65±0.13^{b}	5.91±0.54^{a}	3.09±0.88^{c}	2.37±0.49^{d}
PT	5.65±0.13^{a}	4.44±0.87^{b}	4.05±0.13^{b}	2.93±0.25^{c}
CH+AG	5.65±0.13^{a}	5.72±1.14^{a}	2.85±0.50^{b}	2.63±0.24^{b}
CH+CG	5.65±0.13^{b}	6.66±0.28^{a}	3.43±0.50^{b}	3.66±0.66^{b}
CH+PT	5.65±0.13^{a}	5.22±0.12^{b}	5.08±0.53^{c}	3.64±0.27^{d}
Control	5.65±0.13^{a}	5.06±0.19^{b}	4.33±0.64^{c}	1.59±0.29^{d}

Means within the row represented by different superscript letters are significantly different at $p < 0.05$ using Tukey's Multiple Comparison Test. The values represented (a-d) in the results indicated the range from higher to lower rank. AG – Sodium alginate, CH- Chitosan, CG- Carrageenan, PT- Pectin.

In mangoes, the fruit acidity is attributed to the content of citric acid, being a major organic acid. The organic acids tend to change during ripening and postharvest storage on account of their involvement in aerobic metabolism and as flavor constituents which affect the organoleptic properties of fruit (Maldonado-Celis et al., 2019). The present experiment showed that TA declined significantly ($p<0.05$) in the coated and uncoated samples of fresh-cut 'Totapuri' mango (Table 2). The uncoated mangoes displayed an abrupt decline of TA from 0.18% at 0 days to 0.07% at 6 days, which thereafter consistently decreased throughout the storage time and attained the least amount of 0.05% by 18 days. On the contrary, the multilayer coating of fresh-cut 'Totapuri' mango has significantly ($p<0.05$) delayed TA reduction and therefore, AG+CG coated samples showed the least decline by 19.30% followed by CG+CH coated (22.28%) and PT+CH coated (24.56%), while highest loss (59.64%) was observed for uncoated samples. These shifts were significantly mitigated in coated mangoes, affirming the coatings' role in delaying ripening and acid degradation, as supported by Juric et al. (2023), who noted chitosan-based coatings preserve organic acids in tropical fruits during storage. This positive impact of multilayer edible coatings may be correlated with the good adhesiveness of alginate and antimicrobial activity of citral: β-cyclodextrin inclusion complex, as well as chitosan and thereby, created a protective layer

against atmospheric oxygen and microbial growth, leading to reduced respiration and metabolic changes.

Changes in ascorbic acid (AA)

The results regarding the changing trend of vitamin C in fresh-cut 'Totapuri' mango treated polysaccharide-based edible coatings are presented in Table 3. From these results, it is clear that the concentration of vitamin estimated at 0 days was 43.06±3.66 mg/100 g which significantly increased in all the coated samples on the 6th day of storage, though this increment varied among samples treated with single and multilayer edible coatings. Among the single-layer coated samples of fresh-cut 'Totapuri' mango, AG coated samples exhibited a maximum ~20% increment of ascorbic acid content, while PT coated samples exhibited the least increment (~3%). While considering the effect of multilayer edible coatings on fresh-cut mango, the highest increment (~19%) was noted in CH+AG coated samples followed by CH+CG and CH+PT coated samples. From the 12th day onwards, the reduction ranging from 0.43% to 31% in ascorbic acid content was detected till the end of the storage period. However, the uncoated fresh-cut mango displayed a consistently diminishing pattern throughout the storage period and reaching to its least amount (~13.19 mg/100g) with the greatest decline of ~69% at the end of storage period. The overall interpretation revealed that AA concentration decreased in all coated samples along with the storage period, but the amount remains greater than that of uncoated samples. Vitamin C is susceptible to degradation during storage, especially when exposed to oxygen and moisture, but edible coating creates a physical barrier on the mango's surface that helps regulate the exchange of gases and moisture. Thus by limiting them, the coating can slow down the enzymatic reactions that break down vitamin C (Ngo et al., 2021).

