Effects of Edible Coatings and Storage Conditions on the Postharvest Quality of Papaya (*Carica papaya*)

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ABSTRACT

Postharvest deterioration significantly limits the shelf life and market quality of papaya, often leading to shorter shelf life, high losses, and overdependence on fungicides. Edible coatings have emerged as a promising eco-friendly approach for extending the shelf life and reducing microbial spoilage. This study investigated the efficacy of edible coatings [carboxymethyl cellulose (CMC), moringa oil (MO), neem oil (NO)], and their combinations in preserving the quality and storability of Solo papaya under room (27 °C/78% RH) and refrigerated (10 °C/67% RH) conditions. Fruits were coated, air-dried, and stored for up to 28 days in a completely randomized factorial design. Prochloraz served as a positive control. Key quality parameters (pH, titratable acidity (TA), total soluble sugars (TSS), weight loss, firmness, and vitamin C) were monitored, and pathogenic fungi were isolated and tested for virulence. Results showed that papaya stored at room temperature lasted 9 days, while refrigeration extended shelf life to 21 days. Fruits coated with 1% CMC, 3% Prochloraz, and 1%CMC+1mLNO extended the shelf life of papaya up to 15 days at room temperature storage and 27 days under refrigeration storage. Among treatments, CMC combined with 3% MO best maintained quality attributes. Pathogenic fungi identified included *Fusarium* spp., *Colletotrichum gloeosporioides*, and *Aspergillus niger*. CMCNO and Prochloraz treatments significantly reduced disease incidence. Fewer fungal isolates were observed under refrigeration. These findings demonstrate the potential of edible coatings as a sustainable alternative to synthetic fungicides for extending shelf life, reducing postharvest losses, and maintaining papaya quality under tropical storage conditions.

Keywords: Edible coating, Carboxymethylcellulose, Prochloraz, neem oil, moringa oil, Postharvest quality

1.0 INTRODUCTION

The global market for tropical fruits, including papaya, has experienced significant growth in recent years, due to rising consumer demand for convenient, nutrient-dense foods and improvements in transport and cold-chain logistics (Evans & Ballen, 2012; FAO, 2025). Despite this growth, papaya remains highly perishable, and due to its climacteric nature, ripening continues after harvest, resulting in rapid softening and susceptibility to decay during storage and distribution (Prasad & Paul, 2021; Siddiqui et al., 2022). These changes contribute to substantial postharvest losses.

Papaya (*Carica papaya L.*) is valued for its high vitamin A content, dietary fibre, antioxidant properties, and potential health-promoting properties (Dotto & Abihudi, 2021; Saeed et al., 2014). In Ghana, papaya contributes to both domestic consumption and export earnings, with recent data indicating that production and export volumes, although modest compared with major producers, represent an important niche horticultural value chain (FAOSTAT, 2022). Despite its nutritional and economic importance, papaya remains highly susceptible to postharvest losses due to its short shelf life and high incidence of postharvest diseases, particularly anthracnose caused by *Colletotrichum gloeosporioides*. (Maeda & Nelson, 2014; Prasad & Paul, 2021).

Given that papaya is often consumed fresh in Ghana, preservation strategies must be safe, non-toxic, biodegradable, and composed of naturally derived materials which should preferably be locally available. Edible coatings have emerged as a promising eco-friendly approach for extending shelf life. These thin, edible films act as semi-permeable barriers that modify internal gas exchange, reduce transpiration, moisture loss and can limit pathogen ingress when properly formulated (Jafarzadeh et al., 2021; Dashipour et al., 2014). Among the various film-forming agents, polysaccharides have been widely studied for their ability to delay fruit senescence by modifying internal gas exchange. Carboxymethyl cellulose (CMC), in particular, has been widely studied as a film-forming agent due to its good film transparency, mechanical properties, and ability to delay ripening by lowering gas exchange and respiration rates in coated fruits (Saowakon et al., 2017; Ballesteros et al., 2022). Studies on papaya and other climacteric fruits have shown that CMC-based coatings can slow softening, reduce weight loss, and improve overall sensory quality during storage (Ali et al., 2011; Zillo et al., 2018).

However, CMC lacks inherent antimicrobial properties, which limits its standalone effectiveness (Maeda & Nelson, 2014; Bautista-Baños et al., 2013). To overcome this limitation, CMC-based coatings can be enriched with natural antimicrobials and antioxidants to enhance their protective functions and broaden their application scope. Essential oils and plant extracts can enhance barrier properties, while providing active protection against microbial growth and oxidative degradation (Majdinasab et al., 2020; Ballesteros et al., 2022). Recent work on papaya and other fruits has demonstrated that CMC combined with essential oils or plant extracts delays disease incidence and improves nutritional quality during storage (Zillo et al., 2018; Prasad et al., 2024).

Plant derived oils such as from moringa (Moringa oleifera) and neem (Azadirachta indica) have gained increasing attention as natural bioactive agents in edible coatings due to their potent antimicrobial and antioxidant activities (Anwar et al., 2007; Leone et al., 2016). Extracts and oils from moringa have shown antimicrobial and antioxidant activities that can support quality preservation in fresh produce (Mthembu et al., 2018; Mohanty et al., 2021). Neem oil, obtained from neem seeds, is widely recognised as a botanical biopesticide with antifungal, antibacterial, and insecticidal activities attributed mainly to azadirachtin and related limonoids (Isman, 2006; Chaudhary et al., 2017).

Temperature is another critical factor affecting postharvest quality of fresh produce. Higher temperatures accelerate respiration and microbial growth, whereas excessively lower temperatures can cause chilling injury in tropical fruits (Nunes et al., 2013; Prasad & Paul, 2021). Refrigeration within the range of 10 - 13°C has been shown to effectively extend shelf life and preserve quality without inducing cold damage (Nunes et al., 2013; Shakeel et al., 2022). The inclusion of these storage environments was not intended to evaluate temperature as an independent variable per se, but rather to assess the robustness and efficacy of coatings under practically relevant scenarios. While it is well established that refrigeration alone delays ripening compared to ambient storage, our goal was to determine whether coatings confer additional benefits under both conditions commonly encountered in supply chains.

Although the benefits of edible coatings and natural antimicrobials have been widely documented in fruits and vegetables, there is limited work that systematically evaluates CMC-based coatings enriched with moringa and neem oils on papaya quality and disease suppression under conditions that reflect tropical value chains, particularly in West Africa. This study addresses these gaps by assessing the efficacy of CMC-based edible coatings enriched with moringa and neem oils in maintaining postharvest quality and extending the shelf life of papaya under room (27 °C) and refrigerated (10 °C) conditions. Specifically, the work evaluates how different coating formulations and storage temperatures influence key quality indices and examines the extent to which these coatings suppress major postharvest fungal pathogens associated with papaya. By integrating natural bioactive oils into a polysaccharide matrix and testing their performance under practically relevant storage scenarios, the study contributes to the development of sustainable, locally adaptable postharvest technologies for tropical fruits in Ghana and similar contexts.

