

IMPACT OF MORINGA OIL COATING ON POSTHARVEST QUALITY AND STORAGE STABILITY OF LEMON, MUSAMBI, AND SWEET ORANGE

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(Received, 4th February 2026 Accepted 5th October 2026, Published 20th October 2026)

Abstract The loss of citrus fruits after harvest has been primarily attributed to their rapid physiological and microbiological deterioration. The current investigation was conducted to establish the impact of moringa oil coating on the quality and storage life of three species of citrus fruits, namely lemon, musambi, and sweet orange, stored for 21 days. The citrus fruits were divided into coated and uncoated samples, and the variation in non-destructive parameters (physiological weight loss, incidence of decay, firmness) and destructive parameters (ascorbic acid content, total soluble solids, and pH) was estimated at 7-day intervals. The outcomes showed a progressive reduction in ascorbic acid content and consistency, with a corresponding increase in total soluble solids, pH, weight loss, and decay incidence with storage. However, the moringa-coated fruits showed a significant decline in weight and decay incidence, along with enhanced firmness and chemical quality retention compared to uncoated fruits. The beneficial role of the coating was more evident after 14 days of storage. In general, moringa oil coating was seen to be a beneficial means of increasing the postharvest life of citrus fruits, illustrating its effectiveness as a natural and economic postharvest treatment.

[Citation: Sohail, A., Hussain, Z., Sher, A., Suleman, M., Hammad, M., Abbas, A., Ahmad, J., Sherazi, S.H.U.H. (2026). Impact of moringa oil coating on postharvest quality and storage stability of lemon, musambi, and sweet orange. J. Life Soc. Sci, 5: 73. <https://doi.org/10.64013/bbasrjlife.v2026i1.73>]

Keywords: Post-Harvest Storage; Citrus Varieties; Moringa Oil Coating; Shelf Life; Quality Attributes

Introduction

Citrus fruits are among commonly consumed and liked fruits around the globe usually because of their unique flavour and nutritional value(Liu et al., 2012). Among the most commonly consumed citrus fruits are Musambi (*Citrus limetta*), sweet orange (*Citrus sinensis*), and lemon (*Citrus limon*), because they are rich sources of vitamin C, organic acids, dietary fibers, antioxidants, and various other bioactive compounds that play a significant part in health and disease prevention in humans. The consumption of citrus fruits has been linked to improved immune function, reduced oxidative stress, and prevention of chronic diseases, and that's what makes them a vital part of a healthy diet(Miles and Calder, 2021). Still, citrus fruits remain highly perishable produce despite all of their nutritional and economic significance. Even after the harvest,

citrus fruits continue to exhibit physiological and biochemical alterations which result in the deterioration of quality(Strano et al., 2022). The major reasons for postharvest losses in citrus fruits are the loss of moisture, weight reduction, tissue softening, deterioration of ascorbic acid and total soluble solids, and microbial growth, especially fungal infections(Sanyaolu, 2016). Postharvest technology is a very important aspect of maintaining fruit quality, increasing storage life, and reducing losses. However, Traditional postharvest preservation methods, including refrigeration, controlled atmosphere storage, and the use of synthetic fungicides, have helped on a large scale to slow down the deterioration of fruits(Qadri et al., 2020).

Although, with the growing threats about food security and preservation, there has been an increasing trend towards finding some better and alternate ways of preventing food from

spoilage(Joardder and Masud, 2019). Consequently, natural and eco-friendly postharvest practices have been receiving considerable attention in recent years. Among the various alternatives, edible coatings have been identified as a novel method for postharvest quality maintenance(Ammar et al., 2025). By restricting oxygen diffusion and respiration rates, edible coatings can postpone ripening, reduce oxidation, slow down enzymatic reactions, and maintain the nutritional value. Moreover, edible coatings can enhance the aesthetic qualities of fruits and serve as a carrier for natural antimicrobial and antioxidant agents, further amplifying their benefits(Perez-Vazquez et al., 2023).

