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Research Article

Chitin Nanofibers Retain the Postharvest Quality and Shelf Life of Papaya (*Carica papaya* L.)

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ABSTRACT

Papaya is a nutrient-dense fruit, but due to its climacteric nature, its shelf life is short. The effect of chitin nanofiber (CNF) on the physico-chemical changes, microbial characteristics, and shelf life of papaya cv. Shahi was examined in an experiment conducted during the period from January 29th to February 14th, 2024, at the Germplasm Centre, Horticulture Laboratory, and Plant Pathology Laboratory of the Agrotechnology Discipline, Khulna University, Khulna. The experiment was replicated three times and included five treatments: control, 0.1% chitin nanofiber (CNF), 0.2% CNF, 0.3% CNF, and 0.4% CNF. Total soluble solids (TSS) and weight loss are two physicochemical measures that rise with storage in both treated and untreated fruits. The incidence and severity of the disease showed a rising trend. The amount of vitamin C, however, dropped. The lowest amount of total soluble solids (8.30%) was found in the 0.1% chitin nanofiber treatment. The least amount of weight was lost (11.56%) was found with the 0.2% chitin nanofiber treatment. The 0.3% chitin nanofiber treatment had the lowest disease severity (45.77%) on the ninth day of storage, while the control had the highest disease severity (53.96%). Papaya's shelf life varies greatly depending on the CNF concentrations. The 0.4% CNF had the longest shelf life (10.17 days), whereas the control had the shortest shelf life (6.31 days). Overall, papaya's shelf life and other postharvest quality attributes were better preserved at 0.4% CNF.

Introduction

The popular, delectable, and very valuable fruit papaya (*Carica papaya* L.) belongs to the Caricaceae family and is grown in 66 countries worldwide, with the Dominican Republic, Brazil, Mexico, and India being the top producers (Shu et al., 2023; FAOSTAT, 2021; Srikantharajah et al., 2020). Papaya is rich in alkaloids, flavonoids, carotenoids, phenolics, fiber, vitamins A, B, and C, as well as minerals. Papaya has also been shown to have anticancer properties (Ovando-Martínez et al. 2020; Alara et al., 2020). Green fruits, leaves, and flowers are used as vegetables (Watson, 1997). The active ingredients in papaya leaves are alkaloids, glycosides, tannins, saponins, and flavonoids, which are responsible for their therapeutic properties. Additionally, in patients with dengue, the juice of papaya leaves increases blood platelet counts (Singh et al., 2020).

Papaya is primarily grown in Bangladesh's northern areas, including Tangail, Pabna, Dinajpur, Rangpur, Bogura, Gazipur, Mymensingh, Dhaka, and Kishorgonj. Throughout the year, papayas are a popular fruit and vegetable in the country. From an estimated 8907 hectares, Bangladesh produced 308,000 metric tons of green papaya and 147,000 metric tons of ripe papaya in the fiscal year 2021–2022, respectively (BBS, 2022). As a result, 34.6 t ha^{-1} of green papaya and 30.3 t ha^{-1} of mature papaya were produced. However, due to physical damage, rapid pulp softening, disease incidence, pest infestation, decay, disorders, and improper storage temperature, papaya is very perishable and susceptible to both qualitative and quantitative losses (Sivakumar and Wall, 2013). The papaya diseases, such as stem-end rot, anthracnose, and Rhizopus rot, cause papaya spoilage, and fungal

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diseases alone cause over 50% of losses (Demartelaere et al., 2017; Esguerra et al., 2020;). To reduce the postharvest loss and extend shelf life, fungicides and chlorine treatments are formerly used. However, these chemicals are toxic to both the environment and human health due to their toxicity, carcinogenicity, and persistence (Maqbool et al., 2010; Zahid et al., 2015;).