2.0 MATERIALS AND METHODS

2.1 Preparation of edible coatings

<u>CMC</u>

One percent CMC solution was used in this study. The solution was prepared using the method of Das et al., (2022) with parts of the description reproduced from their wording. One (1) gram of CMC powder was dissolved in 100 mL of distilled water with magnetic stirring for 45 minutes at 70 °C to achieve a clear 1% CMC coating. Under continuous magnetic stirring, 0.5 mL (50% v/w) glycerol (based on CMC weight) as plasticizer was added and further stirred for 10 min at 70 ºC.

Emulsions of CMC in combination with plant oils were obtained by adding concentrations of 1 and 3% of moringa or neem oil and 0.1 and 0.3% Tween 80 based on volume of plant oil. The resultant solution was homogenized at 13,500 rpm for 3 min at 70 ºC. The emulsions were cooled to 55 ºC and left for 2 minutes to exhaust air bubbles constituted during homogenization.

Oils (Moringa/Neem)

Moringa and neem oils obtained from seeds were prepared using the method of Das et. al., (2022). Required volume (1 mL and 3 mL) of oil and (10% v/w) of Tween 80 as emulsifier was measured into a 100 ml volumetric flask and topped up with distilled water. The resultant solution was homogenized at 13,500 rpm for 3 min at 70 ºC.

2.2 Experimental design

A factorial experiment was conducted using a 2 × 7 × 11 treatment structure arranged in a completely randomized design (CRD). The three experimental factors were: storage temperature (room and refrigeration), coating treatment [carboxymethyl cellulose (CMC), moringa oil (MO), neem oil (NO) with their combinations and prochloraz as positive control (PRO)], and storage duration (spanning 28 days for shelf-life studies and 21 days for determination of quality attributes. Data was collected at 3-day intervals. Details of the coating treatment combinations are presented in Table 1. Each replicate of the study had one hundred and fifty-four (154) fruits and a total of four hundred and sixty-two (462) fruits for the 3 replicates.

Table 1: Composition and ratios of edible coating treatments applied on papaya

Treatments					
Treatments	Description	Volume of coating in 100 mL solution / mL			
		1%CMC	Moringa oil	Neem oil	0.3%PRO
T1	CONTROL	0	0	0	0
T2	1% CMC	100	0	0	0
T3	1% CMC+1 mL MO	99	1	0	0
T4	1% CMC+1 mL NO	99	1	0	0
T5	1% CMC+3 mL MO	97	3	0	0
T6	1% CMC+3 mL NO	97	3	0	0
T7	1 mL NO	0	0	1	0
T8	3 mL NO	0	0	3	0
T9	1 mL MO	0	1	0	0
T10	3 mL MO	0	3	0	0
T11	0.3% PRO (Imidazole Fungicide)	0	0	0	100

CMC = Carboxymethylcellulose; MO = Moringa oil; NO = Neem oil; PRO = Prochloraz (Imidazole Fungicide)

2.3 Sample Preparation, Application and Storage

Uniform fruits free from pests, diseases, injuries, bruises, and blemishes were selected for this study. Fruits were washed in chlorinated water (0.4 mg/L) and wiped with clean disposable paper towels. All fruits, except for the control group, were fully submerged in the coating material for 30 seconds (Table 1) and then air-dried at room temperature. The fruits were then either stored under room (27 °C) or refrigerated (10 °C) conditions. Data was collected at three-day intervals.

2.4 Quality Attributes measured

Weight Loss (%)

Physiological loss in weight was calculated using the method described by Kader (2002), based on initial and final weights. Using a Bioline Germany electronic scale with two (2) decimal places, the weight of the fruits was measured at the start of the experiment (day 0) and at the end of each storage interval. The following formula was used to calculate weight loss:

Weight loss (%) = [(Initial weight – Final weight) / Initial weight] × 100

Firmness (N)

Fruit firmness was determined destructively using the TR Turoni (Via Copernico 26, 47122 Forlì, Italy) hand-held penetrometer Model 53200 with a 5 mm probe. The plunger of the penetrometer was pushed against the surface of the fruit till it fully penetrated the skin. The maximum force required to puncture 3 different parts of each fruit was determined and the average computed in Newton (N).

Total soluble solids – Brix (TSS)

TSS was determined using a digital Hanna© refractometer 96801 at room temperature. Two drops of papaya juice were squeezed and placed on the prism of the refractometer. The refractometer was held perpendicular to a light source to look through the lens and the value was read using the internal scale. Total soluble solids of the fruits were expressed in Brix.

Titratable Acidity - % (TA)

TA was determined according to the method as described by Ranganna (1995) and the methods description partly reproduces their wording. For the estimation of TA, longitudinal section of fruit was homogenized and the resultant pulp filtered. Ten (10 mL) of the fruit juices was measured into a conical flask and diluted with 50ml distilled water. This solution was titrated against 0.1 N NaOH using phenolphthalein as indicator. The result was expressed as % total acid (Titratable Acidity).

$$Titratable\ acidity = \frac{D \times 0.064(0.1\ N\ NaOH) \times C}{A \times B} \times 100$$

Where, A= Weight of the sample; B= Volume of the sample taken for examination; C=Volume of the sample made with distilled water; D= Burette reading.

pH

The pH of the fruit juice was determined using a digital Mettler Toledo pH metre calibrated using a 3- point calibration curve with pH buffers ranging from pH 4 to pH 14. Longitudinal section of fruits was homogenized and the resultant pulp filtered into a beaker. The glass electrode of the pH meter was inserted into the papaya juice and the pH recorded.

Vitamin C (mg/100 g)

Vitamin C (ascorbic acid) was determined by the titrimetric method according to (AOAC 2007a). The vitamin C content was calculated using the following formula;

Ascorbic acid (mg/100 g) = Titre × Dye equivalent × dilution factor.

Shelf-Life (days)

The shelf life of stored papaya fruit was determined by counting the days required for the fruits to reach the final stage of ripening where the colour turned completely yellow, and firm enough to be still marketable.

2.5 Isolation and Identification of Pathogens Associated with Papaya Fruit Rot

Media preparation and pathogen isolation

Potato dextrose agar (PDA) was prepared by mixing 39 g PDA with 1 L of water. The PDA was autoclaved for 15 minutes at 121 ^{o}C and cooled in a water bath at 40 ^{o}C. Penicillin was added to the sterile PDA to limit bacterial growth and the cooled PDA were poured into petri dishes and allowed to set. Small portions of symptomatic tissue from fruits were isolated and inoculated onto PDA and the dishes was incubated for 7 days at 25 ^{o}C. Mycelial plugs were removed from sporulating areas close to the growing edge of the plate and transferred onto PDA dishes. The plates were incubated at 25 °C for 7 days. The cultures of the various isolates were evaluated, and the experiment repeated twice. The conidial morphology of the isolates was studied by preparing a conidial suspension by flooding the cultures with sterile distilled water (SDW). Drops of the suspension were then placed on microscope slides and their morphological structures were viewed under the light microscope at 40x and 100x magnification. Pure cultures of fungi were identified using cultural and morphological characteristics e.g., colony texture and zonation, colony diameter and colony colour.

