



Enhancement of chitosan coating performance by hot water treatment: Effects on stability, nutritional quality, and antioxidant retention during storage in litchi cv. China-3

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Author contributions

M.J. Hadika and R.B. Anwar designed and conducted the experiment, analyzed the data, and prepared the draft. S.R. Joy assisted in data collection and contributed to manuscript preparation. M.H. Rahman provided supervision. M.S. Islam and F. Akther contributed to revising the manuscript. As part of the study team, each author read and approved the manuscript.

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Abstract: Litchi (*Litchi chinensis* Sonn.) is a high-value tropical fruit, yet it suffers from rapid postharvest deterioration. This research appraised the combined effects of chitosan (CHT) coatings and hot water (HW) treatments on the shelf life, physicochemical quality, and antioxidant retention of litchi cv. China-3. Fruits were treated with 0.5% or 1% CHT, alone or following HW immersion (50°C for 5 minutes), and stored at ambient temperature. The combination of CHT with HW significantly reduced weight loss, decay, and browning index, while extending shelf life 35.71% longer than untreated fruits. This treatment preserved firmness, attenuated the decline in titratable acidity (TA), and minimized increases in total soluble solids (TSS). After 9 Days of Storage (DAS) at ambient temperature, fruits treated with 0.5% CHT + HW maintained higher levels of β -carotene (6.84 μ g/100 g), total sugar (TS) (21.27%), ascorbic acid (46.99 mg/100 g), phenolics (12.60 mg/g), and flavonoids (3.13 mg/g) compared to untreated fruits, indicating a beneficial effect on the nutritional quality of the fruits. The antioxidant activity (DPPH* scavenging activity) was also significantly higher (45.04%) in treated fruits compared to the control (29.75%). Furthermore, compared to the control, the treatment delayed colour degradation, preserved lightness ($L^*=22.14$), and achieved superior sensory ratings in flavour, sweetness, appearance, and overall acceptability. These findings suggest that combining 0.5% CHT with HW is an eco-friendly postharvest strategy to enhance storage stability, retain nutritional and sensory qualities in litchi.

1. Introduction

Litchi (*Litchi chinensis* Sonn.) is a climatic fruit, a member of the family Sapindaceae, which is universally cultivated in tropical and subtropical regions. Its attractive, brilliant red peel with soft, juicy, sweet pulp and heightened levels of bioactive compounds resulted in an increasing consumer demand globally. Additionally, it is an excellent source of

minerals, vitamins, polysaccharides, and polyphenols (Flavan-3-ol compounds, phenols, terpenes, steroids, and flavonoids) (Castillo-Olvera *et al.*, 2025). These bioactive components can decrease cholesterol, scavenge oxygen pollutants, and reduce the hazards associated with smallpox, dyspepsia, and cardiovascular disease (Gao *et al.*, 2017) and also promote hunger and nourish the brain.

However, litchi is a highly perishable fruit with a short shelf life and lacks postharvest processing technologies; barely 10% of the entire yield is processed (Kumar *et al.*, 2020). The fruit's hot-season maturation leads to rapid water loss due to turgor pressure in the pericarp cells, causing tissue collapse and a dull, brown peel color within 24 to 48 hours after harvest at ambient temperature. The primary causes of pericarp browning and rapid degradation are the oxidation of phenolic substances, the quick breakdown of the anthocyanin color, and increased enzyme activity of PPO and POD (Jiang *et al.*, 2005). Fumigation with sulfur dioxide (SO₂) is commonly used to prevent litchi pericarp browning. However, it poses health risks to humans, as it triggers allergies in individuals with asthma (Huang *et al.*, 2024). Thus, there is a pressing demand for a postharvest solution that is safe to consume, environmentally sustainable, and cost-effective.

The earliest and most basic method of postharvest decay management is HW treatment, which prevents fruit quality loss and post-harvest pathogens (Khalil *et al.*, 2022). This antibacterial action results from heat-induced damage to the cell membranes and proteins of pathogenic microbes, which denatures enzymes, disrupts structural proteins, and ultimately causes cell lysis and death (Brunda *et al.*, 2025). HW treatment showed a promising result by reducing the disease incidence of mango, peach, and banana fruit (Kim *et al.*, 2007; Huan *et al.*, 2017; Ajenifujah-Solebo *et al.*, 2019). Additionally, this treatment accelerated fruit ripening, skin browning, and softening. Therefore, we must discover a novel treatment that can slow down the ripening process, prevent postharvest deterioration, and mitigate the adverse effects of HW treatment.

Edible coatings represent a promising innovation in the field of postharvest technology. They are safe, biodegradable, and capable of enhancing the shelf life of whole and fresh-cut fruits, offering a hopeful outlook for the future of litchi fruit preservation (Prieto-Santiago *et al.*, 2025). It controls respiratory

behavior and acts as a physical barrier, reducing moisture loss and oxidation (Araújo *et al.*, 2024). Among these polysaccharides, CHT stands out due to its high molecular weight, natural origin from chitin, and significant promise in postharvest technology. Its inherent antibacterial qualities, film-forming ability, antioxidant capacity, non-toxicity, and biocompatibility make it a confident choice for improving the postharvest quality of fruit (Martins *et al.*, 2024). This polysaccharide has been used to prolong storage life, reduce post-harvest decay, and decrease ethylene production of mangoes (Parvin *et al.*, 2023), litchi (Kumar *et al.*, 2020), and papaya (Ali *et al.*, 2011) fruit.

Even though edible coatings and HW have been thoroughly studied recently, the combined impact of these treatments, particularly on litchi fruits, has not gotten as much attention. However, to the author's best knowledge, limited information is available on the interactive effects of different concentrations and combinations of CHT and HW treatments on pericarp browning, biochemical attributes, and shelf life of litchi under practical storage conditions. In response to this important gap, this study aimed to determine the best combination of HW and CHT concentrations to develop an edible coating. This coating aimed to prolong the overall quality and shelf life of litchi while fulfilling consumer dietary expectations and ensuring the treatment's safety by excluding any harmful chemical residues.