In this context, chitin nanofibers may be an option. The structural element of insects, crustaceans, and fungal mycelia is chitin, a naturally occurring and abundant mucopolysaccharide (Iñiguez-Moreno et al., 2021). Although chitin is insoluble in water, its nanofibers are soluble. Biodegradability, biocompatibility, renewability, and sustainability are some of the advantageous properties of CNF (Ifuku, 2012). CNF enhances plant growth and development through better root establishment, nutrient absorption, and stress tolerance (Shahrajabian et al., 2021; Shams et al., 2025). Seed coatings or foliar sprays of CNF stimulate plant growth and increase crop productivity (Shahrajabian et al., 2021). It also helps in the removal of cationic and anionic heavy metals from the soil (Shahrajabian et al., 2021), provides biodegradable mulching (Yanat and Schroën, 2023), and protects the crop against diseases and pathogens through antifungal and antibacterial properties (Egusa et al., 2019; Tanpichai et al., 2023). Moreover, CNF can extend the shelf life of banana, mango, cucumber, and coriander (Bagchi et al., 2025; Munira et al., 2025; Tanpichai et al., 2023). We investigated the effectiveness of different concentrations of CNF for postharvest papaya storage. Thus, the purpose of this study was to determine the best concentration of chitin nanofiber for preserving the desired physico-chemical changes in papaya and extending its shelf life.

Materials and Methods

Experimental materials and design

The experimental material used in this experiment was the papaya variety Shahi. This dioecious variety bears fruit – ovate, medium to large with the dimensions of 13-15 cm x 9-11 cm (length and diameter, respectively), flattened base, and deep green at maturity and greenish yellow at ripe – having deep orange pulp with 2 cm thickness with an average fruit weight of 850-950 g. The fruit was collected from the Horticulture Centre of Jashore. Papaya fruits were harvested at maturity – watery latex and pale green fruit – on 29th January 2024 and carried to the laboratory of Khulna University. Upon arrival, fruits were subjected to air cooling, cleaned, and stored at room temperature before starting treatments.

The fruits were placed on the brown paper in a completely randomized pattern on the lab floor under ambient environmental conditions. A total of 120 mature and disease-free fruits were divided into five groups for five treatments: control, 0.1%, 0.2%, 0.3%, and 0.4% chitin nanofiber (CNF). Thus, each treatment consisted of 24 fruits for three replications, and eight fruits were sampled from each replication. Among eight fruits, four were retained to record changes in weight, colour, and other exterior fruit attributes, as well as shelf life, while four were destroyed for physicochemical analyses.

Preparation of chitin nanofiber solutions

Tiger shrimp (*Peneus monodon*) shells were collected and carefully cleansed in water to remove any remaining dust, grime, and other debris. The shrimp shells were repeatedly washed with tap water before being allowed to air dry. The dried shells were ground into particles ranging in size from 2 to 4 mm using a standard grinder. The following stage involved using about 300 g of dried, crushed shrimp shells. The conventional protocol was followed to demineralize, deproteinize, and depigment the shells using HCI (37%), NaOH (99.9%), and 50% ethanol, respectively (Afroj et al., 2025; Ifuku et al., 2011). To create chitin nanofiber, the resulting suspension was then put in a super-speed blender (Vita-Mix Blender, Osaka Chem. Co. Ltd.) and stirred for ten minutes at 37,000 rpm. The suspension was then mixed for ten minutes at 11,000 rpm in a regular-speed blender (Panasonic MX Blender, Panasonic Holdings Corporation). After the required quantity of water has been added, the suspension is prepared for the super colloidal machine. A Super Masscolloider (MKCA6-51) with several milling capabilities from Masuko Sangyo, Honcho, Kawaguchi-shi, and Saitamaken, Japan, was used to mechanically treat the chitin. The grinding stone speed was set at 1500 rpm, and the clearance was set at -0.15. The sample chitin was extracted following 10, 15, and 20 milling cycles in a super-speed blender. The concentration of solution was adjusted to 1% CNF, and diluted to 0.1%, 0.2%, 0.3%, and 0.4% chitin nanofibers by adding distilled water.

Organoleptic evaluation of papaya with CNF treatment

A panel of fifteen university students evaluated papaya pulp organoleptically using a standardized questionnaire.

Measurement of fruit attributes

Colour changes, overall weight loss, TSS, firmness, disease incidence and severity, and shelf life were among the fruit attributes that were recorded.

Using a chromameter (CR-400, Konica Minolta, Japan), the surface color of two sides of jujube fruit on the equatorial zone was measured using the Commission

International de I'Eclairage (CIE) LAB color criteria. The chromaticity L* indicates how light the fruit color is, a* indicates how red (+a*) or green (-a*) the fruit skin is, and b* indicates how yellow (+b*) or blue (-b*) it is. The chromaticity ranges from 0 (black) to 100 (white). Red, yellow, green, and blue were interpreted as having angles of 0°, 360°, 90°, and 180°, respectively. $C^* = (a^{*2} + b^{*2})^{1/2}$, and $h° = \tan^{-1} b^*/a^*$ were used to compute the hue angle (h°) and chroma (C*) (Asha et al., 2025; McGuire, 1992).