Pathogenicity assay

Symptomless fruits were surface sterilized by washing with 70% ethanol. Small pieces of fungal mycelium from pure cultures were inoculated onto artificially injured healthy fruits, while control fruits were inoculated with uninfected PDA media cuttings. The inoculated wounds were covered with sterilized cotton wool and sealed with a tape. The fruits were stored at room temperature (27oC) for 7 days. After seven days of inoculation, disease and incidence were verified by observing spore and mycelial of isolates with the light microscope.

2.6 Data Analysis

All analyses were performed in triplicate. The effects of coating, storage temperature, and storage duration, as well as their two-and three-way interactions on the physico-chemical characteristics, of papaya, were evaluated using Analysis of Variance (ANOVA). The GLM (General Linear Model) procedure using SAS software version 9.4 (SAS Institute Inc., Cary, NC, USA) was used to analyze the factorial structure of the experimental design, following the model:

$$Yijk = \mu + A_i + B_j + C_k + (AB)_{ij} + (AC)_{ik} + (BC)_{jk} + (ABC)_{ijk} + \varepsilon_{ijk}$$

Where:

- Y_{ijk} is the observed response
- μ is the overall mean,
- A, B, and C represent the fixed effects of coating, storage temperature, and storage duration respectively,
- The interaction terms denote their respective factorial interactions, and
- ε_{ijk} is the residual error.

Significance was assessed at $p < 0.05$. The Type III sum of squares was used to test for significance of main and interaction effects. The coefficient of determination (R^2), coefficient of variation (CV), and root mean square error (RMSE) were used to evaluate the goodness of fit and model reliability. When significant effects were observed, means were compared using Dunnet's test to determine differences between control and coated samples.

The pathogens were identified based on their morphological characteristics, and a pathogenicity assay was performed to assess the infectivity of the isolated organisms.

3.0 RESULTS

Shelf life

Edible coatings markedly improved papaya shelf life, especially under refrigeration, where coated fruits lasted about 21–27 days compared to much shorter periods at room temperature (Figure 1). The most effective treatments were 1% CMC combined with 3% moringa or 1% neem oil, which preserved fruits for up to 27 days in cold storage and 16–17 days at room temperature, both outperforming the uncoated control (about 9 days). Overall, CMC-based coatings incorporating moringa or neem oils emerged as promising natural strategies for extending the shelf life of fresh papaya.

Firmness (N)

Papaya firmness decreased over time under both room temperature and refrigerated storage, but the rate of softening depended strongly on temperature, coating type and storage duration (Fig. 2). At room temperature, softening was rapid, yet fruits coated with 1% CMC + 3% moringa oil retained the highest firmness, followed by 1%

CMC + neem oil and 1% CMC + 3% neem oil, which all outperformed the control. In contrast, papayas treated with neem oil alone (1% or 3%) behaved similarly to the uncoated control, while 0.3% prochloraz provided only moderate firmness retention.

Refrigerated storage slowed papaya softening more effectively than room temperature, especially when combined with CMC-based coatings. Coatings that combined CMC with moringa or neem oils, particularly 3% moringa oil, preserved firmness best under both storage conditions. Overall, temperature was the main factor affecting firmness loss, with the edible coatings providing additional protection and helping to extend postharvest quality.

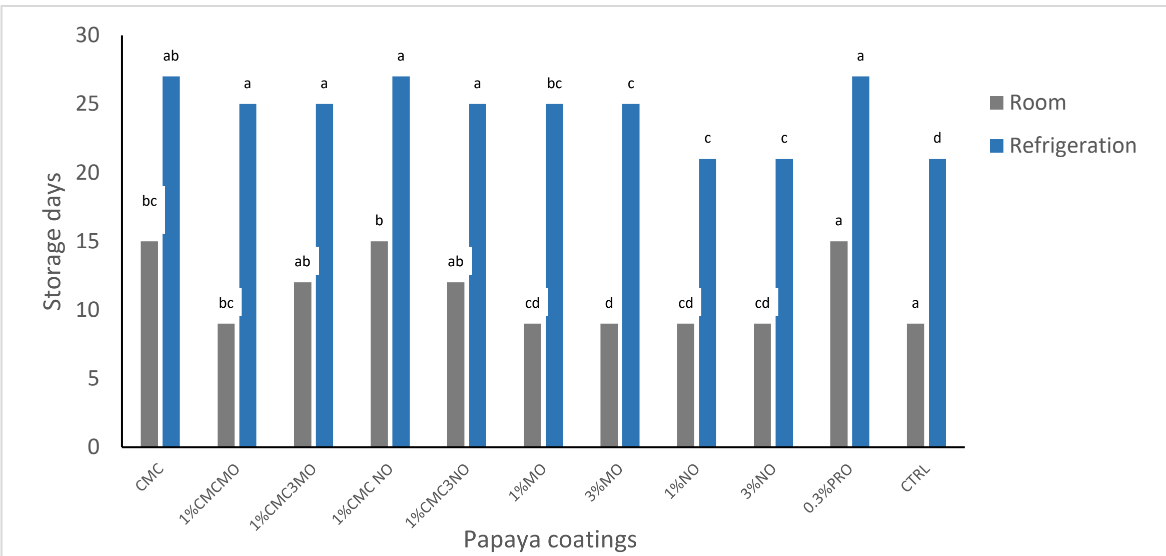

Figure 1: Effect of coating treatments on papaya shelf life under room (27 ± 2 °C) and refrigerated (10 ± 1 °C) storage conditions

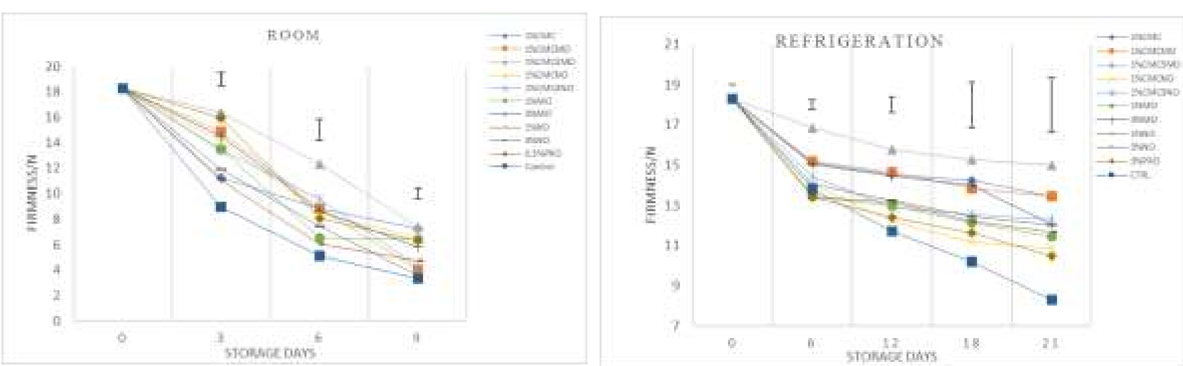

Figure 2: Changes in firmness of coated papaya during storage at room temperature (27 ± 2 °C) until day 9, when most samples became unmarketable, and at refrigeration temperature (10 ± 1 °C), with selected data points presented up to 21 days

