Research Article

Effect of Chitosan and Titanium Dioxide Coatings with and without UV Activation on the Postharvest Quality of 'Nam Dok Mai Si Thong' Mango

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Abstract
This study aimed to assess the individual and combined effects of chitosan and titanium dioxide (TiO_2), with and without UV exposure, on delaying ripening, reducing weight loss, and maintaining postharvest quality of mangoes stored at 25 ± 2 °C for up to 12 days. The evaluation focused on changes in physicochemical properties, antioxidant content, *in vitro* antioxidant activity, and microbial decay. The coating treatments included: 1) control (C), 2) chitosan (CH), 3) CH–TiO_2 (CT), 4) control with UV activation (C-UV), 5) CH with UV activation (CH-UV), 6) CT with repeated UV activation (CT-UV), 7) CT with single UV activation (CT-UV1). CT coatings effectively reduced ethylene production (0.19–0.29 μL/kg.h) and respiration rate (50–78 mg CO_2/kg.h), thereby slowing ripening compared to the control. UV activation did not significantly enhance the suppression of ethylene production or respiration. CT coatings also minimized weight loss (8.34–8.47% vs. 12.62% in C), maintained peel color stability, and better preserved physicochemical properties. In addition, CT coatings delayed the decline in titratable acidity (0.18–0.56% on day 12) and slowed the accumulation of total soluble solids (14.75–14.88 °Brix on day 12). Moreover, antioxidant retention was also improved, as indicated by higher total phenolic content (34.65 mg GAE/g) and FRAP values (110.26 μg TE/g). CT-treated mangoes exhibited the lowest incidence of decay (7.57–7.71%), highlighting the antimicrobial potential of TiO_2 and supporting its use as an effective strategy to extend the shelf life of mangoes.

Keywords: Antioxidant capacity, Chitosan, Mango, Postharvest quality, Titanium dioxide, UV activation

1 Introduction

Mangoes are popular tropical fruits known for their nutritional richness, unique flavor, and global market appeal. However, they are highly perishable and face several postharvest challenges. These include rapid softening and sensitivity to chilling injury when stored below 13 °C [1]. Moreover, mangoes are

susceptible to anthracnose disease, caused by *Colletotrichum gloeosporioides*, which can significantly affect fruit quality and even lead to complete yield loss [2]. These issues highlight the need for suitable preservation strategies. One innovative approach is the application of edible coatings made from natural polymers like chitosan (CH) combined with inorganic compounds such as titanium dioxide (TiO_2) [3], [4].

Chitosan, a natural biopolymer derived from crustacean exoskeletons, is characterized by several interesting properties for food applications, including biodegradability, non–toxicity for humans, antimicrobial activity, because of its polycationic nature, along with film–forming capacity and emulsion stabilization [5]. When applied as a coating, CH can reduce moisture loss and oxygen transmission, thereby slowing respiration and microbial growth [6]. However, the hydrophilic nature of CH limits its ability to control moisture transfer and maintain structural integrity over time [7].

To address these limitations, researchers have added TiO_2 nanoparticles to CH coatings. TiO_2 has photocatalytic and antimicrobial properties. Under UV light, it produces reactive oxygen species (ROS) that can inactivate many types of microorganisms [8]. Studies on CT coatings applied to various fruits, including mangoes, strawberries, and ginkgo, have shown that the coatings enhance barrier properties by forming a dense structure that limits gas and moisture permeability [4], [9], [10]. As a result, these coatings can reduce weight loss, delay ripening, and preserve firmness [11]. CT coatings have also demonstrated strong antimicrobial activity. For instance, Kamal *et al.*, [12] showed that a CT nanocomposite on a cellulose microfiber substrate effectively controlled decay caused by fungi, bacteria, and algae. Its antimicrobial action is due to electrostatic interactions between the positively charged coating and negatively charged microbial membranes. These interactions damage the membranes and block nutrient uptake, which inhibits cell growth. In mangoes, Xing *et al*., [13] reported that CT coatings significantly delayed softening and reduced decay during cold storage. After 20 days at 13 °C, coated mangoes retained a firmness of 8.7 kg/cm², compared to 2.8 kg/cm² in the control. Decay incidence dropped from 34.22% in untreated fruit to 19.73% in treated samples. The coating also stabilized quality parameters such as total soluble solids (9.4% vs. 15.93%) and malondialdehyde (MDA) content (4.42 vs. 5.91 µmol/g), a marker of membrane degradation. These benefits were also linked to enhanced antioxidant defenses, including increased peroxidase activity and decreased polyphenol oxidase activity [13].

TiO_2 extends mango shelf life by degrading ethylene through photocatalysis. Under UV light, TiO_2 becomes photoactivated and generates electron–hole pairs, which react with water and oxygen to produce ROS, such as hydroxyl radicals (•OH) and superoxide anions (O_2•-). These ROS oxidize ethylene into carbon dioxide and water, reducing its accumulation and thereby delaying fruit ripening and senescence. [14].

Research on UV-activated CT coatings has demonstrated enhanced tensile strength, improved barrier properties, and more effective ethylene degradation compared to CH–only films. These improvements highlight the potential of UV–activated coatings for maintaining postharvest quality in climacteric fruits such as mangoes [15], [16].