2. Materials and Methods

Plant materials, design, and treatments

This experiment was carried out using a completely randomized design (CRD) with five treatments and three replications at the Horticultural Laboratory of Hajee Mohammad Danesh Science and Technology University in Dinajpur. Five treatments were T₀= Control (only water), T₁= 0.5% CHT, T₂= 1% CHT, T₃= 0.5% CHT+ HW, T₄= 1% CHT + HW. Commercially matured China-3 litchi fruits were collected directly from the farmer's orchards early in the morning based on their uniformity in size, shape, and color. Then, they were washed in purified water, air dried, and promptly transferred to the laboratory within one hour. To determine the physical and chemical changes at 0, 3, 6, and 9 Days of Storage (DAS), twenty fruits were randomly selected from each replication per treatment and analyzed.

Preparation and application of film

The film was prepared following the methodology outlined by Muthmainnah *et al.* (2019). CHT powder (CAS #:9012-76-4, Laboratory Grade, Merck KGaA, Germany) was solubilized within 1% acetic acid (CAS#:64-19-7, ACS Grade, Merck KGaA, Germany) solution at two different concentrations of 0.5% and 1%. The solution was stirred (at 1500 ± 20 rpm, MS-H380-Pro, DLAB, USA) for 60 ± 2 minutes at $40 \pm 1^\circ\text{C}$ and filtered through a cotton cloth to avoid any undissolved impurities. The solution was then cooled, and 0.5% glycerol (CAS#: 56-81-5, Molecular Biology Reagent Grade, Sigma-Aldrich) was added as a plasticizer. Fresh, clean water was heated to $50 \pm 2^\circ\text{C}$, and measured by a scientific thermometer (ASTM 110°C Mercury Thermometer). Moreover, fruits were treated through immersion in 0.5% and 1% CHT solutions for 5 ± 1 minutes. For combined treatment, fruits were first immersed in HW for 5 ± 1 minutes at $50 \pm 2^\circ\text{C}$, then air-dried, and dipped in the respective CHT solution (0.5% or 1%). Only water was applied to the non-treated litchi fruit. After that, treated fruits were stored at ambient conditions ($27 \pm 2^\circ\text{C}$ and 80-85% RH).

Determination of physiological weight loss, decay percentage, and shelf life

Weight loss measurements were taken using a digital balance (Model: ND EKI-620, Korea, $\text{SD} \pm 0.001$ g). Shelf-life and decay percentage were determined following Akhter *et al.* (2025) with minor modifications, using standardized visual assessment of fruit appearance. Fruits were considered to have reached the end of their shelf life once they became unsuitable for consumption or commercial sale based on predefined quality criteria, including visible decay and excessive browning (>25 browning). Decay was defined based on visible qualitative symptoms, including fungal growth, water-soaked lesions, tissue softening, skin breakdown, and/or off-odor development.

Fruit firmness, total soluble solids, ascorbic acid, titratable acidity, total sugar, and β -carotene

Fruit firmness was determined using a texture analyzer (FR-5120 Lutron Made in Taiwan, $\text{SD}: \pm 5^\circ$) with a 5/16-inch plunger, as stated by Magness and Taylor (1925). TSS were determined using a digital refractometer (Hanna Digital Refractometer, Model HI96801, $\text{SD}: \pm 0.2\%$ Brix). The measurement was recorded as %Brix at room temperature, according to

AOAC (1980).

Ascorbic acid content was determined according to Ranganna *et al.* (1997). Briefly, 1g of pulp tissue was mixed with 50 mL of 3% (w/v) metaphosphoric acid in a pestle and mortar. The mixture was then filtered using Whatman No. 41 filter paper. Following that, 1 mL of the filtrate was mixed with 10 mL of the 2,6-dichlorophenol dye solution in a Falcon tube and vortexed. A spectrophotometer (Shimadzu Europe UV mini-1240) was used to measure the absorbance at a wavelength of 518 nm and reported as mg/100 g.

The TA was quantified using the method of AOAC (1980). The obtained litchi pulp extract (10 mL) was titrated using 0.1 N NaOH and 1% phenolphthalein until a bright pink endpoint observed.

The TS content was measured using the method described by Lane and Eynon (1923). A 50 mL sample was dispensed into a 100 mL volumetric flask, then 5 mL (1:1) HCL was added, heated at 70°C to 80°C for 30 ± 2 minutes, and neutralized by adding sodium carbonate. After cooling, 100 mL of distilled water was added to adjust the volume and calculated through the following equation:

$$\text{Total sugar (\%)} = \frac{\text{Fehling factor} \times \text{Dilution} \times 100}{\text{Weight of sample} \times \text{Titrate}}$$

Subsequently, β -carotene was determined by Ultra Performance Liquid Chromatography (UPLC) at a temperature of 4°C , which was modified from Ahamad *et al.* (2007). In brief, 5 g of material was homogenized in 30 mL of acetone, BHT (1%) was added, and the mixture was filtered and washed twice. After discarding the residue, the filtrate was dried over anhydrous sodium sulfate (20 g).

Total phenolic compounds, total flavonoid content, antioxidant activity

The phenolic compounds were quantified spectrophotometrically as described by Nur Sazwi *et al.* (2013). 1 mL diluted extract (1 g pulp with 10 mL methanol) was combined with 5 mL Folin Ciocalteu reagent (Sigma-Aldrich, Laboratory grade, MDL number: MFCD00132625) (10%, v/v) and 4 mL Na_2CO_3 (7.5%, v/v), then agitated at ambient temperature for 2 hours and quantified using a spectrophotometer (Shimadzu, UVmini-1240) at a wavelength of 765 nm. 1 mL blank was also determined. A calibration curve was generated using gallic acid standard ($R^2 = 0.9997$), and total phenolic

content was expressed as mg GAE/g DW.