Weight loss (%)

Weight loss in papaya increased steadily during storage at both temperatures, but was more pronounced and rapid at room temperature (Figure 3). Under room conditions, uncoated and 1% CMC-coated fruits showed the highest losses, while coatings containing moringa oil (1% MO, 3% MO, and 1% CMC3MO) most effectively reduced moisture loss, with other coatings showing intermediate performance.

Refrigerated storage slowed and reduced papaya weight loss over 21 days compared with room temperature, with the uncoated control consistently losing the most weight. Edible coatings, especially those combining CMC with moringa oil (notably 1% CMC3MO, 1% CMCMO, and 3% MO), were the most effective in limiting moisture loss, while neem oil coatings and prochloraz offered moderate protection. These CMC-plant oil coatings likely acted as semi-permeable barriers that reduced transpiration and respiration. Moringa-enriched formulations consistently performed best at both temperatures, highlighting their promise for commercial use in extending papaya shelf life.

3.1 Effect of coating, temperature, and storage duration on TSS, vitamin C, and titratable acidity of papaya

The effect of coating, storage temperature, and storage duration on the physicochemical quality of papaya fruits was assessed by evaluating total soluble solids (TSS), vitamin C content, and titratable acidity (TA). The results of the factorial analysis of variance under room temperature (27 °C, 77% RH) and refrigeration (10 °C, 67% RH) conditions are presented in Table 2. TSS was mainly driven by storage temperature and duration, with strong temperature × time interactions under both room ($F = 93.35$; $p < 0.05$) and refrigerated conditions ($F = 89.18$; $p < 0.05$). Coatings alone did not significantly affect TSS, but their effect depended on the

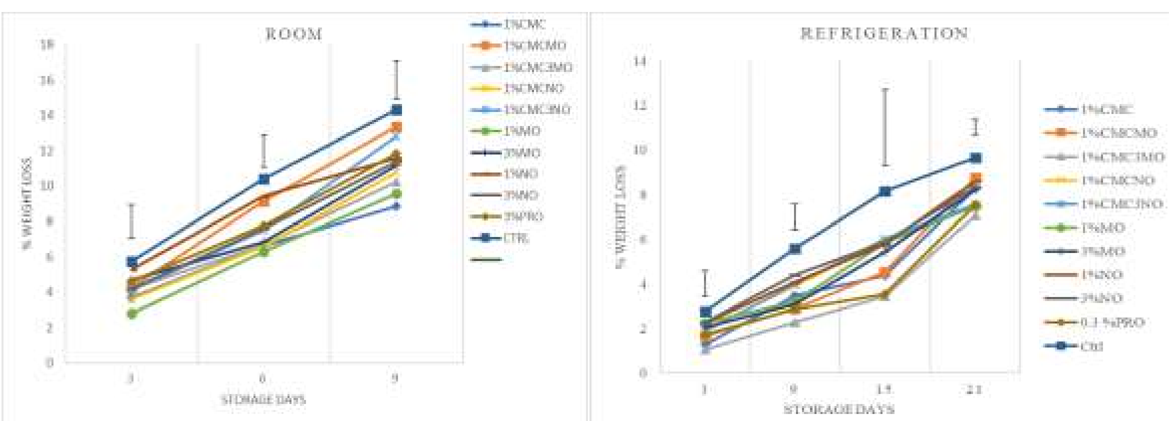

Figure 3: Effect of coating treatments on weight loss of papaya during storage at room temperature (27 ± 2 °C) until day 9, after which most samples became unmarketable, and at refrigeration temperature (10 ± 1 °C), with selected data points shown up to 21 days

combination of temperature and storage time. TSS changes over time followed the typical ripening trend, with a more pronounced increase at room temperature. The model exhibited a moderate fit ($R^2 = 0.71$) and a relatively high CV (64.64%).

Vitamin C

Vitamin C was the quality attribute that was most affected by all treatments and interactions. All two- and three-way interactions were statistically significant ($p < 0.05$). Notably, the temperature × days interaction was exceptionally strong (F = 2831.03 at 27 °C; 2501.53 at 10 °C), demonstrating the dominant influence of storage environment and duration on ascorbic acid degradation. The model explained 98% of the variability ($R^2 = 0.98$) with low error (CV = 11.80%), indicating high reliability. Refrigeration coupled with coatings preserved vitamin C content in papaya better than room temperature storage.

Table 2: Analysis of variance (F values) for the effects of coating, storage temperature, and storage duration on total soluble solids, vitamin C, and titratable acidity of papaya stored under room (27℃/77% RH) and refrigeration (10℃ / 67% RH) conditions

Source	F-value					
	Room temperature			Refrigeration temperature		
	Total soluble solids	Vitamin C	Titratable acidity	Total soluble solids	Vitamin C	Titratable acidity
Coatings	1.58	32.14*	3.13*	1.58	32.14*	3.13*
Temperature	15.61*	327.34*	4.30*	15.54*	328.56*	4.30*
Days	14.73*	457.69*	31.40*	13.68*	386.61*	31.40*
Coating X Temperature	1.46	3.05*	1.83	1.46	3.05*	1.83
Coating X Days	1.41*	5.24*	1.81*	1.41*	5.24	1.81*
Temperature X Days	93.35*	2831.03*	70.86*	89.18	2501.53*	70.86*
Coating X Temperature X Days	1.40*	7.21*	1.85*	1.40*	7.20*	1.85*
Mean	6.30	2.39	0.07	6.30	2.39	0.07
Model R Square	0.71	0.98	0.71	0.71	0.98	0.71
CV	64.64	11.80	99.27	64.64	11.80	99.27
RMSE	4.07	0.28	0.07	4.07	0.28	0.07

F-values followed by an asterisk (*) are significantly different at $p < 0.05$

Titratable Acidity (TA)

TA was significantly affected by coating, temperature, and storage time, with a strong temperature × days interaction (F = 70.86) indicating faster acid loss at higher temperatures and high variability in TA values. Overall, refrigeration better preserved the nutritional and physicochemical quality of papaya than room temperature, and coating effects were most evident for vitamin C and TA. Combinations of 1% CMC with moringa or neem oils were particularly effective in slowing quality deterioration under both storage conditions.