UV light itself contributes to postharvest quality. It delays ripening, inhibits fungal growth, and helps preserve antioxidant activity [17]. UV–C light (250–280 nm) has been shown to inhibit cell wall–degrading enzymes and delay fruit softening. Kaewklin *et al.,* [18] reported that tomatoes packaged in CT nanocomposite films and exposed to UV–C light for 180 minutes daily exhibited slower softening, lower ethylene levels, and delayed accumulation of lycopene and total soluble solids. After 15 days, treated fruits retained firmness (~14 N) compared to ~8 N in controls. Additionally, fungal growth became visible in the control samples by days 13–14, while no signs of fungal development were observed in the treated fruit, indicating the antimicrobial effectiveness of the treatment when combined with UV exposure.

Similarly, González-Aguilar *et al.,* [19] found that a 10–minute UV–C treatment preserved postharvest quality in ‘Tommy Atkins’ mangoes stored at 5 °C for 14 days followed by 7 days at 20 °C. Treated mangoes maintained higher firmness (initially 40–45 N), stable sucrose content (55.95 mg/g FW), and greater retention of organic acids like shikimic acid. Putrescine levels, associated with stress tolerance, increased 2.5–fold, supporting UV–C as a non–chemical method to extend mango shelf life and nutritional quality.

CT coatings also enhance the structural and functional properties of packaging materials. TiO_2

improves dispersion within the CH matrix, increasing surface area, enhancing barrier properties, and improving mechanical and thermal stability. A denser coating reduces gas and moisture permeability, supporting fruit preservation. However, optimal TiO_2 concentration is crucial, as excessive amounts may lead to nanoparticle aggregation and reduced performance [11], [20]–[22].

Overall, CT films show strong potential to improve mango shelf life and quality. Yet, challenges remain regarding the optimal balance between TiO_2 loading and UV exposure. High TiO_2 concentrations or improper UV treatment may compromise coating performance or induce oxidative stress in the fruit, highlighting the need for further optimization.

This research studied the effects of CH, TiO_2, and UV activation—used individually or in combination—on the postharvest preservation of mangoes. The aims of this study were to reduce postharvest losses and enhance shelf life and quality, which are essential for maintaining commercial value and improving agricultural productivity. Mangoes were coated with CH alone or with a CH–TiO_2 composite, with or without UV activation. Quality parameters were evaluated over 12 days of storage at 25 °C, using uncoated and UV–only treated fruits as controls.

2 Materials and Methods

2.1 *Plant materials*

Harvested mature green mangoes (*Mangifera indic*a L. cv. 'Nam Dok Mai Si Thong'), aged 90–100 days after flowering, were harvested from a commercial orchard in Chachoengsao province, Thailand. The fruits were chosen based on their ripeness level, determined through visual inspection for uniform size (300–450g), peel color (light yellow), shape (elongated–oval), and the absence of diseases or defects [23]. A total of 280 mangoes was used for this study.

2.2 *CH and CT coating solutions*

CH flakes from shrimp shells (2,100 kDa) were obtained from Marine Bio Resources, Thailand. The CH coating was prepared following the method described by Koongboonkird *et al*., [24] with some modifications. A dispersion of 1% CH in distilled water containing 1% (v/v) acetic acid was prepared and then heated at 80 °C for 12 h in a shaking water bath until complete dissolution. Then, 0.6% (w/v) of glycerol was added and stirred with a magnetic stirring hotplate until complete dissolution.

The CT coating solution was made according to the method described by Xing *et al.,* [25] with a few modifications. Initially, 0.03 g of TiO_2 was dissolved in 1 g of glycerin, followed by the addition of 100 mL of a 1% aqueous acetic acid solution and 1 g of CH powder. The mixture was heated on a magnetic stirring hotplate at 90 °C for 20 min to facilitate dissolution.

Subsequently, the solution was filtered through eight layers of cheesecloth to remove any undissolved particles. To ensure complete dissolution and homogeneity, the filtered solution underwent ultrasonication for 30 minutes, resulting in a well–dispersed CT coating solution.

2.3 *Treatments*

A total of 280 mango fruits were divided into seven treatment groups. Every two fruits were combined to form one replicate, resulting in four replicates per treatment at each sampling point. The fruits were subjected to seven treatments, consisting of dipping in specific coating solutions, with or without UV exposure, including a 1% acetic acid solution (C), chitosan (CH) and chitosan combined with titanium dioxide (CT). The remaining four treatments included the same dipping solutions combined with UV exposure: C–UV, CH–UV, CT–UV, and CT–UV1. In the CT–UV1 treatment, UV light was applied only once on the day of dipping.

Mango fruits were dipped for 1 min in CH, CT, or control (1% aqueous acetic acid) solutions, followed by air–drying for 30 minutes. For the UV–treated samples, fruits were exposed to UV–C light for 180 minutes using two 15 W black light lamps (wavelength range: 250–280 nm). The CT–UV1 treatment involved a single exposure on day 0, whereas the other UV treatments were applied every three days (on days 0, 3, 6, 9, and 12) [18].

All mangoes were stored at 25±2 °C for 12 days or until the end of their shelf life. Analyses were conducted on samples collected every three days (0, 3, 6, 9 and 12).

2.4 *Weight loss*

Fruit weight was measured by an electronic digital scale. Eight fruits from each treatment were individually weighed. Weight loss was recorded every

3 days throughout the observation period and calculated using the standard procedure described by AOAC [26].

2.5 *Peel color*

Mango peel color was evaluated using a colorimeter (CR–400 tristimulus colorimeter, Minolta, Japan) in the CIE L*a*b* color space mode as described by Ngamchuachit *et al*., [27] and Jongsri *et al*., [28]. Lightness (L*) and chromatic parameters a* and b* were recorded to monitor changes in peel color.