A color rating scale (1–5) was used to visually evaluate the papaya's color; 1 denotes 100% green, 2 1%-25% yellow, 3 26%-50% yellow, 4 51%-75% yellow, and 5 76%–100% yellow (Dang et al., 2008; Dhali et al., 2025).

Weight loss (%)

The weight loss of jujube fruit was calculated according to the following formula (Dhali et al., 2024; Kabir and Hossain, 2024).

$$\text{Weight loss (\%)} = \frac{MO - M1}{MO} \times 100 \quad (1)$$

Here, M_0 and M_1 represent fresh weight of fruit at day 1 and at a particular day (such as day 5), respectively.

Firmness

Firmness of papaya was estimated hedonically according to Hassan (2006) following a rating scale 1-6 where, 1 represents mature hard, 2 is sprung, 3 is between sprung and eating ripe, 5 represents over ripened and 6 means totally unfit for consumption.

Moisture content (%)

Ten grams of fruit pulp were weighed in a Petri dish in a Triple Beam Balance and oven-dried at 65°C for 72 hours. The moisture content (%) was calculated according to the following formula (Kabir and Hossain, 2024).

$$\text{Moisture content (\%)} = \frac{PW - DW}{PW} \times 100 \quad (2)$$

Where,
PW = Primary weight of pulp (g)
DW = Dried weight of pulp (g)

Measurement of TSS & TA

To determine total soluble solids (TSS), one drop of extracted papaya fruit juice was put on the refractometer prism, and the reading was recorded.

A 5.0 mL sample of diluted fruit juice was titrated in order to measure titratable acidity (TA). Each replication's fruits had their fresh juice removed and diluted 1:1 with distilled water (for example, 10 mL of juice and 20 mL of water). A 5 mL aliquot of this diluted solution was then titrated using 0.1 N NaOH (Nerdy, 2018; Dhali et al., 2024; Kabir and Hossain, 2024).

$$\text{TA (\%)} = 100 \times \frac{d \times 0.064 \times c}{a \times b} \quad (3)$$

Here, d is the mean burette reading, a is the sample weight, b is the aliquot volume, and c is the final volume created with distilled water. Since 1 ml of 0.1 N NaOH neutralizes 0.064 g of citric acid, the titration factor is 0.064.

Determination of vitamin C

Vitamin C was estimated using a dye (2,6 dichlorophenol indophenol) titration method according to formula (3) from Nerdy (2018).

$$\text{Vitamin C (mg100g}^{-1}\text{)} = \frac{e \times d \times b}{c \times a} \quad (4)$$

Where, a= Weight of sample b= Volume made with metaphosphoric acid c= Volume of aliquot taken for estimation d= Dye factor e= Average burette reading for sample

Disease incidence (%)

Every day, the papaya fruits from each treatment were carefully inspected for the presence of rot, and on alternate days, the incidence of rot was noted. On the sixth day of storage, the initial count was conducted. When compared to the released documents, the apparent rot was verified.
The incidence of disease was calculated as follows (Kabir and Hossain, 2024) -
% Disease incidence =

$$\frac{Number\,of\,\inf ected\,fruits}{Total\,number\,of\,\,fruitsunder\,study} \times 100 \quad (5)$$

Disease severity

Disease severity defines the area of a fruit that gets infected with diseases. It was determined through an eye estimation and expressed in percentage (Roy et al., 2011).

Shelf life

The number of days required to ripen the papaya fruits from maturity and retain their edibility without blemishes, over-ripening, wrinkling, and mould-growth, was considered the shelf life of papaya.

Isolation and identification of causal pathogens

The infected papaya samples were brought to the Plant Pathology Laboratory of Khulna University for pathogen identification. The samples, after refrigeration, were cut, including healthy tissue, surface-sterilized (0.1% $HgCl_2$), washed (sterile water), and cultured on PDA. Temporary slides were prepared seven days after incubation at room temperature, and the pathogens were identified based on morphological characteristics (Roy et al., 2011).