pH

The pH of papaya fruits increased progressively during storage under both room and refrigerated conditions, reflecting typical postharvest metabolic activity and the degradation of organic acids. However, the extent and rate of pH increase were markedly influenced by storage temperature, coating, and duration of storage (Figure 4). Under room temperature conditions, pH values rose steadily over the 9-day storage period across all treatments. Initial pH values were relatively uniform at approximately 5.3, but by day 9, significant variation was observed. The greatest increase in pH occurred in fruits treated with 1% CMC and 1% CMC + 3% neem oil (1% CMC3NO). Notably, the uncoated fruits, as well as 3% neem oil and 3% prochloraz (PRO) treatments, exhibited the least pH increase, maintaining values closer to 5.5. The observed rise in pH under room temperature conditions is indicative of the metabolic breakdown of organic acids and increased microbial activity typical of ripening and early spoilage. While all coatings provided some delay in the pH increase compared to the control, those incorporating neem or moringa oils in a CMC matrix offered slightly better stability, suggesting their potential role in maintaining acidity and slowing spoilage during short-term room temperature storage.

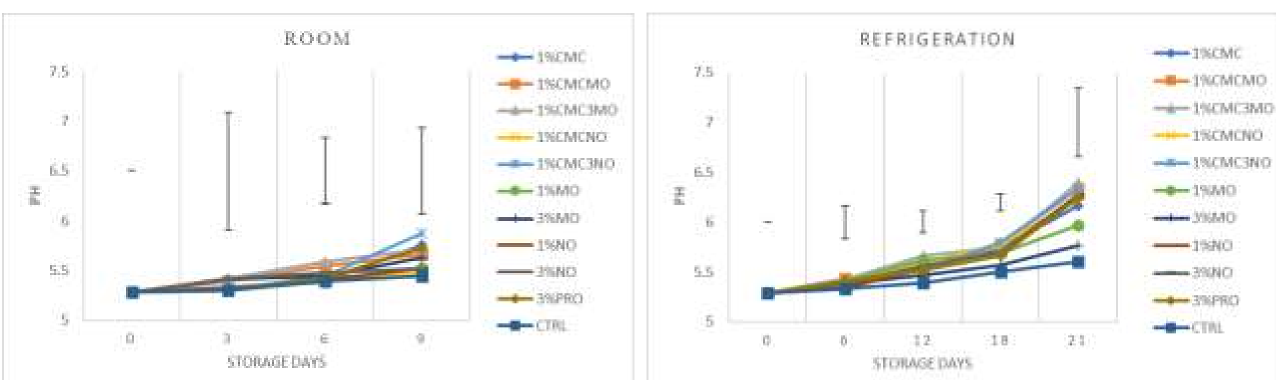

Figure 4: Effect of coating treatments on pH of papaya during storage at room temperature (27 ± 2 °C) until day 9, after which most samples became unmarketable, and at refrigeration temperature (10 ± 1 °C), with selected data points shown up to 21 days

Overall, pH of the papaya increased during storage at both temperatures, reflecting acid degradation during ripening, although the rate and extent of increase depended strongly on temperature, coating, and storage duration. Room temperature caused a faster and sharper rise in pH, while refrigeration slowed this change and better preserved acidity. Edible coatings, especially CMC combined with moringa or neem oils, modified pH evolution by either limiting or enhancing acid loss, showing that suitable coating–temperature combinations can help maintain papaya internal chemistry and overall quality for longer.

3.2 Nature of pathogens isolated after coating under room and refrigeration temperature storage conditions

Nine (9) fungal species were isolated and identified from papaya (Table 3). Six fungal isolates from storage at room temperature (26.8℃/77% RH) and three (3) from refrigerated (10.1℃/68.2% RH) storage. *Fusarium* spp., *Colletotrichum gloeosporioides and Lasiodiplodia theobromae* were common species found at both storage conditions. Generally, fruits stored at room temperature showed disease symptoms on the control fruits after six (6) days whiles, treated fruits showed disease symptoms after twelve (12) days. Disease symptoms showed later under refrigeration storage - twelve (12) days for the control and fifteen (15) days for coated fruits. Pathogens were identified with their cultural and morphological characteristics.

Table 3: Fungal pathogens isolated from symptomatic papaya fruit stored at room (27 °C, 77% RH) and refrigerated (10 °C, 68.2% RH) conditions, identified after PDA culture and morphological characterization.

Coatings	Pathogens
Control	*Lasiodiplodia theobromae, Fusarium* spp., *Colletotrichum gloeosporioides* spp. Orange fungus *(unidentified)*
1%CMC	*Fusarium* spp.
1%CMC+ImLMO	*Fusarium* spp.
1%CMC+3mLMO	*Aspergillus flavus*
1%CMC+1mLNO	*Fusarium* spp.
1%CMC+3mLNO	*Aspergillus niger*
1%NO	*Fusarium* spp.
3%NO	*Penicillium, Aspergillus niger*
1%MO	*Colletotrichum gloeosporioides*
3%MO	*Fusarium, Aspergillus niger*
0.3% PRO	*Aspergillus flavus,* Orange fungus (unidentified)

After 3 days of inoculation, *Aspergillus flavus* colonies exhibited rapid growth, forming powdery green colonies that covered the plate. The colonies consisted of septate hyphae bearing spherical conidia arising from thick-walled foot cells. (Fig. 5A). *Colletotrichum gloeosporioides* colonies were initially white, but turned grey as the culture aged (Fig. 5B) and in 9 days, hyphae grew to fill the entire 90 mm petri dish. In culture, the isolates produced bright orange acervuli with numerous short, conical, with rounded edges spores.

Fusarium sp. colonies grew rapidly, reaching approximately 4.5 cm in diameter within four days (Fig. 5C). The mycelium appeared white to cream, turning almost orange-brown with time. After 4 - 7 days, macroconidia were produced from short, multiseptate conidiophores that formed characteristic sporodochia. The macroconidia were three to five septate, fusiform to cylindrical, and moderately curved.

Lasiodiplodia theobromae isolates initially produced white mycelium, which turned black as the culture aged. Within 5 days, the mycelium grew to fill the entire 90 mm plate. The hyphae were initially hyaline but became septate and darkened over time. After 14 days, mature, brown, uniseptate, ovoid conidia were observed (Fig. 6A).