Measurements were taken at three areas of each fruit (blossom end, middle, and stem end). The data represent the average of measurements from eight mangoes per treatment, resulting in 24 data points per treatment.

2.6 *Firmness*

Mango firmness was evaluated using a texture analyzer (model TA.XT plus, Texture Technologies Corp., Scarsdale, NY, USA) equipped with a 5 kg load cell and an 8 mm diameter flat–tipped cylindrical probe, operating at a test speed of 5 mm s^{-1} [27].

Firmness was measured as the maximum force required to penetrate 5 mm into the cut surface of whole mangoes. Each fruit was measured twice, once on each cheek. A 5 cm wide section of peel was removed from opposite sides before measuring. The results are based on the average of eight mangoes per treatment.

2.7 *Titratable acidity (TA) and total soluble solids (TSS)*

Analyses were performed according to the method reported by Ngamchuachit *et al*., [29] with a few modifications. Juice was extracted from a 10 g mango pulp by pressing it through two layers of cheesecloth using a hand juicer.

TA was determined by titrating 5 g of mango juice with 0.1M NaOH, and the results were expressed as a percentage. TSS were measured from an aliquot of the same juice using a refractometer (Atago, Tokyo, Japan) and expressed in °Brix.

2.8 *Analysis of ethylene and respiration rate*

Mango fruits from each treatment were individually weighed and placed in 2.4 L jars, and hermetically sealed. The samples were equilibrated for 1 h at 25 °C, after which gas sampling was carried out. Ethylene and CO_2 production were measured using the same fruit for each treatment replicate [28].

For CO_2 analysis, 1 mL of headspace gas was collected using a syringe and injected into a gas chromatograph equipped with a thermal conductivity detector (GC–RIA, Shimadzu, Kyoto, Japan). For ethylene analysis, a 1 mL gas sample was injected into a gas chromatograph (GC–14, Shimadzu, Kyoto, Japan) fitted with a flame ionization detector.

2.9 *Decay incidence (DI)*

DI was calculated using the formula described by Zheng *et al.,* [30]. DI of each fruit was scored based on the extent of visible decay on the fruit surface, specifically blackened areas caused by anthracnose infection. A total of eight fruits per treatment were analyzed, with three images taken from three different angles (top, right side, and left side). Decay was quantified using ImageJ software by first calculating the total surface area of the mango, then measuring the decayed area. The result was expressed as a percentage of the total area.

2.10 *Total phenolic compounds (TPC)*

TPC was determined according to the modified method from Della Pelle *et al.,* [31]. An aliquot of 25 µL of the pulp was mixed with 10 µL of Folin–Ciocalteu reagent and gently stirred for 3 min. Next, 100 µL of 7.5% sodium carbonate (Na_2CO_3) and deionized water were added to adjust the final volume to 300 µL. The mixture was then stirred for 60 min at room temperature in the dark. The absorbance was recorded at 760 nm, with all reactions conducted in a 96–well plate.

2.11 *FRAP assay*

A 300 mM acetate buffer solution was prepared by dissolving 0.3 g of sodium acetate trihydrate in 1.6 mL of glacial acetic acid, adjusting the final volume to 100 mL (pH 3.6), following a modified method from Benzie and Strain [32].

For the 20 mM ferric chloride solution, 54 mg of $FeCl_3.6H_2O$ was dissolved in MilliQ water and adjusted to a final volume of 10 mL. The (2,4,6–tris(2–pyridyl)–s–triazine) TPTZ solution was

prepared by dissolving 0.0312 g of TPTZ in 10 mL of 40 mM HCl.

The FRAP solution was obtained by combining 25 mL of acetate buffer, 2.5 mL of ferric chloride solution, and 2.5 mL of TPTZ solution, then incubating the mixture at 37 °C for 15 min. 50µL of the sample was mixed with 250 µL of FRAP solution and incubated at room temperature in the dark for 15 min. The absorbance was measured at 593 nm, and results were expressed as µM TE/g of sample. All reactions were conducted in a 96–well plate.

2.12 *Statistical Analysis*

Statistical comparisons were performed using one–way analysis of variance (ANOVA), with significance considered at *p*–values below 0.05. Mean comparisons were carried out using the least significant difference (LSD) test.

3 Results and Discussion

3.1 *Weight loss*

In Figure 1, the variation in weight loss of differently treated mango fruits is reported as a function of storage time. It could be noted that weight loss (%) increased over time, with C reaching 12.62% by day 12, consistent with natural water loss through evaporation and respiration [33]. CH–treated fruits (CH, CH–UV) showed a reduced weight loss (9.66 % and 11.10 %, respectively), resulting from the chitosan protective film, limiting transpiration [34], [35]. The lowest weight loss was observed in the CT treated fruits (CT, CT–UV, CT–UV1). This improved performance is attributed to the synergistic effect between CH and TiO_2: CH forms a semipermeable film that moderates gas exchange, while TiO_2 fills micropores and reinforces the matrix, enhancing barrier integrity and reducing water vapor permeability [13], [36]. Additionally, the antimicrobial activity of TiO_2 helps preserve fruit integrity, indirectly reducing spoilage–related weight loss.