Statistical analysis

The data were subjected to one-way analysis of variance (ANOVA) and F-test by using IBM SPSS Statistics for Windows (Version 27.0.1.0) [IBM Corp., Armonk, NY, USA]. The mean differences were separated using Tukey's HSD Test at 5% level.

Results

Peel color

Peel color, a visual indicator of fruit ripening, was assessed throughout the 12-day storage (Table 1). A color change from green to yellow was observed in all the fruits; however, in CNF-treated samples, the color change was significantly delayed. The yellowing rate was much slower in fruits treated with CNF, indicating a delayed ripening process compared to the untreated control. The CNF coating may have inhibited chloroplast-to-chromoplast conversion, hence maintaining green color for a longer duration.

Table 1. Effect of chitin nanofiber (CNF) on the change of skin color of papaya at different days after storage (DAS)

Treatments	Color change			
	3 DAS	6 DAS	9 DAS	12 DAS
Control	Pale Green	Greenish yellow	Light greenish yellow	Yellow
0.1% CNF	Pale Green	Greenish yellow	Light greenish yellow	Yellow
0.2% CNF	Pale Green	Greenish yellow	Light greenish yellow	Yellow
0.3% CNF	Pale Green	Greenish yellow	Light greenish yellow	Yellow
0.4% CNF	Pale Green	Greenish yellow	Light greenish yellow	Yellow

Organoleptic evaluation

Sensory evaluation at 3-day intervals revealed CNF treatments preserved significant organoleptic qualities (Table 2). They were aroma, sweetness, juiciness, pulp firmness, and fiber content. As days of storage passed, the pulp changed from whitish to deep orange-red color richness, denoting ripening. The CNF coatings, particularly at 0.3% and 0.4%, preserved heightened sensory appeal, likely because they assisted in the maintenance of turgor pressure and prevented biochemical breakdown at a reduced pace.

Table 2. Organoleptic evaluation of CNF-treated papaya

Sweetness	Juiciness	Texture of pulp	Aroma	Fibreness	Pulp Color			
					3 DAS	6 DAS	9 DAS	12 DAS
Sweet	Medium Juicy	Crispy	Pleasant	Fibreless	Whitish	Whitish Orange	Light orange	Deep orange red

Weight loss

Due to evaporation of water and respiration, weight loss was primarily calculated at 6, 9, and 12 DAS (Table 3). Maximum weight loss (12.70%) occurred in the control group at 12 DAS, while minimum (11.56%) was recorded in CNF-treated fruits with 0.2%. Although all CNF treatments reduced weight loss relative to the control, greater concentrations (0.3% and 0.4%) paradoxically showed somewhat larger losses, perhaps due to initial retention of moisture leading to subsequent rapid loss. However, CNF coatings effectively reduced physiological shrinkage and mass loss.

Firmness

Texture analysis revealed that papaya firmness decreased upon storage, as would be expected from ripening-induced softening. However, CNF-treated fruits, especially at 0.3% concentration, had significantly higher firmness values (up to 4.43) compared to control fruits (3.11) (Table 4). This firmness retention is due to suppressed cell wall enzymatic degradation and improved membrane integrity offered by the protective CNF barrier.

Table 3. Effect of chitin nanofiber (CNF) on the weight loss of papaya at different days after storage (DAS)

Treatments	Initial wt. (kg)	Weight loss (%)		
		6 DAS	9 DAS	12 DAS
Control	0.88	3.60 c	7.39 c	12.70 bc
0.1% CNF	0.96	4.07 b	8.38 bc	12.56 bc
0.2% CNF	0.97	3.97 b	8.36 bc	11.56 c
0.3% CNF	1.01	5.40 a	9.51 ab	14.18 ab
0.4% CNF	0.97	5.23 a	10.36 a	14.51 a
CV (%)	-	2.26	8.87	7.01
LS	-	**	**	**

Firmness was evaluated hedonically following a rating scale 1-6 where, 1 represents mature hard, 2 is sprung, 3 is between sprung and eating ripe, 5 represents over ripened and 6 means totally unfit for consumption (Hassan, 2006). LS for level of significance; ** for significant at the 1% level of probability. The Tukey's Honestly Significant Difference Test indicates that treatment means in a column with a dissimilar letter or letters are statistically significant at the 5% level of probability (p<0.05).