Changes in carotenoids

Table 3 shows the initial concentration of carotenoids in fresh-cut 'Totapuri' mango coated was 4.63±0.023 µg.g^{-1}. The coating treatments lead to the enhancement of the carotenoids throughout the storage period of 18 days at 5°C. However, there was a variation in the accumulation trend of total carotenoids concerning the given treatments of edible coatings. CH, CH+AG, and CH+PT coated and control cut mangoes exhibited a faster accumulation pattern of carotenoids and they reached to its peak values ranging from 71 - 77% on the 12th day of storage, which thereafter declined at the end of storage. However, AG, CG, and PT coated samples displayed a consistently increasing trend during 18 days. Interestingly, CH+CG treated fresh-cut mango significantly ($p<0.05$) delayed accumulation of carotenoids along the storage period of 18 days.

The increased carotenoids accumulation with the storage time might be attributed to the biosynthesis of carotenoids in mango. This suggested that the ripening of mango slices might have continued even at low-temperature storage. Carotenoids act as an antioxidant by reducing the oxidative damage caused by ROS and free radical species and inhibiting lipid peroxidation in foods caused by processing and storage. The fresh-cut processing did not inhibit the synthesis of β-carotene because of the continued ripening of mango (Gonzalez-Aguilar et al., 2008) and this is beneficial as the nutritive property increases during storage in the present study. A similar study by Handojo et al. (2022) found that the edible coating of beeswax and a composite of gum Arabica and chitosan on fresh-cut mango reduced the weight loss, pH, colour of fruits and also maintained its hardness and extended the shelf life at room temperature.

Changes in phenolics

The induction of PPO activity as a result of minimal processing is believed to be the major cause of the phenolics oxidation of many fruits and vegetables (Alikhani-Koupaei, 2015). The phenolic have profound effects on human health due to antioxidant, anti-inflammatory, and antimicrobial effects. Table 3 represents the Phenolic changes during 18 days of storage at 5°C. The reduction of phenolics was significantly ($p<0.05$) highest (~72%) in uncoated samples from 5.65±0.13 $mg.g^{-1}$ at 0 days 1.59±0.29 $mg.g^{-1}$ at 18 days of storage. In this context, Shiri et al. (2011) opined that the decline of phenolics is related to respiration, ethylene production, and PPO activity. However, the single-layer coated samples revealed 48% to 68% decline, whereas the least decline was found in multilayer-coated samples i.e., 38% to 48% depending upon the polysaccharide used. CH+CG coated samples contain ~15% higher phenolics concentration on the 6th day of storage relative to its initial amount but thereafter declined. The multilayer edible coatings with microencapsulated antimicrobial complex (citral in β-cyclodextrin) on fresh-cut 'Totapuri' mango has significantly ($p<0.05$) minimized this loss and helped retain ~20% higher phenolics as compared to a single layer and uncoated samples by 18 days of storage. A similar study by Kumar et al. (2021) documented that chitosan–pullulan composite edible coating significantly controlled the reduction of phenolic in mango fruits at 4°C.

Changes in Malondialdehyde (MDA) and Hydrogen peroxide (H_2O_2)

On account of minimal processing of fresh produces, cell membrane integrity may be affected by the oxidation of lipid which leads to the accumulation of MDA as an intermediate product (Li & Yu, 2001). As shown in Table 4, MDA content was ~35 µmol kg^{-1} at 0 days which gradually enhanced in uncoated samples reaching the highest amount (50.53±1.61 µmol kg^{-1}) at the end of storage. In contrast, a slight increment ranging from 8-16% relative to its initial concentration was observed in mono-layer coated and CH+AG, CH+CG, and CH+PT coated samples at the end of storage. Malondialdehyde (MDA) is one of the crucial markers of lipid peroxidation. Its excessive accumulation exacerbates cell membrane damage, so it can be used to determine the degree of cell membrane damage and lipid peroxidation (Ma et al., 2022). The polysaccharide-based antimicrobial edible coatings on fresh-cut 'Totapuri' mango samples delayed the accumulation of MDA during the storage period of 18 days at 5°C. Present results correspond to those reported earlier in fresh-cut mango (Song et al., 2025; Zheng et al., 2025).