The difference between CH and CT treatments is primarily due to their distinct physicochemical properties. While CH alone may present microstructural defects such as cracks or pores, the incorporation of TiO_2 leads to a denser and more compact film structure with improved mechanical strength. However, while CH is biodegradable and generally recognized as safe, the use of inorganic TiO_2 in CT coatings may raise concerns regarding environmental impact and food safety in long–term commercial applications. Lastly, UV activation (CT–UV, CT–UV1) showed only a marginal effect on further reducing weight loss, suggesting that TiO_2's role is predominant in improving moisture retention [37]. Despite their initial effectiveness, a gradual increase in weight loss was observed across all treatments during the later stages of storage, suggesting a decline in the protective functionality of the coatings over time. This limitation may be due to coating degradation, reduced adhesion, or physical damage during prolonged storage. These findings highlight the need for further optimization to enhance the long–term stability and effectiveness of edible coatings under extended storage conditions.

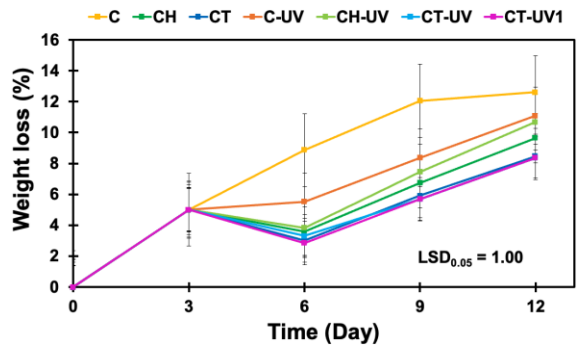

Figure 1: Weight loss of controls and coated mangoes during 12–day storage at 25 ± 2 °C. Statistical analysis was performed using the LSD test at a significance level of *p*-value ≤ 0.05. The $LSD_{0.05}$ value is 1.00, indicating that differences greater than this value between treatments are statistically significant.

3.2 *Ethylene production and respiration rate*

As shown in Figures 2A and 2B, the ethylene production and respiration rate of mangoes varied significantly among treatments during storage. The control groups (C and C–UV) exhibited a typical climacteric pattern, with ethylene production peaking on day 6 at 0.67 and 0.62 µL/kg.h, followed by a gradual decline. Similarly, their respiration rates peaked on day 3 at 200 and 160 mg CO_2/kg·h for C and C–UV, respectively, before progressively decreasing to 49.5–63.7 mg CO_2/kg·h by day 12.

In contrast, CH–coated mangoes (CH and CH–UV) showed lower ethylene production and a reduced respiration rate. CH–UV exhibited a slight ethylene

peak of 0.40 µL/kg.h) on day 6 but remained relatively stable afterward, suggesting a delay in ripening. The CT treatments (CT, CT–UV, CT–UV1) maintained the lowest and most stable levels of both ethylene production (0.19–0.29 µL/kg·h) and respiration (50–78 mg CO_2/kg·h) throughout storage. These results indicate that the combination of CH, TiO_2, and UV activation is highly effective in suppressing fruit metabolic activity, thereby delaying ripening and enhancing postharvest preservation of mangoes.

Ethylene production and respiration rate are closely linked in fruit maturation [38], [39]. As climacteric fruits, mangoes undergo a sharp rise in respiration and ethylene synthesis, driven by ACC synthase and ACC oxidase activity, which amplifies ethylene production through a positive feedback loop. After reaching the climacteric peak, respiration and ethylene levels decline, signaling fruit maturation. As ripening progresses, oxidative stress and cellular degradation impair ethylene synthesis, leading to senescence and reduced metabolic activity [40].

CH's semi–permeable barriers regulate internal gas exchange by adjusting O_2 and CO_2 levels, which helps delay ripening and prolong shelf life. In CH–coated mangoes, the preservation of quality is likely due to lower ethylene production and reduced respiration rate, effectively slowing metabolic processes and extending storage duration [41]–[43].

CT treatments resulted in greater preservation effects in mangoes compared to CH alone, likely due to the enhanced gas barrier properties provided by the incorporation of TiO_2 into the CH coating. This combination more effectively delayed ripening than CH alone, consistent with the findings of Xing *et al.,* [13]. The addition of TiO_2 improved the stabilization of fruit metabolic processes, contributing to reduced ethylene production and respiration rates. TiO_2 exhibits photocatalytic activity, which allows it to degrade ethylene, thereby slowing the ripening process and modulating the fruit's respiration rate. As a result, CT coatings help minimize oxidative stress and preserve the overall quality and freshness of the fruit [44]. When exposed to UV radiation, TiO_2 acts as a semiconductor and generates electron hole pairs that trigger redox reactions, leading to the production of reactive oxygen species (ROS) such as hydroxyl radicals (•OH) and hydrogen peroxide (H_2O_2). These ROS oxidize ethylene by attacking its C–H and C=C bonds, breaking it down into carbon dioxide and water, thus completing the photocatalytic degradation process [45].

Although UV exposure is known to regulate ethylene synthesis by inhibiting related enzymes [46], this study found no significant differences between UV–treated and non–UV–treated samples. Under the tested conditions, UV activation did not further enhance ethylene suppression or reduce respiration. This may be because TiO_2 alone already provides strong antimicrobial and barrier effects, limiting the additional impact of UV.