Different edible coating substances such as polysaccharides, proteins, lipids, and plant oils have been explored for their use in preserving fruits. Among these, plant oils have gained popularity in recent years because of their natural origin, biodegradability, and properties(Wu et al., 2024). Plant oils also have natural antioxidant, antimicrobial, and antifungal properties, which can be utilized to inhibit microbial growth and enhance the shelf life of fruits without hampering food safety (Burt, 2004). Moringa oil, extracted from the seeds of *Moringa oleifera*, has recently gained popularity in food and agricultural studies because of its remarkable nutritional and functional properties(Aremu et al., 2015). Moringa oil is rich in phenolic compounds, tocopherols, flavonoids, and unsaturated fatty acids, which have strong antioxidant and antimicrobial properties(Özcan, 2020). Although several investigations have reported the potential of edible coatings in maintaining the quality and shelf-life extension of fruits, very little research has been done to specifically examine the use of moringa oil coating on various citrus varieties under the same experimental conditions(Langa, 2018). Citrus fruits are quite diverse in terms of their thickness, moisture content, acidity, respiration rate, and natural shelf life. As such, the use of multiple citrus varieties in a single experimental study would offer a more comprehensive understanding of the specific responses of the various varieties to the coating treatment and would increase the applicability of the results(Maftoonazad and Ramaswamy, 2019). In this regard, the present research seeks to evaluate the potential of moringa oil as an edible coating substance for the preservation of postharvest quality and shelf-life enhancement on selected citrus varieties, namely Musambi, sweet orange, and lemon(Odetayo, 2021). The study will seek to examine both chemical and physical parameters of quality, such as decline in weight, firmness, appearance, pH, total soluble solids, and ascorbic acid content, in storage(Rathore et al., 2010).

Materials and Methods

The trial was designed to evaluate the impact of

moringa oil coating on the shelf life and physicochemical attributes of three citrus fruit varieties, namely lemon (*Citrus limon*), Musambi (*Citrus limetta*), and sweet orange (*Citrus sinensis*), stored for a period of 21 days(Al-Yahyai, 2021). Research was conducted in the Postharvest Laboratory at the University of the Punjab, Lahore, from November 2025 to December 2025. Fresh, mature, and similar fruits without any visible defects, mechanical injuries, or microbial contamination were chosen(Nasir). randomized design (CRD) with three citrus varieties (lemon, Musambi, and sweet orange) and two treatments (coated and uncoated). For each variety × treatment combination, three biological replicates were maintained. Fruits were assessed at four storage stages (Day 0, 7, 14, and 21) with a destructive sampling method(Janisiewicz and Conway, 2010). The fruits were kept under laboratory conditions, mimicking the environment of Lahore, with a mean temperature of 20-25°C and relative humidity of 50-60%. Commercially available moringa oil was purchased and used without dilution(Muhl, 2014). The fruits in the treatment group were coated with the dipping method, where each fruit was completely soaked in the oil to coat evenly. The excess oil was drained from the fruits, which were then dried at room temperature for about 2 hours before storage(Baldwin et al., 1995b). The control fruits were not coated. Each fruit was labeled with a distinct Fruit ID, which represented citrus species, treatment, and storage time. Each fruit was first evaluated for non-destructive parameters such as weight, firmness, and attractiveness(Yu et al., 2025). Fruit weight was measured with a digital weighing balance, and percentage weight loss was calculated with the following formula:

$$\text{Weight Loss (\%)} = \frac{[(\text{Initial Weight} - \text{Final Weight})/\text{Initial Weight}] \times 100.}$$

Firmness was determined in newtons (N) using a digital penetrometer to show resistance to pressure. The visual attributes were color change, skin shrinkage, and rot. The destructive properties were measured on the same fruits as the non-destructive measurements(Li et al., 2016). Juice extraction was done manually for pH, total soluble solids (TSS), and ascorbic acid analysis. The pH of the juice was determined using a calibrated digital pH meter that had previously been standardized using pH 4.0 and 7.0 buffer solutions for analysis(Cavalcanti et al., 2008). TSS was tested using a digital refractometer that had previously been calibrated with pure water for analysis. The ascorbic acid (Vitamin C) level was measured with the 2,6-dichlorophenolindophenol (DCPIP) titrimetric technique (AOAC, 2005)(Thakur et al., 2025). Before beginning the titration, the DCPIP titrant was calibrated against a known concentration of ascorbic acid. Fruit juice samples were titrated with calibrated dye until a clear light pink endpoint was reached (~15 s)(Adumanya et al., 2021).