Table 4. Effect of chitin nanofiber (CNF) on the firmness of papaya at different days after storage (DAS)

Treatments	Firmness			
	3 DAS	6 DAS	9 DAS	12 DAS
Control	2.26 b	2.94 a	3.45 bc	3.11 d
0.1% CNF	2.38 ab	2.91 ab	3.39 c	4.23 b
0.2% CNF	2.08 b	3.00 a	3.89 a	4.25 b
0.3% CNF	2.32 ab	2.77 bc	3.62 b	4.43 a
0.4% CNF	2.60 a	2.75 c	3.57 bc	3.62 c
CV (%)	7.37	2.73	3.05	2.04
LS	*	**	**	**

CV for coefficient of variation; LS for level of significance; * and ** define significant at the 5% and 1% level of probability, respectively. The Tukey's Honestly Significant Difference Test indicates that treatment means in a column with a dissimilar letter or letters are statistically different at the 5% level of probability (p<0.05).

Color attributes

Objective color values (L*, a*, b*, C*, and h°) quantified delayed ripening visually. CNF-treated fruits were lighter, and the hue value changed upon storage. Chroma values that were higher indicated vigorous coloration in control fruits, which is associated with faster pigment development [Tables 5 (a) and 5 (b)]. CNF application suppressed this transition, confirming slower senescence.

Table 5 (a). Effect of chitin nanofiber (CNF on the color attributes of papaya at different days after storage (DAS)

Treatments	Color attributes									
	3 DAS					6 DAS				
	L	a*	b*	C*	h°	L	a*	b*	C*	h°
Control	48.98b	-12.48ab	20.20 b	24.03 b	121.73ab	42.08 b	-11.50bc	21.04 c	23.96 b	119.49a
0.1% CNF	43.21a	-13.20b	21.64a	26.65a	121.61 b	43.21ab	-11.79c	21.78 bc	24.87ab	119.27a
0.2% CNF	41.52b	-12.81b	20.05 b	24.29 b	122.63a	43.53a	-11.03ab	23.08a	25.81a	117.38 b
0.3% CNF	42.31ab	-11.66a	21.44a	24.59 b	119.51 c	42.12 b	-10.85a	20.88 c	23.79 b	118.62ab
0.4% CNF	41.83b	-12.47ab	20.04 b	23.88 b	122.20ab	43.38a	-11.35abc	22.24ab	25.20a	118.71ab
CV (%)	1.24	-3.90	3.01	2.11	0.46	1.46	-2.91	2.45	2.52	0.71
LS	*	*	**	**	**	*	*	**	**	NS

NS stands for non-significant; CV for coefficient of variation; LS for level of significance; * and ** define significant at the 5% and 1% level of probability, respectively. The Tukey's Honestly Significant Difference Test indicates that treatment means in a column with a dissimilar letter or letters are statistically different at the 5% level of probability (p<0.05).

The maximum score (3.75) on a visual color rating scale (1–5) was obtained for the 0.2% CNF treatment, showing maximum color development with minimum over-ripening (Table 6). The control and 0.1% CNF treatments received the lowest score, testifying to the efficacy of CNF in yielding a visually attractive product.

Table 5 (b). Effect of chitin nanofiber (CNF) on the color attributes of papaya at different days after storage (DAS)

Treatments	Color attributes									
	9 DAS					12 DAS				
	L	a*	b*	C*	h°	L	a*	b*	C*	h°
Control	47.41a	-9.97	28.35a	30.51a	111.87 b	41.02 b	-11.30d	19.57a	22.61a	120.70a
0.1% CNF	44.87 b	-10.26	23.65c	26.23 b	115.60a	41.18 b	-10.97d	18.72a	21.83a	120.78a
0.2% CNF	43.80 b	-9.65	22.15d	24.39 b	114.30a	39.51 c	-6.09a	15.25 b	16.70 d	113.28 b
0.3% CNF	44.16 b	-9.87	25.85b	27.82ab	111.80 b	42.65a	-6.95b	19.10a	20.40 b	107.83 c
0.4% CNF	44.71 b	-57.63	22.94cd	25.22 b	114.32a	40.11 bc	-9.22c	16.16 b	18.77 c	119.01a
CV (%)	1.89	-6.80	2.70	8.26	0.72	1.46	-3.00	3.68	3.15	1.09
LS	**	NS	**	*	**	**	**	**	**	**

CV for coefficient of variation; LS for level of significance; ** for significant at the 1% level of probability. The Tukey's Honestly Significant Difference Test indicates that treatment means in a column with a dissimilar letter or letters are statistically different at the 5% level of probability (p<0.05).