Litchi pulp extract was diluted in methanol (10 mL) and mixed with 3 mL of 5% (w/v) NaNO₂ and distilled water (40 mL) to determine total flavonoid content as described by Asem *et al.* (2020). Following a 5 min reaction period, 3 mL of 10% (w/v) AlCl₃ was added, and after an additional 5 min, 20 mL NaOH was added. Then the mixture was incubated at ambient temperature for 15 min, and measured with a spectrophotometer (Shimadzu, UVmini-1240) at a wavelength of 415 nm. In the same manner, a blank specimen was made and measured. A calibration curve was established using quercetin as the standard, with a coefficient of measurement (*R*) of 0.9999, and the results were presented as mg/100 g.

The antioxidant activity, as DPPH scavenging activity, was quantified spectrophotometrically (517 nm, Shimadzu, UVmini-1240) as outlined by Do *et al.* (2014). In brief, 1 mL of diluted extract (1g pulp with 10ml methanol) was incubated with 2 mL of 0.004% DPPH for 30 min.

Measurement of color

Hunter color (L*, a*, b*) was measured using a biobased chromameter (BCM110, China). The L*, a*, b* values represent lightness to darkness, greenness to redness, and blueness to yellowness, respectively.

Sensory evaluation

Sensory analysis was performed at 9 DAS by five trained panelists (aged 25-60 years, three men and two women) (Sortino *et al.*, 2017). Prior to the evaluation, the panelists received one week of training focused on litchi fruit attributes, including appearance, flavour, sweetness and overall impression. Each panelist independently evaluated three randomly presented, blind-coded samples per treatment using a structured questionnaire. All assessments were performed under ambient conditions, with water to rinse mouth rinsing between samples. Scores were recorded on a nine-point hedonic scale (1 - Dislike immensely, 2 - Dislike very much, 3 - Dislike moderately, 4 - Dislike slightly, 5 - Neither like nor dislike, 6 - Like slightly, 7 - Like moderately, 8 - Like very much, and 9 - Like immensely) (Nasrin *et al.*, 2025).

Browning index

At 3-day intervals, the browning index of both coated and uncoated litchi fruits was assessed by qualitative analysis based on visual estimation

(Kumar *et al.*, 2013). Randomly, ten fruits were selected from each replication and marked using a 6-point visual scale. The six-scale point included: 0 - No browning, 1 - less than 5% browning, 2 - less than 25% browning, 3 - 25-50% browning, 4 - 50-75% browning, 5 - more than 75% browning (poor quality). The browning index was determined as $\sum$ (browning scale score x percentage of corresponding fruits within each class).

Statistical analysis

The statistical analysis was done using Statistix 10.0 (Analytical Software Inc., Tallahassee, FL, USA, 2010) software. Means and standard deviation were calculated as per the standard procedure. The statistical differences between treatments were evaluated using Tukey's test at a significance threshold of *p*<0.05.

3. Results

Weight loss, decay percentage, and shelf life

CHT and HW treatments significantly impacted the weight loss of litchi fruit during storage. The weight loss was reduced compared to the control with the application of CHT alongside HW (Fig. 1). On 6 DAS, the combination of 0.5% CHT with HW treatment resulted in the lowest weight loss at 13.03%, while the control fruits exhibited the highest weight loss (20.80%). At 9 DAS, application of 0.5% CHT with HW effectively reduced weight loss, resulting in a 1.5-fold decrease in comparison to the control.

According to figure 1, the longer the fruits were stored, the faster they deteriorated. No fruit deterioration was observed in all treatments up to 5 DAS. At 6 DAS, the control and 1% CHT-treated fruit showed a significant decay rate of 20.5% and 2.03%, respectively. Furthermore, after 9 DAS, the control exhibited a maximum decay rate (60%). In contrast, 0.5% CHT+HW and 1% CHT+HW treated litchi fruits showed similar decay rates (1.83% and 2.00%, respectively), which were significantly lower than 0.5% and 1% CHT (5.33% and 10.00%, respectively) treated litchi fruits. Similarly, 0.5% CHT+HW showed the maximum shelf life (14 days), which was 35.71% greater than the control (9 days), as presented in figure 1. Furthermore, our current findings showed that shelf-life was improved by 34.11%, 32.48%, and 27.07% for T₄, T₁, and T₂ treatments, respectively, in