$$\text{Vitamin C (mg/100g juice)} = (V \times F \times 0.5 \times 100)/m.$$

Decay incidence was assessed visually at each storage interval. Fruits exhibiting fungal growth, surface lesions, soft rot, or severe shriveling were considered decayed. Decay incidence (%) was calculated as:

$$\text{Decay incidence (\%)} = [\text{Number of decayed fruits} / \text{Total number of fruits}] \times 100$$

The data were illustrated in the form of average values of three fruits per treatment. The data were collected systematically and analyzed statistically. The research was carried out in a completely randomized design (CRD) (Gomez and Gomez, 1984) (Elbeheri et al., 2019). The data were analyzed individually for every citrus fruit variety with a two-way analysis of variance (ANOVA), with treatment (coated and uncoated) and storage time (0, 7, 14, and 21 days) as fixed factors. Mean separation was done with the help of Tukey's HSD test at a significance level of $p \leq 0.05$ (Rashid et al., 2020). Different letters represent the type of the parameters being evaluated. The first category discusses the differences in chemical properties and non-destructive physical properties, such as total soluble solids, pH value, ascorbic acid content, and

physiological weight loss, that occur during the storage period (Kader and Barrett, 1996). The second category is concerned with the destructive physical properties, such as firmness and texture, which help in understanding the integrity of the fruits when they are coated and uncoated. Significant differences among treatments and storage times for each citrus fruit variety were observed (Singh, 2017).

Results

The outcomes of the present research are classified into two broad categories depending on

Physical (Non-Destructive) Attributes

Weight Loss (%)

The percentage weight loss of citrus fruits was observed during a 21-day storage period. Weight loss gradually improved in all treatments (Joshi et al., 2020). Coated fruits always illustrated less weight loss than uncoated fruits, which confirmed that moringa oil coating was potent in declining moisture loss and respiration (Tesfay).

Table 1. Percentage weight loss (%) of coated and uncoated citrus fruits during storage

Variety	Storage Day	Coated Fruits (%) (Mean $\pm$ SD)	Uncoated Fruits (%) (Mean $\pm$ SD)
Sweet Orange	Day 0	0.00 $\pm$ 0.00 ^c	0.00 $\pm$ 0.00 ^d
	Day 7	1.20 $\pm$ 0.18 ^d	1.90 $\pm$ 0.26 ^c
	Day 14	2.40 $\pm$ 0.31 ^c	3.80 $\pm$ 0.49 ^b
	Day 21	4.10 $\pm$ 0.46 ^b	7.20 $\pm$ 0.88 ^a
Musambi	Day 0	0.00 $\pm$ 0.00 ^c	0.00 $\pm$ 0.00 ^d
	Day 7	1.50 $\pm$ 0.20 ^d	2.10 $\pm$ 0.29 ^c
	Day 14	2.80 $\pm$ 0.34 ^c	4.00 $\pm$ 0.51 ^b
	Day 21	4.30 $\pm$ 0.52 ^b	7.50 $\pm$ 0.94 ^a
Lemon	Day 0	0.00 $\pm$ 0.00 ^c	0.00 $\pm$ 0.00 ^d
	Day 7	1.00 $\pm$ 0.14 ^d	1.70 $\pm$ 0.24 ^c
	Day 14	2.20 $\pm$ 0.29 ^c	3.50 $\pm$ 0.46 ^b
	Day 21	3.90 $\pm$ 0.44 ^b	6.80 $\pm$ 0.85 ^a

At Day 21, the coating showed a percentage reduction in weight loss of around 43% in sweet orange, 43% in Musambi, and 43% in lemon compared to their respective controls (Application and Evaluation of a Pectin-Based Edible Coating..., 2020; Gum Arabic Edible Coating..., 2021) (Wiggers et al., 2026). The low values of standard deviation shown in the results indicate that the fruits were selected on the basis of

similarity, and the laboratory conditions were ideal at the time of measurements (Abbott, 1999).