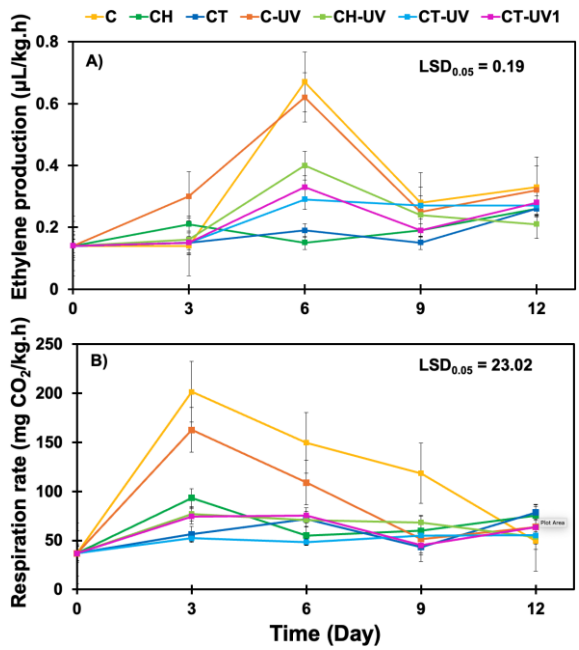

Figure 2: Ethylene production (A) and respiration rate (B) of controls and coated mangoes during 12–day storage at 25 ± 2 °C. Statistical analysis was performed using the LSD test at a significance level of *p*-value ≤ *0.05*. The $LSD_{0.05}$ value is 0.19 (A) and 23.02 (B), indicating that differences greater than this value between treatments are statistically significant.

3.3 *Physicochemical characteristics*

3.3.1 Peel color

The changes in peel color were best described by the lightness (L*), a*, and b* values (Table 1). The results show that CT coatings significantly enhance mango peel color stability throughout storage. Compared to C and CH–only treatments, mangoes coated with CT maintained higher L* values, indicating better lightness retention. They also exhibited lower increases in a* values, reflecting reduced red–shift,

and more stable b* values, indicating better preservation of yellow tones. degradation.

Table 1: Color parameters (L*, a*, b* values) of controls and coated mangoes during 12–day storage at 25 ± 2 °C.

Days	Treatments	L*	a*	b*
0	C	79.51 ± 1.72 b	2.01 ± 1.04 e	35.43 ± 5.02 c
	CH	- -	- -	- -
	CT	- -	- -	- -
	C-UV	- -	- -	- -
	CH-UV	- -	- -	- -
	CT-UV	- -	- -	- -
	CT-UV1	- -	- -	- -
3	C	78.11 ± 1.43 c	3.21 ± 1.06 d	34.28 ± 2.61 d
	CH	77.95 ± 1.43 c	3.44 ± 1.36 d	33.01 ± 2.79 d
	CT	79.69 ± 1.88 a	2.70 ± 0.89 d	24.74 ± 3.96 f
	C-UV	77.87 ± 1.83 c	3.07 ± 1.65 d	36.61 ± 2.92 c
	CH-UV	78.53 ± 1.56 b	3.28 ± 1.39 d	34.47 ± 3.65 c
	CT-UV	80.79 ± 1.82 a	2.20 ± 0.78 d	22.76 ± 4.91 g
	CT-UV1	80.27 ± 1.74 a	2.34 ± 1.45 d	23.04 ± 3.13 g
6	C	77.93 ± 2.00 c	3.65 ± 1.58 c	37.01 ± 5.37 c
	CH	79.30 ± 1.51 b	2.60 ± 0.84 d	33.60 ± 4.00 d
	CT	79.98 ± 2.04 a	2.84 ± 0.93 d	26.06 ± 3.78 f
	C-UV	78.42 ± 0.89 c	2.38 ± 0.80 d	35.40 ± 3.28 c
	CH-UV	78.05 ± 1.27 c	3.63 ± 4.48 c	36.09 ± 4.31 c
	CT-UV	79.63 ± 1.81 b	2.88 ± 0.83 d	25.67 ± 2.76 f
	CT-UV1	79.26 ± 1.91 b	2.60 ± 1.75 d	26.94 ± 3.64 e
9	C	77.87 ± 2.33 c	6.16 ± 1.75 b	44.64 ± 4.74 b
	CH	74.83 ± 2.29 e	6.10 ± 1.80 b	44.89 ± 2.17 b
	CT	78.91 ± 2.34 b	3.86 ± 1.41 c	26.42 ± 3.75 e
	C-UV	74.91 ± 1.23 e	4.96 ± 1.48 b	46.05 ± 2.65 a
	CH-UV	75.59 ± 1.66 d	4.86 ± 1.22 c	44.97 ± 1.82 b
	CT-UV	79.20 ± 2.29 b	3.43 ± 1.06 d	29.03 ± 5.62 e
	CT-UV1	80.21 ± 1.52 a	3.06 ± 0.95 d	25.16 ± 2.69 f
12	C	78.00 ± 1.56 c	7.98 ± 1.91 a	46.44 ± 2.44 a
	CH	72.83 ± 1.17 f	7.91 ± 1.27 a	46.05 ± 2.92 a
	CT	76.50 ± 1.88 d	4.93 ± 1.46 b	28.43 ± 4.31 e
	C-UV	72.98 ± 1.46 f	7.38 ± 1.31 a	47.66 ± 2.28 a
	CH-UV	73.58 ± 1.31 f	7.47 ± 1.52 a	46.87 ± 2.03 a
	CT-UV	78.24 ± 2.11 c	3.89 ± 1.52 c	28.08 ± 3.24 e
	CT-UV1	78.38 ± 1.61 c	3.66 ± 1.12 c	27.40 ± 4.69 e

Statistical analysis was performed using the LSD test at a significance level of p-value ≤ 0.05. Mean values with the same letters in a column are not significantly different (p-value *>0.05*)

These findings suggest that CT coatings exert a protective effect against color degradation. This improvement is likely due to the photoprotective and antioxidant properties of TiO_2, which help minimize carotenoid degradation by limiting fruit surface exposure to light and oxygen [47]. UV activation further enhanced the effect, as CT–UV treated mangoes maintained the most stable color parameters, particularly by day 9 and 12. This can be attributed to TiO_2 photoactivation, which increases antimicrobial action, slows respiration, and delays ripening. Consequently, pigment degradation was mitigated, as seen from reduced chlorophyll loss and delayed synthesis of carotenoids and anthocyanins.