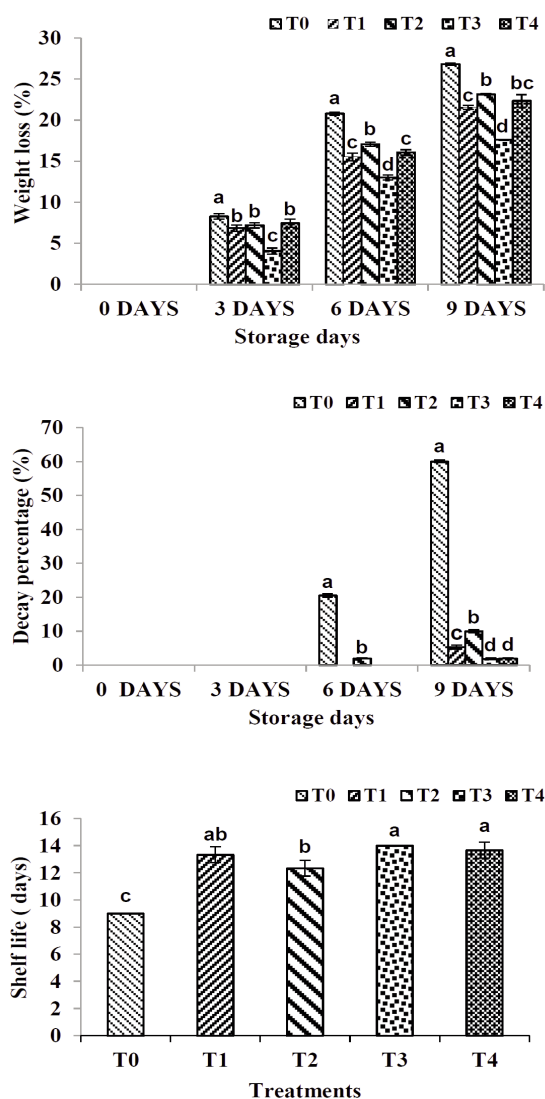


Fig. 1 - Effect of chitosan and hot water treatments on weight loss, decay percentage, and shelf life of litchi fruit during storage. Values denoted by distinct letters exhibit significant differences among the treatments within same storage day ($p < 0.05$). Data are expressed as mean $\pm$ standard deviation (SD), illustrated by vertical bars. T0= control; T1= 0.5% chitosan; T2= 1% chitosan; T3= 0.5% chitosan + hot water; T4= 1% chitosan + hot water.

comparison to the control.

Firmness, total soluble solids, titratable acidity, total sugar, and content of ascorbic acid

CHT and HW treatments significantly influenced fruit firmness during storage (Table 1). At 3 DAS, no significant differences were observed among the treated and untreated fruits ($P > 0.05$), whereas a significant decline in firmness was observed at 6 DAS ($P < 0.05$). However, from the initial to the end of the

storage days, the firmness of the sample coated with 0.5% CHT + HW remained high (from 1.43 to 1.48 kg/cm²); meanwhile, the control group experienced a more substantial loss (from 1.45 to 1.09 kg/cm²).

TSS content gradually increased with the advancement of the storage duration, reaching the maximum value (17.07%) in the control, which is statistically similar with T1 (15.70%) and T2 (15.89%) treated fruits, while the minimum was (15.47%) in T₃ treatment at the ninth day of storage (Table 1). On the initial day, TSS content showed no significant variation among treatments. At 3 DAS, the TSS content was 3% higher in control fruits than in T₃-treated fruits, although the difference was not significant. In contrast, at 6 and 9 DAS, control fruits showed significantly higher TSS (12% and 9%, respectively) compared with the T₃ treatment. At 9 DAS, TSS content in the control was 9.37%, 8.51%, 6.95%, and 8.06% higher than in T₃, T₄, T₂, and T₁, respectively.

As presented in Table 1, TA in both coated and uncoated fruits exhibited a steady decline during ripening at room temperature, with a more pronounced decrease in the untreated fruits. At the initial (0) day, a significantly similar TA level was observed in all treated and untreated fruit. Moreover, the control group showed the lowest levels of 0.22%, 0.15%, and 0.13% while treated with 0.5% CHT, and HW exhibited the highest TA levels of 0.24%, 0.18%, and 0.17%, respectively, at 3, 6, and 9 DAS. Additionally, at the endpoint of storage, the second-highest TA level was in T2, which is statistically non-significant compared to T₃. The TS content in both coated and uncoated samples increased gradually during postharvest storage, while ascorbic acid levels declined (Table 1). The highest TS content was recorded at 21.27% in the 0.5% CHT combined with HW, and the lowest was 15.80% in the control at 9 DAS. By the end of storage, the TS content rose by 25.70% in the 0.5% CHT + HW treatment compared to the control. Additionally, 0.5% CHT + HW-treated fruits exhibited the lowest degradation of ascorbic acid, decreasing from 70.97 to 46.99 mg/100 g, while the untreated group showed the maximum deterioration, dropping from 70.99 to 31.65 mg/100 g during storage.

Beta-carotene, total phenol, flavonoid content, and antioxidant activity

A significant difference was observed across all

Table 1 - Effects of chitosan and hot water treatment on firmness, total soluble solid (TSS), titratable acidity (TA), total sugar (TS), and ascorbic acid content of litchi fruits during storage