Wounding-induced stress causes a transient increase in the production of reactive oxygen species (ROS). H_2O_2 is low molecular weight ROS that oxidizes in nature. Tables 4 shows that the H_2O_2 accumulated up to 6 days of storage. This accumulation trend was faster i.e., 41 - 51% more to its initial amount in mono-layer coated and uncoated samples as compared to bi-layer coated samples where it is ranged from 10 - 33% relative to its initial value. Interestingly, H_2O_2 accumulated moderately in CH+CG coated fruits with the advance of storage time which indicated that the oxidative stress-induced during processing might compensate due to the protective effect of CH+CG coating on the fresh-cut mango. According to Gomes et al. (2022) ascorbate can directly scavenge H_2O_2 via ascorbate peroxidase (APX). The overall interpretation showed that it sustained significantly ($p<0.05$) lower H_2O_2levels in coated samples than that in control at the end of storage. As fruits undergo oxidative stress during postharvest ripening and senescence generating more reactive oxygen species (ROS), which can cause cell structure destruction, membrane lipid peroxidation, protein and DNA damage and abnormal fruit ripening (Zhou et al., 2023).

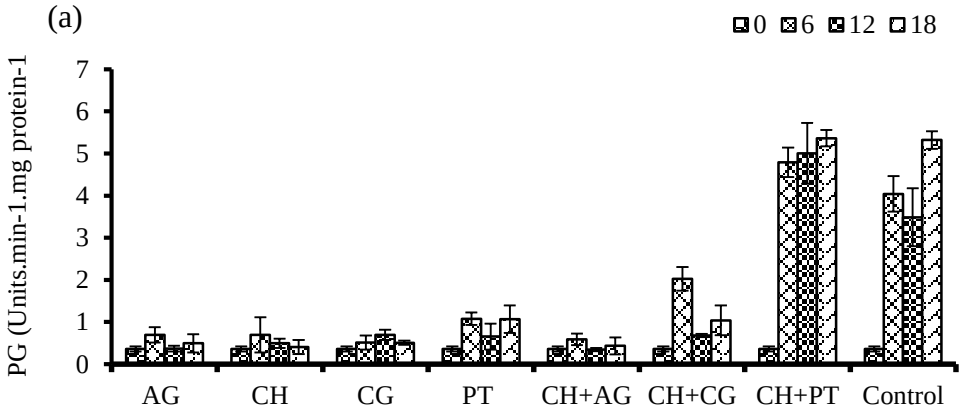
Changes in enzymes activity

Minimal processing as a stressful condition induces the tremendous rise of reactive oxygen species (ROS) which in turn leads to the oxidative breakdown of bio-molecules. Therefore, in order to balance this ROS level, the plants antioxidant system gets activated either through enzymatic induction or antioxidants accumulation (Karakurt & Huber, 2007). The enhanced activity of softening enzymes mainly, PG and PME lead to depolymerization of cell wall pectin causing firmness loss. The fresh-cut processing-induced oxidation may also affect nutritional and thus the marketable shelf-life through the simultaneous action of PPO and PAL on the phenolic. POX involve in mitigating the effect of oxygen free radicals and delays senescence during storage.

Table 4. Changes in Malondialdehyde (MDA) and Hydrogen peroxide (H_2O_2) in fresh-cut 'Totapuri' mango treated with polysaccharides based antimicrobial single and multilayer edible coatings during storage at 5±1°C.