CT–UV1, which involved a single UV exposure, showed a similar trend but was slightly less effective than repeated UV exposure. Continuous activation of TiO_2 likely led to sustained reactive oxygen species (ROS) generation, more effectively inhibiting oxidative enzymes (PPO, POD), suppressing ethylene production, and preserving pigments. Repeated UV treatment thus provided prolonged protection against oxidative and microbial stress, enhancing long–term color stability [48].

3.3.2 Fruit firmness

As shown in Figure 3, fruit firmness varied significantly across treatments and storage time. In the control samples, the fruit softened quickly. Firmness dropped below 3N by day 9 and remained low through day 12. This pattern is typical of mango ripening caused by cell wall and membrane degradation [29], [49]. CH treatment delayed firmness loss until day 9; however, firmness dropped below 5N with longer storage. This aligns with previous studies showing that CH coatings slow early softening but do not maintain firmness over time [50]. CH helps reduce water loss and evaporation, preserving fruit texture in the early stages, but it is not effective in preventing long–term softening. CT treatments (CT and CT–UV) initially improved firmness, with values peaking at 61–68 N on day 3. However, by day 9, firmness declined to levels comparable to the control. This supports the findings of Xing *et al.,* [51], suggesting that while TiO_2 may enhance short–term firmness through its barrier properties, it is not effective in preventing long–term softening. These findings indicate that although CH and CT treatments offer temporary firmness protection, none of the coatings were able to sustain texture quality over extended storage.

Moreover, UV–activated coatings (CH–UV and CT–UV1) showed no significant effect on firmness retention, with firmness trends closely resembling those of the control from day 6 onward. These results suggest that UV activation, under the conditions applied in this study, did not contribute to additional texture preservation beyond what was observed with CH or CT coatings alone.

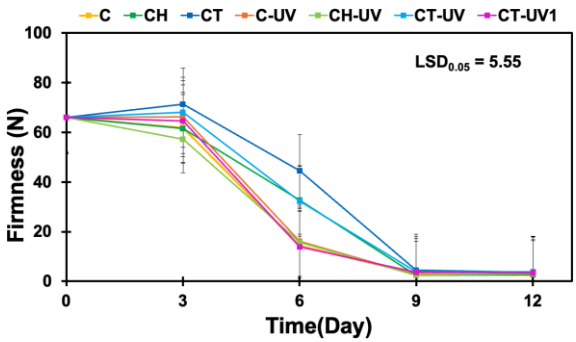

Figure 3: Firmness of controls and coated mangoes during 12–day storage at 25 ± 2 °C. Statistical analysis was performed using the LSD test at a significance level of p-value ≤ 0.05. The $LSD_{0.05}$ value is 5.55, indicating that differences greater than this value between treatments are statistically significant.

3.3.3 TA and TSS

In Figure 4(A), the variation of the TA (%) over 12 days of storage is shown. It is possible to observe a typical ripening trend where organic acids are metabolized as energy sources [52]. In control treatments (C and C–UV), TA progressively decreased, reaching values close to zero by day 9. CH–treated mangoes maintained higher TA until day 6 before decreasing to values similar to the control by day 9, indicating CH temporarily slows acid degradation [35].

CT coatings (CT, CT–UV, CT–UV1) delayed TA reduction, maintaining an acidity higher than that of the C throughout storage. The photocatalytic effect of TiO_2 may have slowed respiration and acid metabolism, stabilizing TA until day 6, with a sharper decline on day 9 [51]. UV–activated TiO_2 (CT–UV, CT–UV1) extended acidity retention longer than CT, though the effect was not sustained beyond day 9 [37].

As regard TSS (Figure 4B), values showed to increase over time, indicating starch–to–sugar conversion during ripening [53]. Control mangoes (C, C–UV) reached values of 18 °Brix by day 9, followed by a slight decrease. CH-treated fruits followed a similar trend, with a more gradual increase. CH initially reduced the increase of the TSS (low TSS by day 6) but later accelerated ripening, balancing sugar production and utilization [54]. CT–treated mangoes exhibited delayed TSS accumulation, remaining lower than control in early storage but stabilizing by day 12, suggesting CT coatings slow ripening without compromising final quality [51]. UV activation (CT–UV, CT–UV1) further slowed early sugar accumulation but later accelerated ripening, potentially due to UV–enhanced metabolic activity [35].