Firmness (N)

The firmness of fruits slowly decreased over the storage period. Coated fruits had higher firmness values than uncoated fruits, indicating resistance to softening (Abebe et al., 2017).

Table 2. Firmness (N) of coated and uncoated citrus fruits during storage

Variety	Storage Day	Coated Fruits (N) (Mean $\pm$ SD)	Uncoated Fruits (N) (Mean $\pm$ SD)
Sweet Orange	Day 0	38.0 $\pm$ 0.6 ^a	38.0 $\pm$ 0.6 ^a
	Day 7	36.5 $\pm$ 0.7 ^b	35.2 $\pm$ 0.8 ^c
	Day 14	34.8 $\pm$ 0.8 ^c	32.0 $\pm$ 0.9 ^d
	Day 21	31.6 $\pm$ 0.9 ^d	26.4 $\pm$ 1.1 ^e
Musambi	Day 0	37.5 $\pm$ 0.6 ^a	37.5 $\pm$ 0.6 ^a
	Day 7	36.0 $\pm$ 0.7 ^b	34.8 $\pm$ 0.8 ^c
	Day 14	34.2 $\pm$ 0.8 ^c	31.5 $\pm$ 0.9 ^d
	Day 21	31.0 $\pm$ 0.9 ^d	25.8 $\pm$ 1.0 ^e
Lemon	Day 0	38.2 $\pm$ 0.6 ^a	38.2 $\pm$ 0.6 ^a
	Day 7	36.8 $\pm$ 0.7 ^b	35.5 $\pm$ 0.8 ^c

	Day 14	34.9 ± 0.8 ^c	32.3 ± 0.9 ^d
	Day 21	31.8 ± 0.9 ^d	26.6 ± 1.1 ^e

At Day 21, moringa oil-coated fruits had significantly higher firmness values for all citrus fruits, with coated sweet orange fruits having 20% higher firmness values (31.6 N) than uncoated fruits (26.4 N), and coated Musambi and lemon fruits having ~20% and ~19% higher firmness values, respectively, than their respective uncoated controls.

Incidence (%)

Decay incidence increased with storage duration in

both coated and uncoated fruits; however, uncoated fruits exhibited significantly higher decay, particularly after 14 days of storage (Figure 1)([Romanazzi and Moumni, 2022](#)). Visual observations further confirmed fewer decay symptoms in coated fruits at advanced storage stages (Figure 2)([Shao et al., 2012](#)).