Treatments	Storage period (Days)			
	0	6	12	18
Malondialdehyde (MDA) (µmol.kg-1)				
AG	34.84±1.10^{d}	40.04±0.71^{a}	38.75±0.37^{b}	37.72±2.15^{c}
CH	34.84±1.10^{c}	37.85±1.16^{b}	42.32±7.38^{a}	37.98±0.83^{b}
CG	34.84±1.10^{b}	39.14±0.20^{a}	39.70±1.68^{a}	39.91±1.73^{a}
PT	34.84±1.10^{d}	37.42±1.45^{c}	36.69±0.71^{b}	41.55±5.42^{a}
CH+AG	34.84±1.10^{c}	36.00±3.27^{b}	38.49±2.09^{a}	38.49±1.93^{a}
CH+CG	34.84±1.10^{c}	37.12±1.37^{b}	39.83±1.92^{a}	39.91±1.25^{a}
CH+PT	34.84±1.10^{d}	35.05±1.34^{c}	38.37±2.52^{b}	41.51±1.31^{a}
Control	34.84±1.10^{d}	35.66±0.82^{c}	39.35±0.59^{b}	50.54±1.61^{a}
Hydrogen peroxide (H_2O_2) (µmol.kg-1)				
AG	1.59±0.25^{d}	2.71±0.07^{a}	2.65±0.39^{a}	2.43±0.37^{a}
CH	1.59±0.25^{d}	3.24±0.07^{a}	2.56±0.09^{b}	2.22±0.24^{c}
CG	1.59±0.25^{d}	2.88±0.23^{a}	2.95±1.18^{a}	2.70±0.39^{a}
PT	1.59±0.25^{b}	2.71±0.01^{a}	2.85±0.14^{a}	1.05±0.44^{c}
CH+AG	1.59±0.25^{a}	2.39±0.12^{a}	2.33±0.07^{a}	2.00±0.17^{a}
CH+CG	1.59±0.25^{b}	1.78±0.07^{b}	2.35±0.21^{a}	2.54±0.36^{a}
CH+PT	1.59±0.25^{c}	2.13±0.09^{b}	2.50±0.37^{a}	1.02±0.29^{d}
Control	1.59±0.25^{b}	2.94±0.10^{a}	2.72±0.43^{a}	2.88±0.18^{a}

Means within the row represented by different superscript letters are significantly different at $p < 0.05$ using Tukey's Multiple Comparison Test. The values represented (a-d) in the results indicated the range from higher to lower rank. AG – Sodium alginate, CH- Chitosan, CG- Carrageenan, PT- Pectin.