Table 6. Effect of chitin nanofiber (CNF) on the peel color of papaya at different days after storage (DAS)

Treatments	Color			
	3 DAS	6 DAS	9 DAS	12 DAS
Control	1.71 d	2.62 a	3.08 a	3.11 d
0.1% CNF	2.30 a	2.59 ab	2.80 c	3.33 c
0.2% CNF	2.04 bc	2.50 bc	3.0 ab	3.75 a
0.3% CNF	2.19 ab	2.42 c	2.95 b	3.50 b
0.4% CNF	1.96 c	2.69 a	3.04 ab	3.41 bc
CV (%)	3.95	2.20	2.01	2.50
LS	**	**	**	**

CV for coefficient of variation; LS for level of significance; ** for significant at the 1% level of probability. The Tukey's Honestly Significant Difference Test indicates that treatment means in a column with a dissimilar letter or letters are statistically different at the 5% level of probability (p<0.05).

Total soluble solids (TSS)

TSS, indicative of sugar content and total sweetness, increased with storage period in all samples. Control fruits had the highest value of TSS all along, indicative of quicker ripening and sugar biosynthesis (Table 7). The 0.4% CNF-treated fruits achieved a slow rise to 8.43% Brix at 12 DAS, as compared to 9.13% in the control. The lower sugar in CNF-treated fruits indicates delayed metabolic activity and extended storage life.

Table 7. Effect of chitin nanofiber (CNF) on the total soluble solid (TSS) of papaya at different days after storage (DAS)

Treatments	TSS (% Brix)			
	3 DAS	6 DAS	9 DAS	12 DAS
Control	5.16	9.53 a	9.40 a	9.13 a
0.1% CNF	6.53	7.66 bc	7.83 c	8.30 d
0.2% CNF	5.43	8.00 bc	8.80 b	8.73 b
0.3% CNF	6.10	8.63ab	7.93 c	8.63 bc
0.4% CNF	6.73	7.13 c	7.80 c	8.43 cd
CV (%)	18.52	6.82	2.60	1.74
LS	NS	**	**	**

NS stands for non-significant; CV for coefficient of variation; LS for level of significance; NS stands for non-significant; CV for coefficient of variation; LS for level of significance; ** for significant at the 1% level of probability. The Tukey's Honestly Significant Difference Test indicates that treatment means in a column with a dissimilar letter or letters are statistically different at the 5% level of probability (p<0.05).

Titratable acidity (TA)

TA content showed moderate differences between storage time and treatments. Fruits of 0.4% CNF treatment contained the highest percentage of acidity (5.20%) at 12 DAS, showing slower degradation of organic acids, which allowed for preservation of flavor balance. Control fruits contained the lowest acidity (4.18%), as predicted for more developed ripening (Table 8).

Table 8. Effect of chitin nanofiber (CNF) on the titratable acidity (TA) of papaya at different days after storage (DAS)

Treatments	TA (%)			
	3 DAS	6 DAS	9 DAS	12 DAS
Control	4.33 ab	4.81 ab	7.27 a	4.18 c
0.1% CNF	4.24 ab	3.41 c	6.12 c	4.88 b
0.2% CNF	4.21 b	5.39a	6.53 b	4.94 ab
0.3% CNF	4.61a	4.08 bc	6.37 bc	4.44 c
0.4% CNF	4.47ab	4.38 abc	6.16 c	5.20 a
CV (%)	4.64	13.95	2.39	3.14
LS	*	*	**	**

LS = Level of significant; * and ** define significant at the 5% and 1% level of probability, respectively; CV = Coefficient of variation. Treatment means in a column with dissimilar letter(s) are statistically different according to the Tukey's Honestly Significant Difference Test at 5%.

Vitamin C content

Vitamin C, which is an unstable antioxidant compound, had dropped steadily in all treatments during storage (Table 9). However, CNF treatments, particularly 0.3% and 0.4%, were effective in maintaining vitamin C levels. The highest reading (10.84 mg/100 g) was observed from 0.3% CNF treatment at 9 DAS, indicating the success of the coating in suppressing oxidative stress and nutrient degradation.