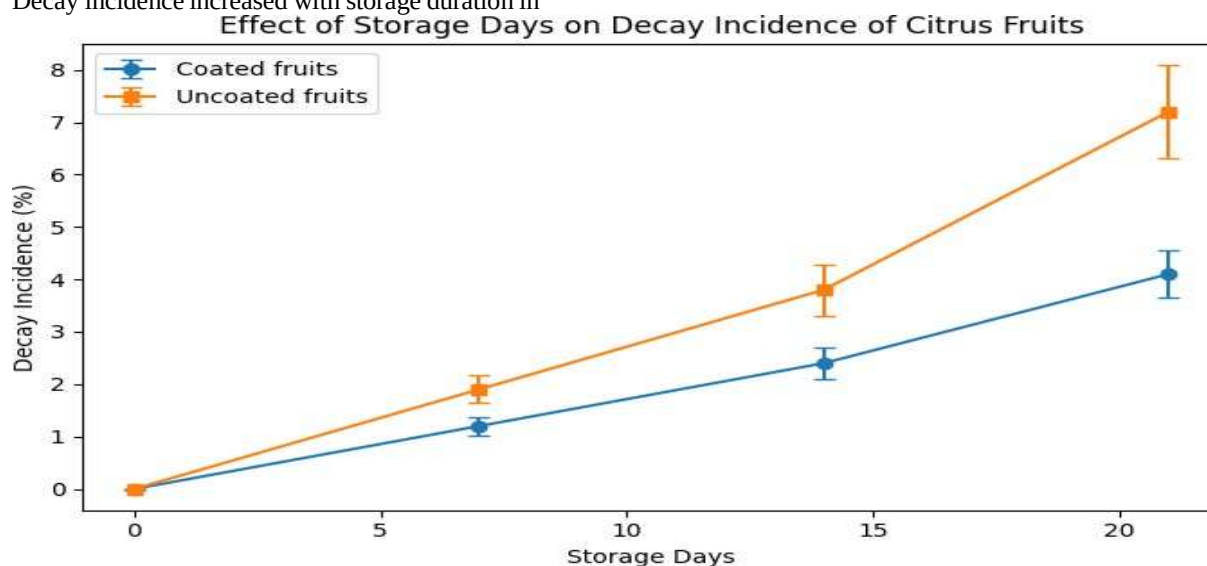


Figure 1. Effect of storage duration on decay incidence (%) of moringa-coated and uncoated citrus fruits. Values represent mean ± SD (n = 3).

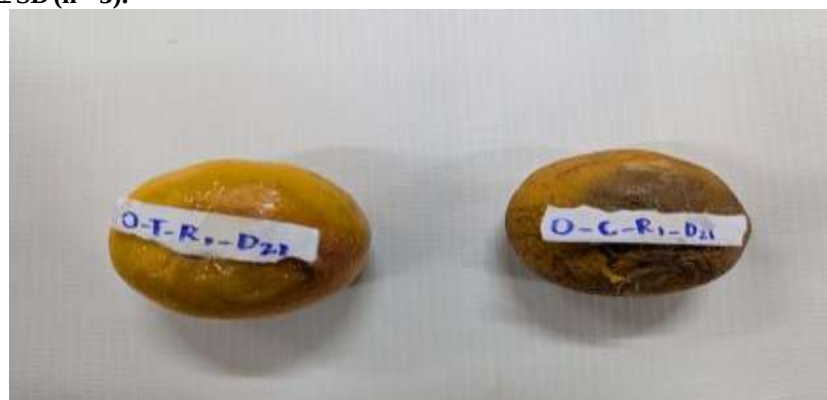


Figure 2. Visual Decay incidence of coated and uncoated fruits after 21 days

Chemical (Destructive) Attributes

Incidence of decay was higher with increased storage period for both coated and uncoated fruits,

but incidence of decay was significantly higher in uncoated fruits, especially after 14 days of storage (Figure 1)([Peralta-Ruiz et al., 2020](#)).

Table 3. Impacts of storage days on Ascorbic Acid (mg/100 g), TSS (°Brix), and pH of coated citrus fruits. Values are mean ± standard deviation (n = 3)([Baldwin et al., 1995a](#))

Variety	Storage Day	Ascorbic Acid (mg 100 g ⁻¹)	Total Soluble Solids (°Brix)	pH
Lemon	Day 0	58.9 ± 0.7 ^a	9.0 ± 0.1 ^c	2.43 ± 0.02 ^c
	Day 7	52.4 ± 0.6 ^b	9.2 ± 0.1 ^b	2.48 ± 0.01 ^b
	Day 14	44.7 ± 0.6 ^c	9.4 ± 0.1 ^b	2.52 ± 0.01 ^b
	Day 21	36.4 ± 0.5 ^d	9.6 ± 0.1 ^a	2.56 ± 0.01 ^a
Musambi	Day 0	51.2 ± 0.6 ^a	11.9 ± 0.1 ^c	4.07 ± 0.02 ^c

	Day 7	45.8 ± 0.6 ^b	12.1 ± 0.1 ^b	4.12 ± 0.02 ^b
	Day 14	38.2 ± 0.4 ^c	12.3 ± 0.1 ^b	4.16 ± 0.02 ^b
	Day 21	31.4 ± 0.6 ^d	12.5 ± 0.1 ^a	4.22 ± 0.02 ^a
Sweet Orange	Day 0	47.6 ± 0.6 ^a	12.6 ± 0.1 ^c	4.21 ± 0.02 ^c
	Day 7	41.8 ± 0.6 ^b	12.8 ± 0.1 ^b	4.26 ± 0.01 ^b
	Day 14	34.7 ± 0.5 ^c	13.0 ± 0.1 ^b	4.30 ± 0.02 ^b
	Day 21	27.9 ± 0.6^d	13.2 ± 0.1^a	4.35 ± 0.01^a