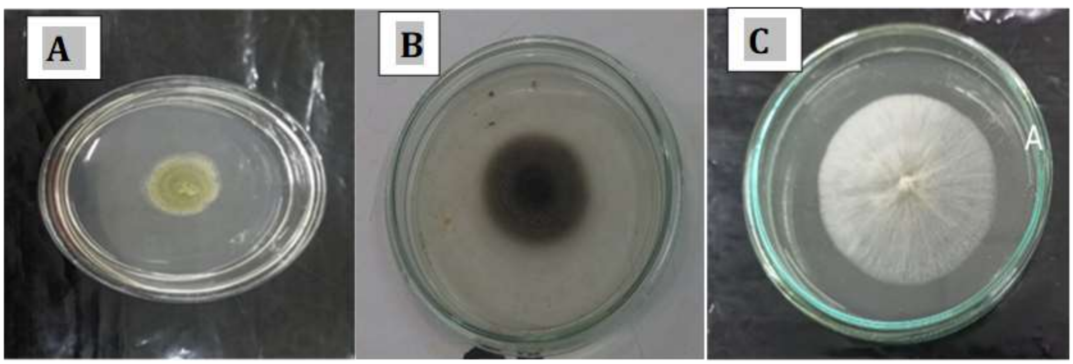

Figure 5: Colony morphology of *Aspergillus flavus* (A), *Colletotrichum gloeosporioides* and (B) and *Fusarium* s*pp* (C)

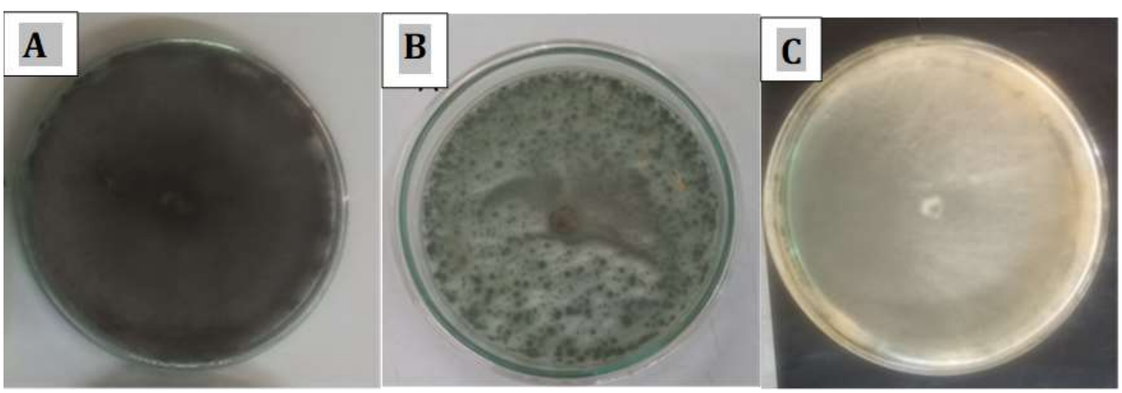

Figure 6: Colony morphology of *Lasiodiplodia theobromae* (A), *Penicillium* spp. and (B) and an unidentified orange fungus (C)

Penicillium spp. colonies grew fast, consisting of green dense conidiophores. Microscopically, chains of single-celled conidia were observed in basipetal succession from a phialide (Fig.6B). An orange-coloured fungus was observed, which showed morphological characteristics, such as pigmentation, mycelial appearance, and rapid growth, similar to those of a common fungus associated with the Ghanaian fermented maize food "Fante kenkey". It produced orange mycelium that extended beyond the edges of the petri dish. The hyphae were aseptate and lacked conidia (Fig. 6C). As this fungus could not be identified based on cultural and morphological characteristics alone, further identification using molecular methods such as PCR and sequencing is recommended.

3.3 Effect of coating treatments on disease incidence of papaya under room and refrigerated storage

The incidence of disease in papaya fruits was significantly influenced by both the type of coating and the storage condition (Table 4). Uncoated fruits had the highest decay (about 77%), whereas fruits treated with 0.3% prochloraz and 1% CMC + 3% neem oil showed the lowest disease levels (about 37–40%.). CMC coatings enriched with neem or moringa oils further reduced disease compared with CMC alone, indicating added antifungal benefits from the plant oils.

Table 4: Disease incidence (%) in coated papaya stored at room (27°C,78% RH) and refrigeration (10 °C, 67% RH) conditions using PDA mycelial-plug inoculation of surface-sterilized, wounded fruits and light-microscopy after 7 days at 27 °C

Coating	Room (27 °C/78 RH)	Refrigeration (10°C/ 67RH)
1%CMC	63.33 ± 3.33^{g}	33.33 ± 3.33^{abcd}
1%CMC+1mLMO	$43.33 \pm 3.33d^{ef}$	30.00 ± 0.00^{abc}
1%CMC+3mLMO	46.67 ± 3.33^{ef}	30.00 ± 5.77^{abc}
1%CMC+1mLNO	43.33 ± 3.33^{def}	23.33 ± 3.33^{a}
1%CMC+3mLNO	40.00 ± 5.78^{cdef}	26.67 ± 3.33^{ab}
1%MO	50.00 ± 0.00^{f}	33.33 ± 3.33^{abcd}
3%MO	43.33 ± 3.33^{def}	33.33 ± 3.33^{abcd}
1%NO	40.00 ± 5.77^{cdef}	30.00 ± 0.00^{abc}
3%NO	46.67 ± 3.33^{ef}	33.33 ± 5.77^{abcd}
0.3% PRO	$36.6\ 7 \pm 6.67^{bcde}$	36.67 ± 0.00^{bcde}
Control	76.67 ± 3.33^{h}	46.67 ± 3.33^{ef}

Means ± standard error of means followed by different lowercase superscripts within each column indicate statistically significant differences ($p < 0.05$) among treatments under the same storage condition. Treatments that share at least one superscript letter are not significantly different from each other, while those with no letters in common differ significantly.

Under refrigerated conditions, disease incidence was consistently lower across all treatments, with values ranging from 23.33% to 46.67%. The most effective treatment was 1% CMC + 1 mL NO, which recorded the lowest disease incidence (23.33 ± 3.33%), followed by 1% CMC + 3 mL NO (26.67 ± 3.33%) and 1% NO alone (30.00 ± 0.00%). In contrast, the control still exhibited the highest incidence under refrigeration (46.67 ± 3.33%), although the disease incidence was lower than the value observed at room temperature. Overall, the incorporation of neem oil or moringa oil into CMC-based coatings markedly reduced disease incidence, with neem oil-based formulations performing better under both room temperature and cold storage. Overall, papaya showed much lower disease incidence during refrigeration storage (about 23–47%), with neem oil-based coatings, especially 1% CMC + neem oil, giving the best protection. Although the control still had the highest decay, it was less than at room temperature, and combining CMC with neem or moringa oils clearly improved disease control, with neem formulations performing best across both storage conditions.