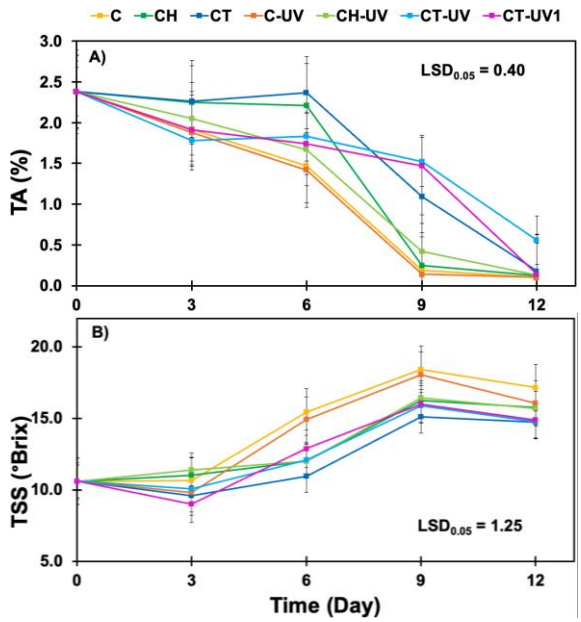

Figure 4: Titratable acidity (A) and total soluble solids (B) of controls and coated mangoes during 12–day storage at 25 ± 2 °C. Statistical analysis was performed using the LSD test at a significance level of p-value ≤ 0.05. The $LSD_{0.05}$ value is 0.40 (A) and 1.25 (B), indicating that differences greater than this value between treatments are statistically significant.

3.4 *Antioxidant properties and disease incidence*

3.4.1 TPC

In Figure 5, TPC of the differently treated mango fruits is reported as a function of storage time. It is possible to observe that TPC decreased over time in control mangoes (C, C–UV), due to the natural oxidation process and the utilization of phenolic compounds in metabolic processes, such as the conversion into other compounds (e.g., pigments or sugars), and in defense responses against oxidative stress during ripening [55]. A slight increase was observed after day 9, reaching 21.52–23.08 mg GAE/g by day 12, likely due to the water loss and increased dry matter as related to the weight loss.

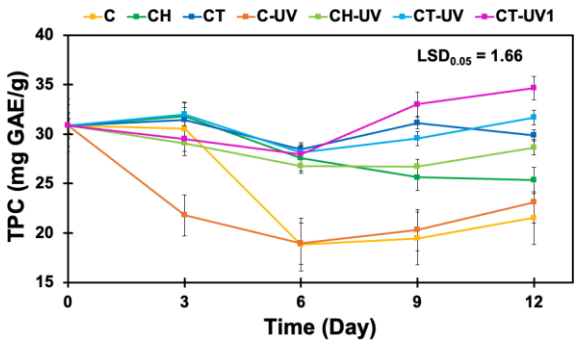

Figure 5: Total phenolic compounds of controls and coated mangoes during 12-day storage at 25 ± 2 °C. Statistical analysis was performed using the LSD test at a significance level of *p*-value ≤ 0.05. The $LSD_{0.05}$ value is 1.66, indicating that differences greater than this value between treatments are statistically significant.

CH–treated mangoes (CH, CH–UV) showed a slight decrease in the TPC, reaching values of 25.32 and 28.64 mg GAE/g by day 12, respectively, suggesting that CH could inhibit phenolic oxidation by forming a protective barrier against oxygen exposure [34]. In CT–treated mangoes (CT, CT–UV, CT–UV1), phenolic content increased significantly toward the end of storage, peaking at 29.86–34.65 mg GAE/g on day 12.

This suggests that CT coatings not only slow phenolic degradation but may also stimulate phenolic production in response to oxidative stress or light exposure [25]. The UV–activated TiO_2 treatments (CT–UV, CT–UV1) further enhanced phenolic stability, promoting a consistent antioxidant response, which may contribute to better quality preservation and extended fruit shelf life.

3.4.2 FRAP assay

Figure 6 illustrates the antioxidant capacity of treated mangoes during storage, as measured by the FRAP assay. In the control groups (C, C–UV), antioxidant levels declined steadily, reaching 84.93–85.92 µg TE/g by day 12, indicating oxidative stress and degradation of bioactive compounds. Mangoes treated with chitosan (CH, CH–UV) showed a slower decline, with values stabilizing around 89.11–92.83 µg TE/g after day 3. Similar trends were reported in other studies, where CH–treated mangoes stabilized after an initial drop [56], likely due to the semipermeable barrier formed by CH, which reduces oxygen penetration and respiration. Adiletta *et al.*, [57] also observed delayed senescence and preserved antioxidant capacity in CH–coated loquats, attributed to higher ascorbic acid levels and enhanced antioxidant enzyme activity.

These findings suggest that while CH can mitigate early–stage oxidative damage, it may be insufficient for long–term antioxidant preservation. Prior studies support this, showing that CH's efficacy often improves when combined with other agents such as essential oils, calcium salts, or modified atmosphere packaging [50], [58], [59].

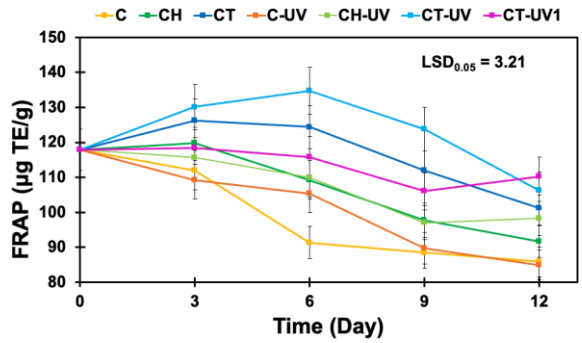

Figure 6: FRAP assay of controls and coated mangoes during 12–day storage at 25 ± 2 °C. Statistical analysis was performed using the LSD test at a significance level of *p*-value ≤ 0.05. The $LSD_{0.05}$ value is 3.21, indicating that differences greater than this value between treatments are statistically significant.