Treatments	Storage periods (days)			
	0	3	6	9
<i>Fruit firmness (kg/cm²)</i>				
T0	1.45±0.01 a	1.49±0.09 a	1.21±0.03 c	1.09±0.04 c
T1	1.46±0.14 a	1.54±0.21 a	1.39±0.06 b	1.33±0.01 b
T2	1.47±0.17 a	1.58±0.09 a	1.37±0.03 b	1.32±0.02 b
T3	1.43±0.04 a	1.62±0.21 a	1.52±0.04 a	1.48±0.01 a
T4	1.41±0.17 a	1.59±0.12 a	1.41±0.03 b	1.39±0.04 b
CV (%)	8.56	10.01	2.74	2.16
LSD	0.33	0.42	0.10	0.07
<i>TSS (% Brix)</i>				
T0	14.59±0.57 a	15.07±1.09 a	16.57±0.50 a	17.07±0.78 a
T1	14.23±1.15 a	14.61±0.18 a	15.12±0.22 b	15.70±0.33 ab
T2	14.40±0.20 a	14.62±0.53 a	15.40±0.22 b	15.89±0.48 ab
T3	14.35±0.57 a	14.59±0.11 a	14.64±0.50 b	15.47±0.52 b
T4	14.40±0.43 a	14.89±0.28 a	15.09±0.58 b	15.62±0.42 b
CV (%)	3.42	2.47	2.82	3.31
LSD	1.32	0.98	1.16	1.42
<i>Titratable acidity (%)</i>				
T0	0.253±0.005 a	0.22±0.01 b	0.15±0.01 b	0.133±0.005 b
T1	0.250±0.001 a	0.236±0.001 ab	0.176±0.005 a	0.15±0.01 ab
T2	0.256±0.005 a	0.240±0.005 ab	0.183±0.005 a	0.16±0.01 a
T3	0.253±0.005 a	0.243±0.005 a	0.180±0.001 a	0.170±0.001 a
T4	0.253±0.005 a	0.243±0.005 a	0.176±0.025 c	0.157±0.015 ab
CV (%)	2.04	3.27	4.45	6.27
LSD	0.01	0.02	0.02	0.03
<i>Total sugar (%)</i>				
T0	12.33±0.34 a	13.61±0.09 b	14.83±0.14 c	15.80±0.27 c
T1	12.34±0.17 a	14.49±0.19 a	16.85±0.28 b	18.36±0.29 b
T2	12.24±0.16 a	13.64±0.34 b	17.10±0.11 b	17.99±0.36 b
T3	12.22±0.08 a	14.55±0.23 a	18.21±0.54 a	21.27±0.34 a
T4	12.29±0.08 a	14.47±0.06 a	17.50±0.40 ab	18.46±0.21 b
CV (%)	1.92	1.81	2.44	1.99
LSD	0.64	0.69	1.11	0.98
<i>Ascorbic Acid (mg/100 g)</i>				
T0	70.99±0.19 a	59.96±0.90 b	48.24±0.37 c	31.65±0.78 d
T1	71.05±0.90 a	63.69±0.91 a	53.65±0.15 b	42.81±0.18 c
T2	71.82±0.95 a	61.58±0.35 b	54.64±0.41 ab	41.64±0.50 c
T3	70.98±0.38 a	64.64±0.56 a	57.20±1.97 a	46.99±0.33 a
T4	71.05±0.90 a	64.31±0.59 a	55.07±1.34 ab	44.19±0.24 b
CV (%)	1.03	1.11	2.40	1.11
LSD	1.98	1.88	3.47	1.24

Values denoted by distinct letters exhibit significant differences among the treatments within same storage day ($p < 0.05$). Data are expressed as mean $\pm$ standard deviation (SD). T0 = control; T1 = 0.5% chitosan; T2 = 1% chitosan; T3 = 0.5% chitosan + hot water; T4 = 1% chitosan + hot water.

treatments during the period from 3 to 9 DAS (Fig. 2). Initially, all treatments showed similar carotenoid levels, with no significant differences among them. However, during 3 to 9 DAS, both coated and uncoated fruits experienced an increase in

carotenoid content. The highest carotenoid content observed was 6.84 $\mu\text{g}/100\text{ g}$ in the 0.5% CHT+HW treatment, which increased by almost 1.49-fold, while the untreated fruit had the lowest level at 5.29 $\mu\text{g}/100\text{g}$, experiencing a 1.14-fold increase from the

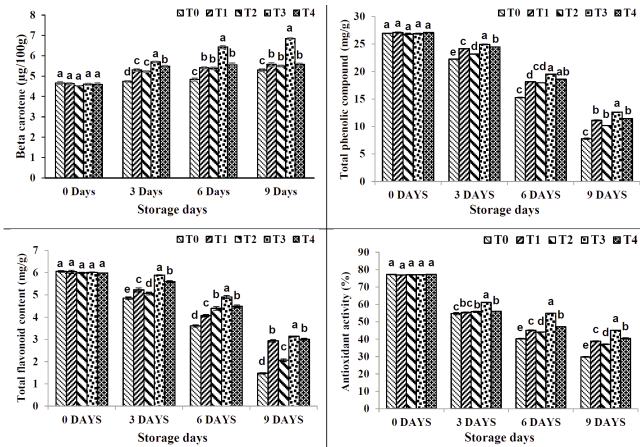


Fig. 2 - Effects of chitosan and hot water treatment on beta-carotene, total phenol, flavonoid content, and DPPH* scavenging activity of litchi fruit during storage. Values denoted by distinct letters exhibit significant differences among the treatments within same storage day ($p < 0.05$). Data are expressed as mean $\pm$ standard deviation (SD), illustrated by vertical bars. T0= control; T1= 0.5% chitosan; T2= 1% chitosan; T3= 0.5% chitosan + hot water; T4= 1% chitosan + hot water.

beginning of the study. A comparable upward pattern was also observed for T_1 , T_2 , and T_4 , which increased by nearly 1.2 times from the beginning to the last day of storage (9).

Figure 2 demonstrates that the total phenolic and flavonoid content in litchi decreased consistently throughout the storage period for both treated and untreated fruits. Based on the data, it can be observed that throughout the storage period (0-9 DAS) the combined 0.5% CHT + HW treatment maintained the highest total phenol content among all treatments. The application of 0.5% CHT with HW showed twice the flavonoid content (3.13 mg/g) compared to the control (1.47 mg/g) at 9 DAS. Correspondingly, DPPH* scavenging (antioxidant) activity gradually decreased during the storage period (Fig. 2). The combined application of 0.5% CHT with HW showed the highest DPPH* scavenging activity (77.0% to 45.04%), whereas the control displayed the lowest, ranging from 77.18% to 29.75% at 9 DAS. The results indicated that T_3 (0.5% CHT + HW) treated fruit produced 33.94% more antioxidant content in comparison to the untreated fruits on 9 DAS.