Table 9. Effect of chitin nanofiber (CNF) on the vitamin C content of papaya at different days after storage (DAS)

Treatments	Vitamin C (mg $100g^{-1}$)			
	3 DAS	6 DAS	9 DAS	12 DAS
Control	8.05	7.84 a	10.02 b	6.64 c
0.1% CNF	7.91	6.45 c	10.57 a	6.47 c
0.2% CNF	8.07	7.07 b	7.94 c	7.30 a
0.3% CNF	7.90	6.93 b	10.84 a	6.95 b
0.4% CNF	7.65	6.30 c	9.81 b	7.42 a
CV (%)	4.86	3.66	2.91	1.90
LS	NS	**	**	**

CV for coefficient of variation; LS for level of significance; ** for significant at the 1% level of probability. The Tukey's Honestly Significant Difference Test indicates that treatment means in a column with a dissimilar letter or letters are statistically different at the 5% level of probability (p<0.05).

Diseases incidence and disease severity

Postharvest disease is crucial for fruit preservation. CNF coatings possessed good resistance against microorganism infections by minimizing disease incidence and severity levels compared to the control (Table 10). Severity level was lowest (45.77%) for 0.3% CNF-treated fruits at 9 DAS. Pathogen isolation identified *Colletotrichum gloeosporioides* as the most common spoilage organism, which is the causative agent for

Table 10. Effect of chitin nanofiber (CNF) on the disease incidence and disease severity of papaya at 9 days after storage (DAS)

Treatments	Disease incidence (%)	Disease severity (%)
Control	62.5	15.32
0.1% CNF	54.17	20.69
0.2% CNF	66.67	21.21
0.3% CNF	50	22.52
0.4% CNF	44.17	13.75
CV (%)	16.47	20.85
LS	NS	NS

NS stands for non-significant; CV for coefficient of variation; LS for level of significance;

Shelf life

Shelf life varied with the treatments. The shelf life was the lowest in control (6.31 days) and highest (10.17 days) in 0.4% CNF-treated fruits (Fig. 1). The increase is attributed to various factors, including a reduction in weight loss and disease severity, and a slowing down of biochemical properties. CNF treatments were found to enhance shelf life more and more in the pattern of 0.4% > 0.3% > 0.2% > 0.1% > control. This ranking reflects CNF's cumulative benefits for senescence retardation, fruit quality, and long marketability.

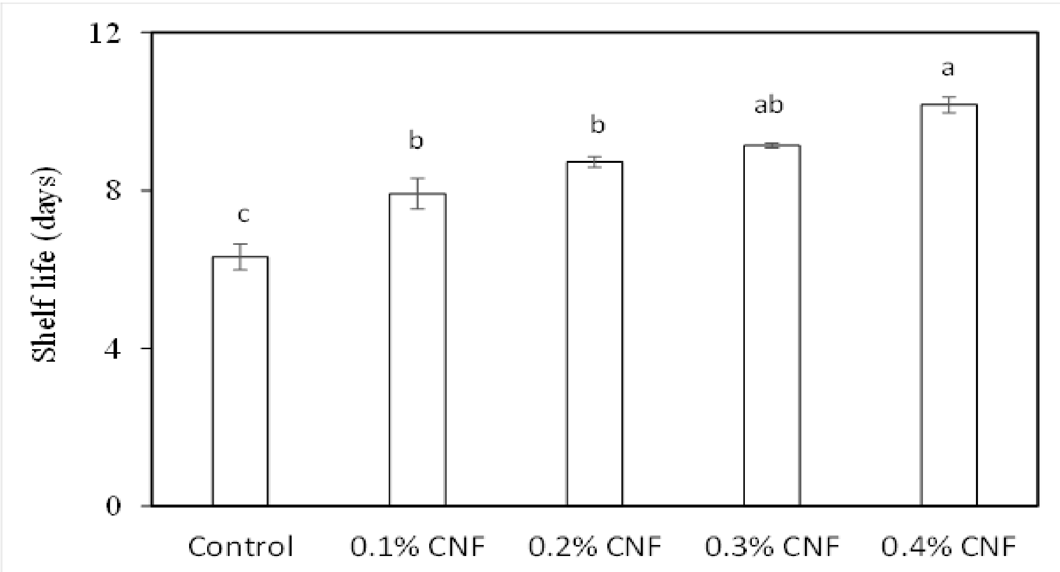

Fig.1. Shelf life of papaya as affected by chitin nanofiber (CNF) treatments. The error bar represents mean ± standard error (SE) of three measurements. Different letter(s) on a bar represent statistically significant difference at 1% probability according to Tukey's HSD Test.

