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Research Article

Synergistic Effect of Macadamia Nut Oil and Chitosan Coatings on Physicochemical Characteristics of Tomatoes During Storage

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A significant portion of globally produced fruits are lost between the farmer and consumer, necessitating solutions like natural edible coatings for preservation due to their low cost and less toxicity. This study aimed to assess whether the combination of macadamia nut oil and chitosan posed synergistic effects on physicochemical properties of tomato fruits or the macadamia nut oil alone. A completely randomized design (CRD) with eight treatments was employed: S1 (control), S2–S4 (combined macadamia nut oil and chitosan coating), S5–S7 (macadamia nut oil coating), and S8 (chitosan). The experimental setup was conducted over 20 days at refrigeration (4°C) and postharvest shed conditions (23.8°C–30°C, 65.8%–97.5% RH). The coating solution made up of a combination of 2.5% v/v macadamia nut oil and 1% w/v chitosan showed significant differences ($p \leq 0.05$) in slowing down the changes in pH from 3.95 to 4.3, total chlorophyll content from 0.19 mg/100 to 0.12 mg/100 mL, and lipid peroxidation from 13.5 to 19.71 meq/kg. Moreover, coating solutions made by macadamia nut oil alone, especially with 1% v/v, showed the smallest increases in total soluble solids (TSS) and total sugar content, and also they exhibited the smallest decreases in titratable acidity (0.64 to 0.08 g/L), ripening index (5.78 to 84.74), total carotenoids (17.02 to 24.585 μg/g), and firmness (355 N to 130 N). Comparative analysis indicated that 1% v/v macadamia nut oil had higher mean differences ($p < 0.05$) for most physicochemical parameters than coating solutions comprising 2.5% v/v macadamia nut oil and 1% w/v chitosan. However, this finding highlighted that the combination of macadamia nut oil with chitosan offers a synergistic effect on specific crucial parameters (pH, total chlorophyll content, and lipid peroxidation) compared to macadamia nut oil alone. Further studies could investigate the antimicrobial effect of tomatoes treated with a combination of macadamia nut oil and chitosan.

Keywords: edible coatings; firmness; physicochemical; postharvest shed; refrigeration

1. Introduction

Climacteric fruits, such as apples (*Malus domesticus*), bananas (*Musa* spp.), and tomatoes (*Solanum lycopersicum*), undergo a significant increase in respiration and ethylene production as they ripen, which makes them particularly susceptible to postharvest losses [1]. Effective postharvest management and loss mitigation strategies are crucial for extending their shelf life and preserving quality. Techniques like controlled atmosphere storage, refrigeration, and the application of ethylene inhibitors can significantly reduce these losses [2]. By implementing these strategies, the agricultural sector can enhance the availability of fresh produce, reduce food waste, and improve economic outcomes for growers and retailers alike. Recent data indicate that approximately 20%–40% of tomatoes (*S. lycopersicum*) experience postharvest losses in Tanzania [3, 4]. Significant postharvest losses in tomatoes result from quality deterioration driven by moisture loss, microbial spoilage, respiration, and enzymatic activity [4].

Consequently, there has been a recently growing demand for alternative preservation methods that are environmentally friendly, economically viable, and socially acceptable for managing tomato value chains. Several studies have shown the use of natural products, such as the application of 1% w/v chitosan (ch) and 1% v/v *Aloe vera* gel that extended the shelf life of tomato fruits up to 42 days at room temperature [5]; *Citrus sinensis* essential oil that delayed the growth of fungi and extended the shelf life up to 8 days of storage [6]; the application of Neem extract (*Azadirachta indica*) on tomato fruits, which maintained the physicochemical parameters up to 20 days [7]; and *Opuntia oligocantha* and grape extracts (*Vitis vinifera*) [8], which efficiently extended the shelf life and maintained the quality of tomatoes. The performance of the extracts is highly associated with the presence of phytochemicals such as tannins, saponins, flavonoids, tocopherol, and phenolic compounds [9]. Phytochemicals have been shown to play a significant role in preserving the firmness and physicochemical properties of tomato fruits through various biochemical mechanisms. These mechanisms include the inhibition of cell wall-degrading enzymes such as polygalacturonase and pectin methylesterase, which are responsible for the softening of fruit tissue [10]. By limiting the activity of these enzymes, phytochemicals such as beeswax and salicylic acid maintain the structural integrity of the cell walls, thereby preserving fruit firmness [11]. Additionally, phytochemicals such as rosemary extract (*Rosmarinus officinalis* L.) contain compounds like rosmarinic acid and carnosic acid, known for their antimicrobial and antioxidant effects [12]. Neem extract, abundant in azadirachtin and other triterpenoids, provides antimicrobial properties that protect against spoilage [13]. *Aloe vera* extract contains a rich mix of polysaccharides, phenolic compounds, and other bioactive substances, which has been found to effectively reduce the rate of respiration and ethylene production in tomatoes [14].