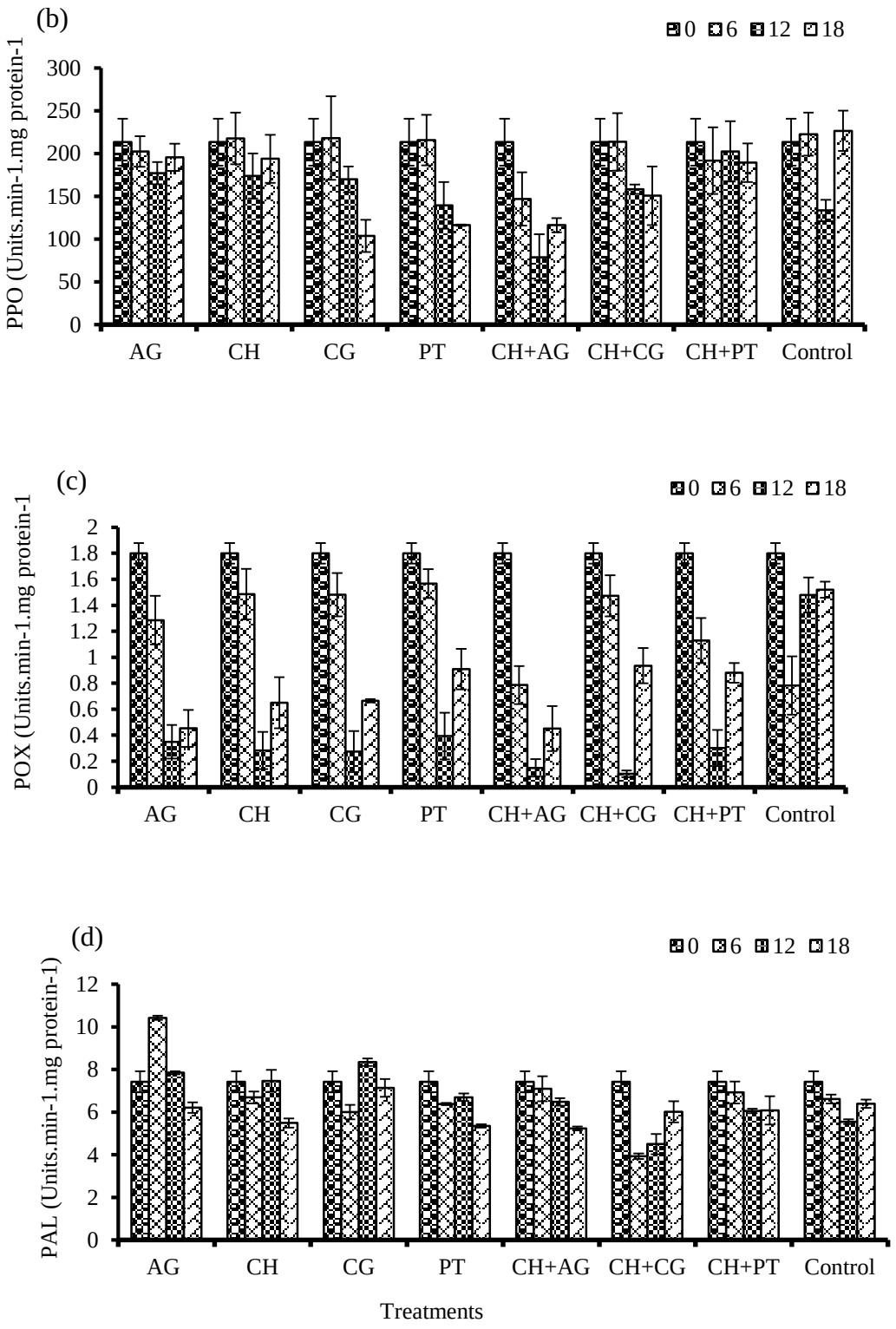


Fig. 2. Changes in specific activity of (a) Polygalacturonase (PG), (b) Polyphenol oxidase (PPO), (c) Peroxidase (POX) and (d) Phenylalanine ammonia lyase (PAL) in fresh-cut 'Totapuri' mango treated with polysaccharides based antimicrobial single and multilayer edible coatings during 18 days of storage at 5±1°C.

Polygalacturonase (PG) activity

The effect of polysaccharide-based single and multilayer edible coatings on PG activity of fresh-cut mango is represented in Figure 2a. At 0 day of storage, PG activity was 0.36 Units min^{-1} mg^{-1} protein. CH+AG and CH+CG samples had approx. 45 – 50% lower PG activity on 6^{th} day of storage than that exhibited by CH+PT and uncoated samples. With the subsequent storage, PG activity declined but remained in the range between 0.43 – 1.06 Units min^{-1} mg^{-1} protein in single-layered, CH+AG and CH+CG coated samples. While PG activity noticed for CH+PT including uncoated samples was increased to more than 90% relative to its initial activity. Long et al. (2025) also found a gradual increment in activities of PG, PME, β-galactosidase, and cellulase which is correlated with the enhanced softening of mango fruit. Among the coated samples PG activity was least i.e., 0.41 Units min^{-1} mg^{-1} protein in CH coated samples, followed by CH+AG treated mangoes (0.43 Units min^{-1} mg^{-1} protein) during 18 days of storage period. In this study, the application of layer-by-layer edible coatings on Totapuri slices revealed that the use of CH as a single layer and with AG for layer-by-layer deposition helped delayed PG activity through the storage period of 18 days at 5°C as compared to the rest of treatments. This positive influence may be attributed to its binding with pectin cause formation of a strong CH-pectin complex and effectively preventing the reaction of PG with its substrate and thereby maintaining the fruit texture (Toivonen & Brummell, 2008). Similar results for the activity of softening enzymes were also reported by Ngo et al. (2021) in mango fruits.