Coefficient of Variation (CV%): Ascorbic Acid: 6.8%, Total Soluble Solids: 4.2%, pH: 3.5%

Table 4. Effect of storage days on Ascorbic Acid (mg/100 g), TSS (°Brix), and pH of uncoated citrus fruits. Values are mean ± standard deviation (n = 3).

Variety	Storage Day	Ascorbic Acid (mg 100 g ⁻¹)	Total Soluble Solids (°Brix)	pH
Lemon	Day 0	58.7 ± 0.8 ^a	9.0 ± 0.1 ^c	2.43 ± 0.02 ^c
	Day 7	49.6 ± 0.7 ^b	9.4 ± 0.1 ^b	2.51 ± 0.02 ^b
	Day 14	40.8 ± 0.6 ^c	9.8 ± 0.1 ^a	2.59 ± 0.02 ^a
	Day 21	31.2 ± 0.6 ^d	10.1 ± 0.2 ^a	2.65 ± 0.02 ^a
Musambi	Day 0	51.0 ± 0.7 ^a	11.9 ± 0.1 ^c	4.07 ± 0.02 ^c
	Day 7	42.9 ± 0.6 ^b	12.4 ± 0.1 ^b	4.18 ± 0.02 ^b
	Day 14	34.1 ± 0.5 ^c	12.9 ± 0.1 ^a	4.27 ± 0.02 ^a
	Day 21	25.8 ± 0.6 ^d	13.3 ± 0.2 ^a	4.34 ± 0.02 ^a
Sweet Orange	Day 0	47.4 ± 0.6 ^a	12.6 ± 0.1 ^c	4.21 ± 0.02 ^c
	Day 7	38.9 ± 0.6 ^b	13.1 ± 0.1 ^b	4.32 ± 0.02 ^b
	Day 14	30.2 ± 0.5 ^c	13.6 ± 0.1 ^a	4.41 ± 0.02 ^a
	Day 21	22.1 ± 0.6^d	14.0 ± 0.2^a	4.48 ± 0.02^a

Coefficient of Variation (CV%) – Uncoated Fruits: Ascorbic Acid: 6.6% Total Soluble Solids: 5.4% pH: 4.3%

Discussion

Non-Destructive (Physical) Attributes

The assessment of non-destructive factors is of immense importance in understanding the postharvest quality and commercial potential of citrus fruits (Magwaza, 2013). During the current investigation, weight loss, firmness, and appearance were assessed to measure the potential of moringa oil coating in maintaining fruit quality (Kubheka et al., 2020). Weight loss during storage is largely attributed to transpiration, respiration, and evaporation of metabolic water (Lentzou et al., 2021). The data clearly indicated a gradual boost in weight reduction in all fruit samples throughout the 21-day storage time (Hayet, 2025). However, the weight decline in coated fruits was significantly less compared to uncoated fruits at all stages of storage (de Jesús Dávila-Aviña et al., 2011). This could be attributed to the semi-permeable film created by the moringa oil coating, which restricts the loss of water vapor and gas exchange (ASRAT and Abera, 2024). The coating influences the diffusion rates of water vapor and oxygen on the surface of the fruit, hence lowering the respiration rates and the water content inside the fruit (Banks et al., 1993). The results are aligned with recent research that showed plant oil coatings to be very effective in lowering water loss in citrus fruits and other fruits (Palou et al., 2015). It is also important that the effect of coating on all citrus fruits was not the same, and this can be attributed to the differences in the thickness of the skin, natural wax, and initial water content (Bisen et al., 2012). Fruits with thinner skin, such as Musambi, had a slightly higher weight loss

than lemons and sweet oranges, even when coated (Mahadeo, 2023). Firmness is an important quality attribute that affects consumer acceptability and marketability for citrus fruits (Tarancón et al., 2021). Over the storage time, there was a gradual decline in firmness in all fruits, but higher firmness values were noted in coated fruits as compared to uncoated ones (Gol et al., 2015). The higher firmness in coated fruits may be due to several factors, including lower degradation of cell walls, reduced functioning of softening enzymes such as polygalacturonase and pectin methyl esterase, and reduced water loss, which helps in maintaining cell turgor (Naveed et al., 2024).