Discussion

The latest studies confirmed that the postharvest nature and preservation of papaya fruit quality can be influenced using chitin nanofiber (CNF) coating. The CNF treatments led to remarkable improvements in physiological, biochemical, and microbiological characteristics, which enhanced marketability and extended the shelf life of the fruits.

Papaya skin color development is a powerful visual indicator of ripening. The delayed yellowing of CNF-treated fruits points to delayed chloroplast to chromoplast conversion, which can be due to restricted ethylene action or respiration. Rashid et al. (2015) also reported delayed pigment changes in chitosan-treated fruits, which supports the visual color and colorimetric readings taken in this study. The higher hue angle and lower chroma of treated fruits indicated less degradation of green pigments and less carotenoid accumulation.

The preservation of good eating qualities (organoleptic characteristics) such as pulp firmness, juiciness, sweetness, and pleasant aroma in CNF-coated fruits further indicates the protective effect of the coating.

The weight loss of fruits is primarily due to transpiration and respiration. CNF significantly reduced these physiological processes by acting as a moisture retention layer, which minimized gas exchange. Fruits with a greater concentration of CNF (especially 0.2% and 0.3%) showed minimum weight loss, supporting the results of Mia (2003), which exhibited the same effects for chitosan. The improvement in firmness, especially in 0.3% CNF, reflects inhibited pectin degradation, characteristically linked to ripening-induced softening.

Instrumental color analysis confirmed smaller changes in the pigments in CNF-coated fruits. Objective color parameters such as L*, a*, b*, C*, and h° remained unchanged for extended durations in treated samples. Rashid et al. (2015) also mentioned the same inhibition of pigment formation, which confirmed the efficacy of CNF in visual appearance during storage.

TSS increased with storage duration, but in a more controlled manner in CNF-treated fruits, through delayed sugar accumulation and slow metabolism. A similar trend was observed in chitosan, where lower levels result in faster ripening and higher sugar levels (Ali et al., 2010). Titratable acidity (TA) was also greater in CNF-treated fruits, indicating the preservative effect of the coatings on fruit acids. This agrees with the findings of Wojcik et al. (2008), which indicate suppressed acid degradation in chitosan-based films.

Vitamin C is an unstable antioxidant that inactivates at a rapid rate while stored after harvest. The relatively greater vitamin C retention in the CNF-treated fruits, especially with 0.3% CNF, indicates the decreased oxidative state and lower respiration stress. Wall et al. (2006) had posited that oxygen-permeability-inhibiting films preserve ascorbic acid content, in conformity with observation in the present work.

The most promising result was reduced occurrence and severity of the disease in the CNF-treated fruit. The coating likely prevented oxygen and water penetration, which restricted the fungal growth. *Colletotrichum gloeosporioides*, isolated as the pathogen, was more evident in the control fruit. Mendy et al. (2019) also mentioned chitosan's protective effect against fungal pathogens in tomato (*ToLCV*) and attributed it to the polysaccharide network, limiting microbial invasion. Moreover, *Colletotrichum gloeosporioides* was identified through morphological assessment of spores and growth in colonies by following previous research (Rodrigues et al., 2021). The multiplication of the pathogen in uninoculated fruits confirmed CNF's inhibitory property against the growth of the fungal population.

CNF increased the papaya's shelf life. Postharvest quality was preserved up to 10.17 days in 0.4% CNF-treated fruits, while control fruits spoiled after 6.31 days. The reason behind this is the synergy between reduced physiological weight loss, suppressed microbial infection, and reduced biochemical reactions.

These findings point to the commercial potential of CNF for fruit handling in locations lacking cold storage facilities. As a natural, biodegradable product, CNF addresses consumer requirements for chemical-free fruit. Its dual role as a physical protector and biochemical preservative could transform postharvest supply chains in developing agricultural economies.

Conclusion

This study validates that CNF is a reliable postharvest preservative for papaya fruits. Of the tested concentrations, 0.4% CNF had the optimal effects in improving shelf life, retaining nutritional and sensory quality, and reducing microbial spoilage. CNF is thus a suitable, environmentally friendly, and safe replacement for synthetic preservatives in fruit storage and transportation.

Competing interest

The authors report that there are no competing interests to declare.

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