In contrast, CT–treated mangoes maintained significantly higher antioxidant levels than both controls and CH–treated samples, reaching up to 101.27 µg TE/g by day 12. This enhancement is likely due to TiO_2–induced mild oxidative stress, which stimulates cellular antioxidant defenses. UV–activated coatings (CT–UV, CT–UV1) amplified this effect, with FRAP values of 106.19–110.26 µg TE/g, demonstrating the added benefit of UV activation.

CH gives some protection. However, when combined with TiO_2, especially with UV activation, it becomes more effective in keeping antioxidant capacity. However, CH combined with other natural treatments may still be a viable alternative where TiO_2 use is a concern.

3.4.3 DI

The DI of the differently treated mango fruits as a function of storage time is reported in Figure 7. Control groups (C, C–UV) showed a sharp decay,

reaching values of the DI of 27.74 and 26.90% by day 12, respectively. This rapid deterioration reflects typical senescence in climacteric fruits, driven by increased respiration, ethylene production, enzymatic degradation, and microbial growth. The absence of a protective barrier in these treatments permitted rapid moisture loss and activation of degradative enzymes such as pectinases and polygalacturonases. UV treatment alone did not provide sufficient antimicrobial action or physiological protection, as evidenced by decay levels similar to the untreated control [60].

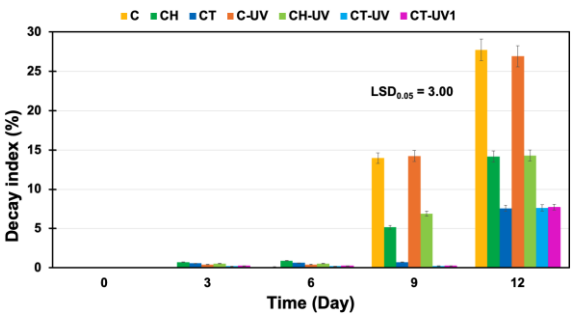

Figure 7: Decay index of controls and coated mangoes during 12–day storage at 25 ± 2 °C. Statistical analysis was performed using the LSD test at a significance level of *p*-value ≤ *0.05*. The $LSD_{0.05}$ value is 3.00, indicating that differences greater than this value between treatments are statistically significant.

In contrast, mangoes treated with CH (CH, CH–UV) demonstrated significantly lower decay (14.15% and 14.27%, respectively; *p*-value < 0.05), likely due to CH's known antifungal properties. CH forms a semipermeable coating that reduces gas exchange and transpiration, thereby slowing respiration and delaying senescence. Its cationic nature enables interaction with negatively charged microbial membranes, leading to structural disruption. However, the lack of additional DI reduction in UV–CH–treated fruits suggests that the effect of UV activation was minimal or redundant under the tested conditions [61].

The lowest DI values (7.57–7.71%) were observed in mangoes treated with CT (CT, CT–UV, CT–UV1), indicating effective decay suppression. This outcome is attributed to the synergistic action of CH and TiO_2: CH acts as a semipermeable barrier and exhibits antimicrobial activity, while TiO_2 enhances structural integrity and generates reactive oxygen species (ROS) that disrupt microbial cells. These combined effects also help reduce enzymatic degradation and oxidative stress. In contrast, the high DI values in the C and C–UV groups (26.90–27.74%) reflect the absence of such protective mechanisms, allowing rapid moisture loss, microbial growth, and enzymatic activity. UV activation did not significantly lower DI beyond CT alone, likely because TiO_2's antimicrobial function remained effective under ambient light. Overall, DI trends were influenced by the coating's barrier properties, antimicrobial effects, and its regulation of fruit physiology.

Beyond the primary objective of delaying ripening, this study highlights several other important benefits. The CT coating significantly reduced microbial decay, helping to minimize fruit loss during distribution. Additionally, by extending shelf life and reducing the amount of organic waste sent to landfills, this technology has the potential to lower the production of harmful fermentation gases such as methane and volatile organic compounds (VOCs), supporting sustainability goals within the food system.

4 Conclusions

This study demonstrates that CT coatings, particularly when combined with single UV activation, effectively delay ripening, reduce weight loss and microbial decay, and enhance antioxidant retention in mangoes. TiO_2 played a key role in reinforcing the barrier and antimicrobial properties of CH, whereas UV activation provided selective benefits, notably in preserving titratable acidity and phenolic content—most effectively through a single, not repeated, application. Compared to previous studies using natural antimicrobials like essential oils or calcium-based treatments, CT coatings offer comparable or superior preservation effects with fewer sensory changes and broader antimicrobial action. However, the protective effects tend to decline over extended storage, likely due to environmental factors affecting coating stability.

From an economic perspective, the initial cost of coatings like CT may be higher than traditional postharvest methods. However, they can help reduce spoilage and food waste. They also extend shelf life, which can lead to more products being sold and better economic returns, especially for export-focused supply chains. A formal cost–benefit analysis under commercial conditions is recommended to validate

this potential. Future studies should explore more durable composite coatings or natural additives that enhance film stability and reactivation under variable storage conditions. Optimizing UV activation protocols and comparing alternative coating materials may also lead to more scalable, cost-effective, and environmentally sustainable solutions for postharvest mango preservation.

Author Contributions

S.D.: conceptualization, investigation, data analysis, and writing of the original draft. P.N.: conceptualization, research design, methodology, reviewing and editing, supervision, funding acquisition, and project administration. P.P.: conceptualization, supervision, and reviewing and editing. K.S.: conceptualization, and reviewing and editing. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors utilized the ChatGPT tool to enhance the language and readability of the manuscript.

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