Color (a^* , b^* , L^*)

Color is a crucial characteristic of fruit, indicating freshness and influencing consumer acceptance. Our study showed a significant increase in the a^* (green-to-red transition) and b^* (yellow to blue), while the

L^* (lightness) of the fruits decreased during storage (Fig. 3). A significant difference was observed between all coated treatments (T_1 - T_4) and control (T_0). In contrast, differences among coated treatments (T_1 - T_4) showed no significant differences for a^* and L^* value, while b^* value varied significantly. Fruits coated with 0.5% CHT + HW exhibited the lowest increasing rate of the a^* value, achieving 9.45 to 10.41, denoting a slow color transformation in comparison to the uncoated (9.85 to 14.25) fruits. The b^* value was higher in untreated

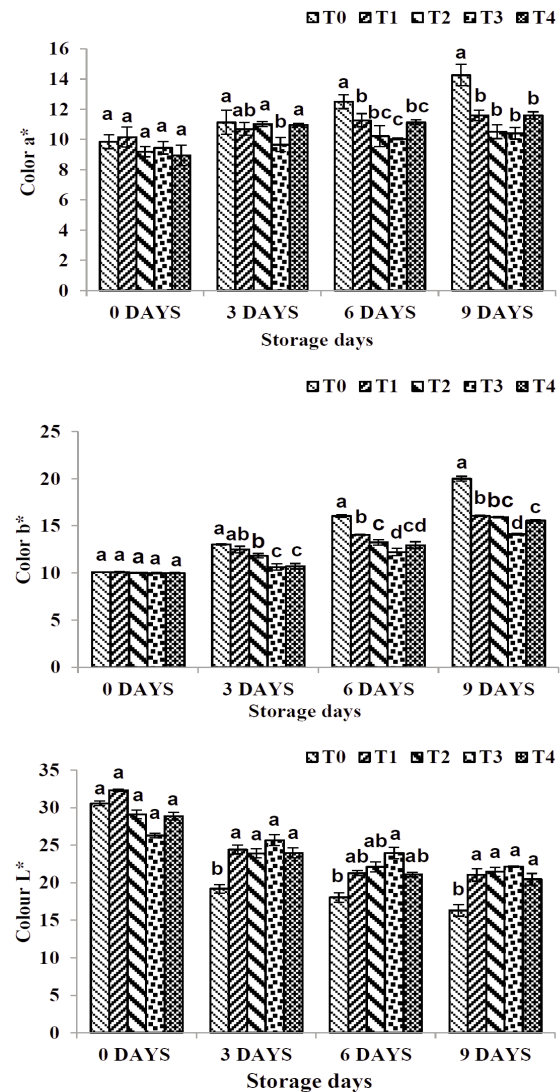


Fig. 3 - Effects of chitosan and hot water treatment on color a^* , b^* , and L^* of litchi fruit during storage. Values denoted by distinct letters exhibit significant differences among the treatments within same storage day ($p < 0.05$). Data are expressed as mean $\pm$ standard deviation (SD), illustrated by vertical bars. T0= control; T1= 0.5% chitosan; T2= 1% chitosan; T3= 0.5% chitosan + hot water; T4= 1% chitosan + hot water.

fruits (20.01) compared to the T_3 (14.09) treatment at 9 DAS. Regarding the treatment of 0.5% CHT + HW, higher lightness (L^*) values were preserved. On the 9th day, the 0.5% CHT + HW group exhibited a maximum L^* value (22.14), while the untreated group recorded the minimum (16.31).

Browning index (scale)

The browning index of litchi fruits, which measures the enzymatic browning that occurs when phenolic substances interact with enzymes, leading to the formation of brown color (Zhang *et al.*, 2015). According to figure 4, the browning index significantly increased over time across all samples (treated and untreated), while a significant. The browning index of untreated fruits gradually increased. At 3, 6, and 9 DAS, maximum browning index (3.63, 4.40, and 5) was found in the control, while the minimum (0.1 and 2.93) was observed in T_3 -treated fruits.

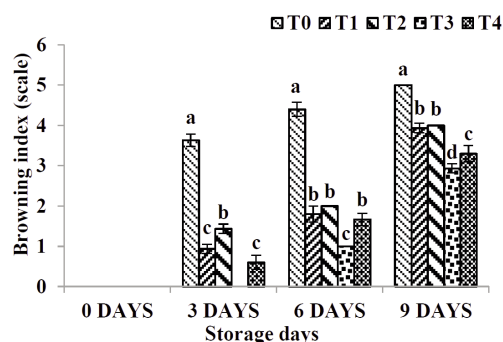


Fig. 4 - Effects of chitosan and hot water treatment on the browning index of litchi fruit during storage. Values denoted by distinct superscript letters exhibit significant differences among the treatments within same storage day ($p < 0.05$). Data are expressed as mean $\pm$ standard deviation (SD), illustrated by vertical bars. T0= control; T1= 0.5% chitosan; T2= 1% chitosan; T3= 0.5% chitosan + hot water; T4= 1% chitosan + hot water.

Sensory evaluation

The treated fruits demonstrated a significant improvement in sensory evaluations compared with the untreated fruits. (Fig. 5). Overall, after 9 DAS, fruits treated with 0.5% CHT + HW attained superior scores in flavour (8.00), sweetness (8.33), appearance (6.67), and overall acceptability (7.67), markedly outperforming the untreated fruits, which registered scores of 5.33, 6.00, 4.33, and 4.33, correspondingly.

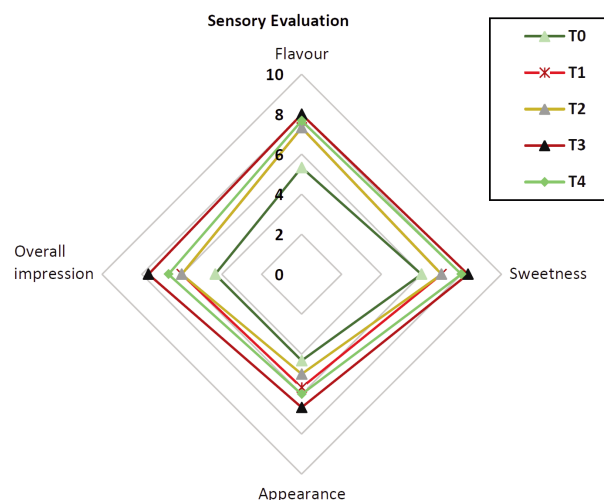


Fig. 5 - Effects of chitosan and hot water treatment on the sensory characteristics of litchi fruits at 9 DAS. T0 = control; T1 = 0.5% chitosan; T2 = 1% chitosan; T3 = 0.5% chitosan + hot water; T4 = 1% chitosan + hot water.