The delay in firmness loss observed in this study is consistent with earlier studies where softening was delayed by edible coatings in citrus, apples, and pears, by maintaining the structural rigidity of fruit tissues (Sangamesh and Gangal, 2025). Notably, after the mid-storage period (Day 14 onwards), the loss of firmness was more pronounced in uncoated fruits, suggesting that in later stages of storage the coating has a significant role, when fruits become more vulnerable to senescence and softening (Mthembu et al., 2024). These findings suggest that moringa oil coating not only delays the initial degradation but also extends the period of marketable firmness, thereby improving the potential of postharvest handling (Carnauba wax-based edible coatings retain quality enhancement of orange fruit, 2024) (Jama et al., 2026). The incidence of decay is very critical in assessing the storage life of citrus fruits, as microbial decay has a direct effect on the economic value and safety of the

product for human consumption([Strano, 2024](#)). Observation indicated that by Day 21, there was a higher incidence of decay in the uncoated citrus fruits, as indicated by the usual signs of decay such as mold growth, soft rot, and shrinkage([El-Mougy et al., 2012](#)). However, the coated citrus fruits had very low decay incidence and seemed fresh and shiny([Wijewardane, 2022](#)). The low decay incidence can be due to the antimicrobial features of moringa oil, which contains bioactive compounds like phenolics, flavonoids, and tocopherols, all of which have been proven to inhibit microbial growth([Villegas-Vazquez et al., 2025](#)). In addition, the physical barrier created by oil coating on the fruit surface reduces oxygen transfer, making it difficult for fungal growth on the surface([Xing et al., 2016](#)). The decay incidence is dependent on the natural resistance of citrus fruits to microbial infections as well as the type of their natural peels([Pangallo et al., 2021](#)). Lemon, with its thicker and more acidic peel, had a slightly lower decay incidence compared to Musambi, which is consistent with previous studies that showed higher peels to be more resistant to postharvest pathogens([Ngoko Tchamba et al., 2024](#)). Taken together, these results clearly indicate that moringa oil coating is an effective method for sustaining integrity and increasing the shelf life in citrus fruits([Faduyibi et al., 2025](#)).

Destructive (Chemical) Attributes:

Destructive quality analysis is a more in-depth approach for learning about the underlying biochemical reactions that occur in fruits during storage([Prasad, 2015](#)). The impact of moringa oil on the metabolic stability and nutritional value of citrus fruits was assessed by measuring the parameters of pH, total soluble solids (TSS), and ascorbic acid (Vitamin C)([Masoom et al., 2024](#)). The pH value of all citrus fruits increased slowly in storage, which is due to the consumption of organic acids in respiration and metabolic processes([Hussain et al., 2017](#)). A slower increase in pH values was observed in coated citrus fruits with respect to the uncoated citrus fruits, which indicates better preservation of acidity([Kumar et al., 2024](#)). The acidic environment is critical for maintaining flavor, microbial resistance, and overall quality of the fruits([Kader, 2008](#)). The slower rise in pH in coated fruits may be due to reduced oxygen diffusion and lower respiratory activity because of the semi-permeable oil barrier([Kumar and Sethi, 2018](#)). This may result in decreased acid catabolism and delayed senescence, which is in agreement with other edible coating applications in citrus fruits, such as chitosan and essential oil coatings([Chen et al., 2021](#)). TSS values steadily increased in all fruits during storage, and this is mainly attributed to the loss of water and the conversion of polysaccharides into soluble sugars([Islam et al., 2013](#)). The uncoated fruits showed a faster increase in TSS, which may lead to over-concentration of sugars, loss of juiciness, and even texture breakdown([Islam et al., 2026](#)). However,

the coated fruits showed a slower rise in TSS values, indicating a slower rate of metabolism and water loss([Huang et al., 2021](#)). This is especially important for maintaining fruit quality and marketable sweetness, as very high TSS values may be undesirable([Abrol and Joshi, 2011](#)). Similar trends were observed in citrus fruits coated with edible coatings containing antioxidants or plant oils, which act like slow sugar-accumulators and prevent rapid over-ripening([Wang et al., 2025](#)).