Polyphenol oxidase (PPO) activity and Peroxidase (POX) activity

Enzyme PPO is responsible for the undesirable enzymatic browning in fruits during storage and marketing. This process involves PPO reacting with free phenolic compounds in the presence of oxygen, leading to the formation of dark-colored pigments (Moon et al., 2020). Figure 2b showed the PPO activity trend of coated and uncoated fresh-cut 'Totapuri' mango fruit during 18 days of storage. The PPO activity at 0 days was 213.36±27.36 Units min^{-1} mg^{-1} protein which declined on the 12^{th} or 18^{th} day of storage depending on the given treatments. PPO activity showed maximum reduction in CH+AG coated samples with ~31% on the 6^{th} day and ~63% during 12 days of storage, while in the rest of the coated samples PPO activity reduction was the range between 5-34% on 12^{th} day of storage. At the end of storage, samples of CG, PT, CH+AG, and CH+CG had statistically significant ($p<0.05$) lower PPO activity as compared to the uncoated samples. In general, the overall data on PPO activity in fresh-cut mango showed no further induction during 18 days of storage period due to application of polysaccharide-based edible coatings supplemented with microencapsulated antimicrobial complex (citral in β-cyclodextrin). The results are in agreement with Cegri et al. (2023) who extended shelf life of Zucchini by application of polysaccharide based edible coating.

In the present investigation, the change in POX activity in the coated and uncoated fresh-cut mango during storage is illustrated in Figure 2c. The measured POX activity at 0 days was 1.8 Units min^{-1} mg^{-1} protein. During a storage period of 18 days, POX activity was reduced by 40-90% in coated fresh-cut mango fruit up to 12 days of storage, but it enhanced significantly ($p<0.05$) at the end of storage and remained in the range between 0.45–1.00 Units min^{-1} mg^{-1} protein. However, the uncoated samples exhibited a declining trend in their POX activity and showed ~17% reduction till the end of storage, relative to its initial activity, and still, it was found to be significantly greater i.e., 1.52±0.06 which is ~50% higher than that recorded in coated samples during the same time. According to Adiletta et al. (2021) reduced POX activity in the fruit treated with edible coatings is attributed to decline oxidative stress on the cut fruit due to its protective layer forming ability which prevents the direct

contact of atmospheric oxygen with the fruit surface. Similarly, Rukunuzzaman et al. (2025) found that chitosan along with aloe vera gel preserves the quality of mango fruits.

Phenylalanine ammonia-lyase (PAL) activity

The data represented in Figure 2d, depicts the effect of single and multilayer edible coating of fresh-cut mango on PAL activity. The browning of tissue, often observed after wounding, is largely due to the activation of the phenylpropanoid pathway, which leads to the accumulation of phenolic compounds which causes browning of tissue (Guo et al., 2023). In the present study, the PAL activity was fluctuated depending on the applied polysaccharide-based edible coatings throughout the storage period. PAL activity at 0 days was 7.42±0.49 Units min^{-1} mg^{-1} protein, which decline in the coated fresh-cut mango during 6 days of storage, except AG, coated samples. Among single layer coated samples, CG coated samples showed a maximum ~19% reduction in PAL activity, whereas, among multilayer-coated samples, CH+CG coated fruit had the highest ~47% reduction of its PAL activity as compared to that measured at 0 days. By the 18 days of storage period, the measured PAL activity in coated samples was ranged between 5.23 – 7.13 Units min^{-1} mg^{-1}, while control showed 7.64±0.19 Units min^{-1} mg^{-1} protein. The applied coating showed the inhibitory effect on PAL activity in fresh-cut mango fruit. Similar results were obtained by application of chitosan in guava fruits (Silva et al., 2018).