Furthermore, fruits treated with 0.5% and 1% CHT alone showed significantly higher flavour (7.33) and sweetness (7.00) compared to the control (T_0); however, their appearance and overall impression scores were lower than the corresponding combined treatments (0.5% and 1% CHT + HW). Notably, fruit flavour scores were statistically similar between samples treated with CHT alone and those receiving the combined CHT + HW treatments, whereas sweetness, appearance, and overall impression scores were significantly higher in the combined treatments (T_3 and T_4), indicating their superior overall sensory performance.

4. Discussion and Conclusions

Extending the shelf life of litchi fruit is crucial for minimizing post-harvest losses. In the present study, CHT treatment reduced weight loss compared to the control, with the combined application CHT and HW showing the greatest weight loss (Fig. 1). Notably, the combination of 0.5% CHT + HW and 0.5% CHT alone reduced weight loss by approximately 1.5-fold and 1.2-fold compared to the control. This reduction can be attributed to the formation of a semipermeable coating on the fruit's surface by CHT, which limits transpiration and O_2 and CO_2 exchange, thereby reducing moisture loss (Saberi Riseh *et al.*, 2024).

Moreover, short-duration HW treatment enhanced cuticle integrity, decreasing respiration and minimizing transpiration, making this combination more effective (Brunda *et al.*, 2025). Similar findings were observed in CHT and HW treated mango fruit (Khalil *et al.*, 2022). Furthermore, prolonged storage increases susceptibility to browning and drying, which is a key indicator of litchi fruit quality. Our results indicate reduced decay percentage and extended shelf life, suggesting a potential reduction in disease-related deterioration. CHT demonstrates notable antibacterial and antifungal properties that effectively inhibit the growth of harmful microbes by forming a continuous, thick, and flexible semi-permeable layer on the coated surface (Wang *et al.*, 2021). In addition, HW can either directly inhibit pathogen growth or spore germination or boost the fruit's defense against diseases by triggering a defense response (Ferreira Da Silva *et al.*, 2020). Moreover, coating with CHT and HW enhanced the storage life of litchi (Fig. 1), likely due to reduced weight loss and lower fruit decay, which helped maintain quality during storage. The reduction in respiration rate leads to low ethylene production, thereby improving shelf life (Kumarihami *et al.*, 2021). Similar trends have been reported by Nguyen *et al.* (2020), Khalil *et al.* (2022), and Zhou *et al.* (2020), where the combination of CHT and HW improved antimicrobial activity and shelf life.

Fruit firmness is an important quality attribute reflecting structural and metabolic changes during storage. Litchi fruits subjected to CHT and HW treatments exhibited significantly higher firmness towards the end of shelf-life (day 6-9) compared to the control (Table 1), indicating improved maintenance of tissue integrity. This effect can be attributed to the ability of CHT coatings to form a protective barrier and inhibit cell-wall-degrading enzymes, thereby preserving structural components of the fruit. In addition, such treatments may regulate carbohydrate metabolism and ethylene activity, contributing to the delayed softening and enhanced firmness (Dai *et al.*, 2025). Similar effects of coating treatments in maintaining fruit firmness during storage have been reported for fig and apple fruits (Shao *et al.*, 2012; Kaur *et al.*, 2024). Changes in TSS during storage reflect ongoing metabolic processes, including sugar accumulation and utilization (Xu *et al.*, 2018). TSS increased with storage for all treatments (Table 1) and indicated

conversion of polysaccharides and organic acids to soluble sugars, as a result of ripening (Zhang *et al.*, 2018). The higher TSS in control fruits at later stages is an outcome of water loss induced acceleration in respiration and metabolic activity. On the other hand, the TSS increased more slowly in fruits treated with chitosan, probably due to the semi-permeable coating affecting the O_2/CO_2 balance, thereby suppressing respiration, ethylene production and hydrolysis of carbohydrates (Gholami *et al.*, 2017; Zhou *et al.*, 2025). Also, coated fruits showed reduced transpiration which further limited the solute concentration that resulted in delayed ripening and lower TSS in total (Xing *et al.*, 2020). Similar trends were reported for chitosan-coated strawberries (Bertolo *et al.*, 2025) and mangoes (Akhter *et al.*, 2025), where coatings delayed ripening and maintained lower TSS throughout storage.

TS content gradually increased in coated samples compared to the control (Table 1). TS is an important indicator of fruit ripening, influenced by ethylene and associated enzymatic activities (Farcuh *et al.*, 2018). Furthermore, this increase in TS can also be attributed to the breakdown of polysaccharides and the conversion of starch into simpler sugars during ripening (Kumar *et al.*, 2020) processes that the hydrolytic action of heat could further facilitate. Additionally, mild heat treatment may enhance enzymatic hydrolysis of polysaccharides, contributing to sugar accumulation (Lu *et al.*, 2018). Similar trends in sugar dynamics have been reported in coated papaya and mango fruits (Ban *et al.*, 2015; Khalil *et al.*, 2022).