4.0 DISCUSSION

Shelf life

The results indicate that both storage temperature and coating formulation significantly affected the shelf life of papaya fruits. Refrigerated storage extended shelf life by approximately 10–13 days across treatments compared to room temperature conditions. This aligns with previous findings that refrigeration slows metabolic activity and microbial proliferation in climacteric fruits like papaya (Prasad & Paul, 2021; Prasad et al., 2024; Loh et al., 2024; Yahia & Carrillo-Lopez, 2019). This highlights temperature as the primary driver of postharvest quality retention.

Among coatings, combinations of CMC with moringa or neem oil consistently outperformed the single applications. The better performance of 1% CMCNO and 1% CMC3MO under both temperature storage conditions may be attributed to the synergistic action of CMC as a film-forming agent and the antimicrobial and antioxidant properties of moringa and neem oils. These composite coatings likely form semi-permeable barriers that reduce respiration and moisture loss while inhibiting microbial growth (Adetunji et al., 2013; Tesfay et al., 2017; Ngubane et al., 2024; Passafiume et al., 2022).

Weight loss

Weight loss is a key physiological indicator of postharvest deterioration in fresh produce, which is often a result of transpiration and respiration processes that lead to reduced marketability and quality. In this study, both storage temperature and edible coating type significantly influenced the weight loss in papaya fruits during storage. The findings align with earlier reports that higher temperatures accelerate moisture loss and metabolic activity (Prasad & Paul, 2021; Adissie *et al.,* 2020; Yahia & Carrillo-Lopez, 2018). Fruits stored under room temperature conditions lost up to

14.5% of their initial weight within just 9 days, while those kept under refrigeration recorded a similar maximum only after 21 days. This emphasizes the role of low-temperature storage in effectively slowing down water loss, respiration, and other degradative changes (Siddiqui et al., 2022).

The addition of edible coatings further enhanced moisture retention, with clear differences observed between formulations. Coatings which included moringa oil specifically 1% CMC3MO, was consistently better able to minimize weight loss across both storage conditions. These findings are consistent with earlier studies (Ali et al., 2011; Mkandawire & Aryee, 2018), who reported that oil-based coatings reduce water vapor permeability and form protective films that limit transpiration. Moringa oil, known for its high lipid content and antimicrobial properties, likely enhanced barrier function when combined with the film-forming capacity of carboxymethyl cellulose (CMC) (Antunes et al., 2012; Salehi, 2020; Krishnan et al., 2025).

Neem oil-based coatings also slowed down moisture loss in the coated papaya though to a lesser extent than moringa oil. Their performance was improved when integrated with CMC, possibly due to the synergistic interaction between the oil's hydrophobicity and CMC's moisture retention capability (Prasad & Paul, 2021). Meanwhile, the control fruits, which were uncoated, exhibited the highest and fastest weight loss under both conditions, confirming the protective role of edible films in postharvest handling.

Overall, the study highlights that while refrigeration alone reduces weight loss, combining it with effective edible coatings, particularly those incorporated with bioactive plant oils further enhanced storage outcomes. Formulations of CMC combined with Moringa oil emerged as the most promising treatment, offering a sustainable, natural approach to preserving postharvest quality and extending the marketability of papaya.

Firmness

Fruit firmness is a critical indicator of postharvest quality, influencing both consumer acceptability and market value. In this study, firmness degradation in papaya was significantly influenced by storage temperature, coating, and storage duration. These findings align with previous studies emphasizing temperature as a major factor affecting tissue softening in climacteric fruits (Siddiqui et al., 2022; Prasad & Paul, 2021). Under room temperature conditions, rapid loss of firmness was observed across all treatments. This is consistent with the accelerated ripening and metabolic activity that occurs at higher temperatures of climacteric fruits such as papaya (Prasad & Paul, 2021; Alam et al., 2010). In contrast, refrigerated storage markedly slowed softening, consistent with studies on minimally processed papaya that report better retention of firmness and overall quality at low temperatures than at ambient conditions (Alam et al., 2010; Prasad & Paul, 2021). Even under refrigeration, however, uncoated control fruits softened fastest, highlighting the vulnerability of unprotected papaya tissues to postharvest deterioration (Vyas et al., 2014; Hazarika et al., 2017).

Across both storage regimes, coatings based on 1 % carboxymethyl cellulose enriched with essential oils, particularly 3 % moringa or neem oil, were most effective in moderating firmness loss (Vyas et al., 2014; Hazarika et al., 2017; Ali et al., 2010). Similar polysaccharide and CMC based films containing plant derived bioactive compounds have been reported to form semi permeable barriers that limit moisture loss and gas exchange while providing antioxidant and antimicrobial protection (Ali et al., 2010; Dashipour, 2015).

The superior performance of the 1 % CMC plus 3 % moringa oil treatment is consistent with work showing that moringa oil and extracts possess strong antioxidant and antimicrobial activity and can enhance firmness retention in coated fruits (Silva et al., 2021; Al-Rashdi et al., 2024).

Total Soluble Solids (TSS)

The progressive increase in TSS observed under both room and refrigerated conditions reflects the natural conversion of starches to sugars during ripening, a typical pattern in climacteric fruits like papaya (Prasad & Paul, 2021). Although the main effect of coating on TSS was not significant, significant interactions with temperature and storage time indicate that coatings modulate sugar accumulation under specific conditions. The more moderate increase in TSS under refrigeration confirms earlier findings that lower temperatures slow ripening and sugar accumulation in fresh-cut papaya (Waghmare & Annapure, 2013). Coatings may act as semi-permeable barriers, thereby modulating gas exchange and respiration rate, which in turn influence sugar metabolism (Dashipour et al., 2015; Jafarzadeh et al., 2021).

Vitamin C

Vitamin C, which is a key nutritional quality parameter, showed a sharp decline with increasing storage time, particularly at room temperature, consistent with its susceptibility to oxidative and enzymatic degradation (Siddiqui, 2018). This degradation was significantly reduced under refrigeration, especially in fruits treated with CMC-based coatings enriched with moringa or neem oil. These results are consistent with the work of Farina et al. (2020) and Jafarzadeh et al. (2021), who noted that edible coatings can reduce ascorbic acid degradation by minimising oxidative stress and microbial activity. The enhanced preservation under cooler conditions is attributable to reduced enzymatic and respiratory activities, which are major contributors to vitamin C loss (Siddiqui, 2018). The high coefficient of determination (R^2 = 0.98) further underscores vitamin C's sensitivity to environmental and treatment factors, as also reported for fresh-cut fruits where vitamin C is among the most responsive quality attributes to handling and protective technologies (González-Aguilar et al., 2010; Ayala-Zavala et al., 2010).