Sensory evaluation

The sensory shelf-life of fresh-cut fruit directly affects the marketing shelf-life. A previous study revealed that fresh-cut 'Totapuri' mango stored maintained external quality up to 8 days at 5°C and thereafter found with declined overall quality by 12 days of storage (Sharma & Rao, 2017). As indicated in Table 5, the uncoated samples showed the least overall acceptability scores (1.62±0.21) based on color, taste, firmness, and odor by 18 days of storage. However, AG, CH, and AG+CH edible coatings demonstrated better retention of sensory quality traits as these samples received overall acceptability scores 5.68±0.25, 5.62±0.28, and 5.69±0.23, respectively when compared to the other treated samples and therefore remained acceptable according to the consumer point of view at the end of storage. While observing the visual quality, the control samples displayed translucency and browning whereas no signs of translucency were seen in coated samples at the end of the storage period. The slight browning at the edges of mango slices was observed in samples coated with AG, CG, PT, CG+CH, and PT+CH samples, whereas CH, and AG+CH, coated samples were appeared fresh-like at the end of storage. The used polysaccharide on the fresh-cut mango has no negative impact on the color, taste, and odor, but firmness scores were significantly ($p<0.05$) lowered during storage. Multilayer edible coatings of AG+CH on fresh-cut mango displayed higher overall acceptability scores than that for CG+CH and PT+CH. Moreover, the incorporation of a microencapsulated antimicrobial complex (citral in β-cyclodextrin) into the edible coatings has no negative impact on the sensorial properties. In this study, most coating treatments better maintained the sensory quality attributes as compared to the control, which is consistent with the findings of Seifi and Bekran (2024) in Pomegranate. As application of edible coating improve the quality and it also extends the storage, delays ripening and retain quality properties, hence it is regarded as a safe material (Alhassan & Ndomakaah, 2024).

Table 5. Sensory evaluation of fresh-cut 'Totapuri' mango treated with polysaccharides based antimicrobial single and multilayer edible coatings on 18th day of storage at 5±1°C.

Treatments	Color	Taste	Firmness	Odor	Overall acceptability
AG	5.83±0.29^{a}	6.07±0.25^{a}	4.10±0.10^{b}	6.70±0.36^{a}	5.68±0.25^{a}
CH	5.63±0.23^{a}	6.33±0.35^{a}	4.46±0.47^{b}	6.03±0.06^{a}	5.62±0.28^{a}
CG	4.53±0.21^{c}	4.23±0.06^{c}	4.13±0.21^{b}	5.40±0.17^{b}	4.58±0.16^{b}
PT	4.33±0.15^{c}	3.83±0.61^{d}	3.67±0.38^{c}	5.40±0.10^{b}	4.31±0.31^{b}
CH+AG	5.37±0.23^{b}	5.57±0.29^{b}	5.53±0.21^{a}	6.30±0.20^{a}	5.69±0.23^{a}
CH+CG	4.53±0.21^{c}	4.70±0.36^{c}	3.97±0.32^{c}	5.23±0.15^{b}	4.61±0.26^{b}
CH+PT	5.30±0.26^{b}	5.33±0.25^{b}	5.23±0.12^{a}	3.07±0.46^{c}	4.73±0.27^{b}
Control	1.87±0.32^{d}	0.00±0.00^{d}	1.50±0.44^{d}	3.10±0.10^{c}	1.62±0.21^{c}

Means within the column represented by different superscript letters are significantly different at $p < 0.05$ using Tukey's Multiple Comparison Test. The values represented (a-d) in the results indicated the range from higher to lower rank. AG – Sodium alginate, CH- Chitosan, CG- Carrageenan, PT- Pectin.