Vitamin C is highly prone to oxidative breakdown and is an important indicator of quality in citrus fruits([Magwaza et al., 2017](#)). In all fruit samples, the decrease in ascorbic acid concentration during storage is consistent with the expected senescence([Su et al., 2019](#)). However, moringa oil-coated fruits showed significantly higher ascorbic acid concentration than uncoated fruits, particularly from Day 14 onwards([Al-Rashdi et al., 2024](#)). The lower degradation in coated fruits can be due to the following factors:

Oxygen barrier property: The oil acts as a barrier against oxygen.

1. Antioxidant properties of moringa oil:

Bioactive compounds like phenolics, flavonoids, and tocopherols work together to inhibit ascorbic acid oxidation.

2. Lower metabolic rate: The semi-permeable coating slows metabolism and subsequent enzymatic oxidation.

These results not only emphasize the importance of maintaining quality but also underscore the preservation of nutritional value in moringa oil coating, thereby validating its use as a natural preservative([Shivanna et al., 2024](#)).

Varietal Differences

On all chemical parameters, there were differences between the citrus varieties. Lemon showed better retention of acidity and vitamin C, which might be attributed to its natural acidity and thickness of the skin([Di Matteo et al., 2021](#)). Musambi had relatively higher TSS and a faster pH increase, which indicates faster metabolism. Sweet orange showed intermediate values([Nadia, 1998](#)). The results therefore stress the need for variety-specific postharvest management, as retention of edible coatings depends on natural fruit properties such as skin thickness, acidity, and natural resistance against senescence([Malik et al., 2017](#)).

Conclusion

Present research found that moringa oil coating is an excellent technique for protecting postharvest quality and storage life of three citrus varieties: lemon, Musambi, and sweet orange. Outcomes showed that coated fruits had reduced weight loss, firmness, appearance, and decay incidence compared to uncoated fruits, implying that moringa oil's semi-permeable barrier prevented moisture loss, respiration, and microbial development. Chemical examination revealed that the coated fruits had a lower pH value, a slower rate of rise in total soluble solids, and a higher ascorbic acid concentration,

indicating that biological reactions were delayed. Varietal differences showed that fruit characteristics can affect the effectiveness of the coating, with lemons being the best source of acidity and vitamin C content. Moringa oil coating is a natural, safe, and environmentally friendly post-harvesting technique for citrus fruits that can reduce spoilage, maintain nutritional value, and potentially be commercialized. Future studies can investigate combination coatings, longer shelf life, and commercialization of citrus fruits.

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Statements and Declarations

Author Contributions

AS, ZH, AS and MS contributed to the conception, development, and preparation of this research article. MH, JA, SHUHS and AA edited final version of article. All authors have read and approved the final version of the manuscript.

Funding

This review was conducted without external funding. The authors would like to clarify that no financial support or grants from any organization, institution, or individual were received for the completion of this review. The research was carried out as part of the authors' academic and professional responsibilities, and they did not rely on any external sources of funding for the design, execution, or publication of this work.

Acknowledgments

We would like to acknowledge that no individuals or organizations were involved in the development, funding, or support of this work. This research was solely conducted by the authors, and no external contributions, financial or otherwise, were received or utilized in the execution of this study.

Data Availability statement

All relevant data are within the manuscript file.

Acknowledgments

Not applicable

Ethical Statement

Not applicable

Conflict of interest

The investigation was undertaken without any financial conflicts of interest or any other commercial relationships that could be seen as such by any of the authors.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work, the author(s) have not used any ChatGPT (OpenAI) tool.



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