Titratable Acidity (TA)

The decline in TA over time reflects the use of organic acids as respiratory substrates during fruit senescence, a trend widely reported in postharvest physiology studies (Choque-Quispe et al., 2022; Pasquariello et al., 2013). The more pronounced reduction at room temperature, compared to refrigeration, highlights the role of temperature in accelerating respiration and acid metabolism (Choque-Quispe et al., 2022). Although the main effect of coating on TA was modest, significant interactions with storage time indicate that surface treatments subtly modulated acid depletion. In particular, CMC-based coatings enriched with moringa or neem oil likely slowed acid degradation by acting as semi-permeable barriers that restrict gas exchange and lower metabolic activity, in line with reports that CMC and plant-extract coatings can maintain higher TA and delay ripening in mango, avocado and papaya (Ali et al., 2022; Brasil et al., 2012; Langa, 2018; Ngubane et al., 2024).

Taken together, the results indicate that storage temperature and duration are the primary drivers of postharvest quality loss in papaya, while coating composition fine-tunes these responses for labile attributes such as vitamin C and TA. The strong three-way interaction between coating, temperature and time for vitamin C suggests synergistic benefits when natural antimicrobial constituents in the coating are combined with low-temperature storage. Similar synergistic effects, expressed as improved retention of vitamin C and TA and extended shelf life, have been documented in coated fresh and fresh-cut papaya stored under refrigeration and in other tropical fruits treated with polysaccharide- and plant-extract-based coatings (Brasil et al., 2012; Kohli et al., 2018; Farina et al., 2020; Careli-Gondim et al., 2019; Raju et al., 2023; Ngubane et al., 2024). Together, these findings position CMC–moringa/neem coatings, used in combination with cold storage, as a promising strategy for preserving both the sensory and nutritional quality of papaya during extended storage.

pH

The progressive increase in pH observed in papaya fruits during storage under both room and refrigerated conditions aligns with typical postharvest biochemical changes, notably the degradation of organic acids and respiration induced metabolic activity (Ali et al., 2011; Siddiqui et al., 2022). This increase was more pronounced at room temperature, where higher respiration and microbial activity accelerate acid degradation, consistent with studies showing faster changes in acidity and pH at ambient conditions compared with cold storage (Prasad & Paul, 2021; Escamilla-García et al., 2018).

Differences among coating formulations suggest that barrier properties and antimicrobial activity strongly influence acid metabolism. The relatively sharp pH rise in fruits coated with 1% CMC and 1% CMC + 3% neem oil indicates that not all CMC-based coatings are equally effective in slowing acid loss under rapid ripening, whereas more moderate pH increases under 1% CMC + moringa oil formulations are consistent with reports that polysaccharide–essential oil systems can restrict gas exchange, respiration, and microbial growth (Dashipour et al., 2015; Nadim et al., 2015). The control and 3% neem oil coated fruits exhibited lower pH changes, which may reflect either limited metabolic activity due to stress or onset of spoilage that hindered acid metabolism (Siddiqui et al., 2022). Refrigerated storage substantially reduced the rate of pH increase, confirming the central role of low temperature in preserving acidity by slowing respiration and enzyme activity (Prasad & Paul, 2021; Siddiqui et al., 2022). Even under refrigeration, however, coatings containing moringa or neem oil in a CMC matrix still showed higher pH by day 21, which suggests that oil-containing coatings can modify internal gas balance and moisture dynamics sufficiently to alter acid metabolism, as reported for pectin- and chitosan-based coatings on avocado and other fruits (Maftoonazad & Ramaswamy, 2008). In contrast, the relatively stable pH in uncoated fruits and those treated with prochloraz or 3% neem oil at low temperature indicates suppressed microbial activity and improved acid retention, in line with work on coated papaya under cold storage that reports combined benefits of edible coatings and refrigeration for maintaining pH, titratable acidity, and overall quality (Ali et al., 2011; Batista et al., 2020; do Nascimento et al., 2023; Silva et al., 2023).

Incidence of pathogens on produce treated with different edible coatings

Edible coatings in this study clearly reduced disease incidence in papaya, especially when combined with low-temperature storage. Disease development was highest in fruits kept at room temperature, which is consistent with broader evidence that high temperature and relative humidity accelerate microbial growth, senescence, and decay in tropical fruits (Kader & Yahia, 2011; Zainalabidin et al., 2019). Under these conditions, uncoated control fruits showed the greatest disease incidence, confirming the high vulnerability of untreated papaya to rapid spoilage and postharvest losses. Coatings that incorporated neem oil in a CMC matrix coatings significantly reduced disease incidence under both room temperature and refrigerated conditions. This is consistent with reports that neem seed oil and extracts exhibit broad-spectrum antifungal activity against a range of postharvest pathogens in fruits and can significantly reduce decay when applied as biopreservatives (Shahbaz et al., 2022; Brishti et al., 2013). Neem oil disrupts microbial cell membranes and inhibits spore germination, providing a biochemical barrier to infection (Raghav et al., 2016).

Moringa oil (Moringa oleifera) based coatings also showed a moderate reduction in disease incidence, though their efficacy was slightly lower than that of neem oil treatments. Moringa seed oil is rich in bioactive compounds, including phenolics and flavonoids with documented antimicrobial properties, but its antifungal potency against postharvest pathogens may be lower than neem in practical applications (Anwar, 2007; Leone et al., 2016). Refrigerated storage alone reduced disease incidence across all treatments, supporting the widely accepted practice of cold storage for perishable produce (Maqbool et al., 2011; Paull & Chen, 1997. However, the combination of refrigeration with bioactive coatings, particularly neem oil in a CMC matrix, resulted in the greatest reduction in disease development, underscoring the value of integrated preservation strategies, mirroring findings from other fruits where edible coatings plus cold storage synergistically delay decay and maintain quality (Maqbool et al., 2011; Khalid et al., 2022).

4.0 CONCLUSION

This study demonstrated that edible coatings based on carboxymethyl cellulose (CMC) enriched with moringa and neem oils significantly enhanced the postharvest quality of papaya fruits stored under both room temperature and refrigeration. Coatings such as 1% CMC combined with 3% moringa oil (CMC3MO) consistently reduced physiological weight loss, delayed loss of firmness, stabilized pH, and preserved vitamin C content better than other treatments and the control. While refrigeration alone extended shelf life, its effectiveness was markedly enhanced when used in combination with functional coatings. The integration of essential oils into CMC matrices provided synergistic effects likely due to their barrier and antimicrobial properties, contributing to overall fruit quality maintenance.

RECOMMENDATIONS

The findings support the potential of CMC-based coatings enriched with moringa or neem oils as effective, natural postharvest treatments for extending the shelf life of papaya. It is recommended that further studies investigate the consumer acceptability, sensory impact, and scalability of these coatings in commercial settings. Moreover, exploring the antimicrobial spectrum of the plant-based oils used and their residual safety will be critical for regulatory approval and broader adoption. While neem oil has been explored for its antifungal effects on produce, regulatory approval and dosage considerations vary by region, and further toxicological assessment is recommended before widespread commercial approval. Adoption of these coating technologies could significantly reduce postharvest losses, improve market value, and contribute to sustainable fruit preservation systems, especially in regions with limited cold chain infrastructure.

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