Ascorbic acid is a key component in quality assurance during postharvest storage and influences fruit ripening and stress tolerance in secondary metabolites (Zheng *et al.*, 2022). Our results showed that ascorbic acid content decreased with storage time; however, fruits treated with CHT combined with HW retained higher levels of ascorbic acid than the untreated control (Table 1). The decrease in ascorbic acid content appears to be primarily associated with the oxidative degradation during storage. The improved retention of ascorbic acid in treated fruits may be more appropriately explained by the barrier function of CHT coating, which reduces oxygen permeability and associated oxidative reactions (Mohamed *et al.*, 2020). In addition, HW treatment has been reported to have no direct adverse effect on ascorbic acid content while helping

to maintain overall postharvest fruit quality (Brunda *et al.*, 2025).

Fruits' ascorbic acid and phenolic levels are closely related to their antioxidant action (Njus *et al.*, 2020). The total phenolic content decreased in all treatments during storage while fruits treated with CHT+HW consistently maintained higher levels compared to the control (Fig. 2). This may be attributed to the inhibitory effect of CHT coating on polyphenol oxidase (PPO) (Zhang and Quantick, 1997), a primary enzyme that is responsible for oxidative degradation of phenolics (Tilley *et al.*, 2023). The decline in phenolic content in the control group could be due to vacuolar disruption and increased oxidative stress under ambient conditions (Xu and Wang, 2025). Similarly, flavonoid content declined over time in all samples (Fig. 2). However, CHT+HW-treated fruits retained nearly double the flavonoid levels compared to the controls at 9 DAS. Flavonoids, a key antioxidant synthesized via the phenylpropanoid pathway, are essential for delaying fruit senescence and protecting against reactive oxygen species (ROS) (Chen *et al.*, 2022). The higher flavonoid content retention in CHT-HW treated fruits is likely due to HW treatment modulating physiological responses and reducing microbial load, while CHT coating acts as a semi-permeable barrier that limits oxygen exposure, reduces oxidative degradation, and preserves cellular integrity during storage (Wang *et al.*, 2023; Brunda *et al.*, 2025; Dai *et al.*, 2025). Moreover, in 'Sanhua' plum fruit, the combined application of CHT and heat treatment resulted in higher levels and improved retention of total phenolics and flavonoids compared to the untreated controls (Chang *et al.*, 2019).

Antioxidant activity, as measured by DPPH radical scavenging capacity, decreased progressively during storage in all samples (Fig. 2). At 9 DAS, the combined treatment maintained approximately 33.94% higher antioxidant activity than the control and about 15-20% higher than individual treatments. This trend corresponds with the preservation of phenolic compounds, flavonoids, and ascorbic acid, which collectively contribute to antioxidant capacity. The higher antioxidant activity in treated fruits can therefore be attributed to reduced oxidative degradation and better retention of antioxidant compounds under modified atmospheric conditions created by the coating (Ummarat *et al.*, 2011; Huan *et al.*, 2017). These findings largely corroborate those

of previous studies, which have shown that CHT application retains higher levels of antioxidant activity during ripening in mango (Akhter *et al.*, 2025). β -carotene content increased during storage in all treatments (Fig. 2), likely due to ripening-associated carotenoid biosynthesis and enhanced metabolic activity during fruit maturation (Wisutiamonkul *et al.*, 2015; Jahan *et al.*, 2025). The CHT and HW treatments may have modulated the ripening process and reduced oxidative degradation by limiting oxygen availability and moisture loss. Since carotenoids are highly susceptible to oxidation during storage (Salinas-Roca *et al.*, 2018), the barrier properties of chitosan likely contributed to better retention of β -carotene, as previously reported in coated papaya and mango fruits (Akhter *et al.*, 2025).

Our findings suggest that the changes in L^* , a^* , and b^* values occur more slowly in treated fruits (Fig. 3). The L^* (lightness and darkness) value decreased, while values for a^* (ranging from greenness to redness) and b^* (from blueness to yellowness) rose. Additionally, the browning index of the pericarp has significantly risen in control fruits; however, this increase is more pronounced in uncoated fruit compared to coated fruit (Fig. 4). According to Sun *et al.* (2020), variations in overall phenolic levels and the activity of PPO significantly impact fruit browning during storage. Similarly, Medeiros *et al.* (2012) stated that CHT formed a semipermeable layer on top of fruit peel and changed the environment by raising CO_2 and decreasing O_2 , which prevented the generation of ethylene, postponed ripening, decreased color changes, and maintained chlorophyll content. Additionally, HW may have also stimulated the metabolic pathways involved in pigment and phenolic compound synthesis, resulting in improved color retention by delaying ethylene production and lowering respiration rates. These treatments helped to maintain the desired pulp and peel color for a longer period in dragon (Nguyen *et al.*, 2020) fruit during storage.

Sensory evaluation revealed that treated fruits maintained higher scores for flavor, sweetness, appearance, and overall acceptability compared to the control (Fig. 5). These results indicate that the treatments were effective in preserving desirable sensory attributes during storage rather than merely preventing deterioration. Higher sensory scores in treated fruits were associated with improved firmness, reduced browning, higher L^* values, and

better retention of sugars and antioxidants. Similar trends have been reported in coated papaya, mango, and grape fruits (Vilaplana et al., 2020; Khalil et al., 2022; Tavasolinasab et al., 2023).

This study demonstrates that the combined application of 0.5% CHT and HW treatment effectively enhances postharvest stability and extends storage life of litchi cv. China-3 by limiting weight loss, pericarp browning, and decay development. The treatment further preserves fruit quality attributes, including firmness, TSS, β -carotene, titratable acidity, ascorbic acid, and antioxidant-related metabolites (phenolics and flavonoids), indicating a comprehensive delay in senescence and oxidative deterioration. Beyond its biological efficacy, this cost-effective and scalable approach requires minimal technological modification, facilitating its integration into existing postharvest systems and supporting commercial adoption to reduce losses and improve supply chain efficiency. Its implementation may further improve postharvest performance and sustain market acceptability.

However, validation under commercial conditions and across diverse cultivars is required to enable large-scale industrial application.

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