Microbial contamination

The microbial safety of fruits is one of the most critical factors determining the acceptability and marketability of products of the fresh-cut industry. The low total aerobic plate counts and yeast and molds counts are positively correlated with the longer shelf-life of fresh-cut fruits (Kader, 2002). Fresh-cut processing releases moisture and sugars which provides suitable media for microbial growth. Table 6 shows the results regarding the total mesophilic bacterial and yeast and mold counts on coated and uncoated fruits during storage. Cisse et al. (2015) reported that chitosan coatings with lactoperoxidase inhibit the fungal proliferation in fresh-cut mango. The present study showed the total mesophilic bacterial and yeasts and mold counts in uncoated mango reached above 4 log CFU/g by 12 days of storage which further increased to the spoilage level at the end of storage. While considering the effect of the single-layer coatings on the total mesophilic bacterial count, AG and CH coated fresh-cut mango has 2.77±0.07 and 2.86±0.07log CFU/g, comparatively lesser than that found for CG (3.11±0.09log CFU/g) and PT (3.42±0.07log CFU/g) coated samples during 18 days of storage. Among the multilayer-coated samples, AG+CH prevented the growth of total mesophilic bacteria and yeasts and molds and remained below the detection level throughout the storage period of 18 days. Poverenov et al. (2014) found reduced the bacteria, yeast, and fungi counts on fresh-cut melon by 1–2 log CFU with the layer-by-layer of alginate and chitosan coating. Therefore, the application of single and layer-by-layer edible coatings with microencapsulated antimicrobial (citral in β-cyclodextrin) significantly ($p<0.05$) reduced the microbial contamination and helped extend the shelf-life during 18 days of storage period. A similar interpretation was also made by Gu et al. (2024) in blueberry coated with different edible coatings with antimicrobial complex (β-cyclodextrin + Fennel oil) for 8 days at 25°C.

Table 6. Microbial contamination in fresh-cut 'Totapuri' mango treated with polysaccharides- based antimicrobial single and multilayer edible coatings during storage at 5±1°C.

Treatments	Storage time (Days)			
	0	6	12	18
	Total mesophilic bacterial count (log CFU/g)			
AG	0.0	0.0	2.63±0.06	2.77±0.07
CH	0.0	0.0	2.67±0.07	2.86±0.07
CG	0.0	0.0	2.42±0.10	3.11±0.09
PT	0.0	2.26±0.24	2.69±0.09	3.42±0.07
CH+AG	0.0	0.0	0.0	0.0
CH+CG	0.0	0.0	2.81±0.03	3.06±0.06
CH+PT	0.0	2.59±0.26	3.10±0.07	3.55±0.05
Control	0.0	3.28±0.07	4.01±0.03	tntc[1]
Yeast and Mold count (log CFU/g)				
AG	0.0	2.46±0.15	2.99±0.04	3.13±0.11
CH	0.0	0.0	2.10±0.17	2.69±0.09
CG	0.0	2.56±0.07	2.59±0.11	3.38±0.02
PT	0.0	3.23±0.05	2.92±0.0.3	3.89±0.02
CH+AG	0.0	0.0	0.0	0.0
CH+CG	0.0	2.16±0.15	2.49±0.10	2.99±0.04
CH+PT	0.0	2.91±0.12	3.46±0.05	3.93±0.06
Control	0.0	3.89±0.07	4.12±0.03	tntc[1]

1 – tntc stands for too numerous to count.

CONCLUSION

The impact of layer-by-layer antimicrobial edible coatings with microencapsulated citral in a β-cyclodextrin complex on the quality and shelf-life of mango was evaluated and compared with the single-layer and uncoated samples during 18 days of analysis at 5°C. The delayed the changes in color quality determining parameters, *L**, *h°*, and chroma *C*, minimized firmness and weight loss, retained vitamin C and carotenoids, declined the accumulation of H_2O_2 and MDA, specific activities of PG, PPO, POX, and PAL enzymes, and microbial contamination was significantly inhibited along with maintained sensorial attributes over the entire storage period by application of multilayered antimicrobial edible coatings as compared to uncoated samples. Thus, The study suggest that application of AG and CH as single layer and layer-by-layer polysaccharide-based edible coating of CH+AG and CH+CG are effective and safe method of preserving the quality and extending the shelf-life of fresh-cut 'Totapuri' mango for 18 days at 5°C.

Conflict of interest

The authors declare no potential conflict of interest.

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