ch, a natural polysaccharide derived from chitin, has gained significant attention in postharvest preservation due to its unique properties. Its antimicrobial activity arises from the interaction between its positively charged amino groups (NH_4^+) and the negatively charged carboxylate groups (COO^-) on bacterial cell membranes. This electrostatic attraction disrupts the membrane and inhibits microbial growth. [15]. ch is a cost-effective and sustainable material. Its widespread availability and low production costs further enhance its economic viability for large-scale agricultural applications. Additionally, ch forms a semipermeable film on the fruit surface, which reduces respiration rates, moisture loss, and oxidative stress, thereby extending shelf life. Its compatibility with other natural compounds, such as *Aloe vera* and citric acid, has been demonstrated in various studies, showing enhanced preservation efficacy when used in composite coatings. For instance, a combination of ch and *Aloe vera* in a ratio of 1: 10 has been effective in delaying the decay rate and maintaining the physicochemical parameters of mangoes (*Mangifera indica*) for up to 28 days [16]. Similarly, a formulation containing 30% *Aloe vera* and 1.5% ch has been shown to preserve antioxidant enzymes in peaches (*Prunus persica* L.) for 36 days [17]. Additionally, the incorporation of 1% CMC into 30% *Aloe vera* gel has been found to extend properties such as weight retention and color preservation in cucumbers (*Cucumis sativus*) for up to 20 days [18]. These findings highlight the versatility and potential for synergistic applications of these natural compounds in postharvest preservation.

Macadamia nut oil (mo), derived from *Macadamia integrifolia*, is another promising natural preservative. mo, though relatively more expensive, is increasingly accessible due to the growing cultivation of macadamia nuts in Tanzanian regions. The oil's extraction process can be integrated into existing agricultural value chains, providing an additional revenue stream for farmers while reducing postharvest losses. It is rich in bioactive compounds such as fatty acids, tocopherols, squalene, flavonoids, and phenolic compounds; it offers both antimicrobial and antioxidant properties [19]. These compounds help scavenge free radicals, inhibit lipid peroxidation, and prevent microbial spoilage, thereby maintaining the physicochemical properties of fruits. Studies have shown that a 1% v/v concentration of mo effectively preserves the antioxidant activity, weight, color, and phenolic content of tomatoes [13]. Its hydrophobic nature also provides a barrier against moisture loss, which is critical for maintaining fruit firmness and quality during storage.

The independent roles of ch and mo in postharvest preservation highlight their complementary mechanisms. ch provides structural integrity and antimicrobial protection [20], while mo offers antioxidant activity and a moisture barrier [21]. Their combined use could potentially create a synergistic effect, enhancing the preservation of fruits by addressing multiple causes of postharvest deterioration simultaneously. This synergy could be particularly beneficial for tomatoes, which are highly susceptible to moisture loss, microbial spoilage, and oxidative stress during storage.

Further investigation of synergistic effects of other edible coatings is of paramount importance. However, to our knowledge, there is no literature reporting the synergistic effect of ch when incorporated with mo on physicochemical properties of tomatoes. The purpose of the present study was to evaluate the effect of ch coating combined with mo on physicochemical properties of tomatoes during refrigeration and postharvest shed storage.

The simplicity of dipping application methods used in this study supports scalability, making it accessible to both smallholder farmers and large-scale producers. This approach aligns with global trends toward sustainable agriculture by reducing reliance on synthetic chemicals and minimizing postharvest losses, thereby improving economic outcomes for farmers, enhancing food security, and ensuring a consistent supply of high-quality produce to consumers. Additionally, the use of locally available materials like mo promotes circular economies and fosters local industries. The findings are expected to provide sustainable solutions for postharvest preservation, mitigate climate change impacts caused by postharvest losses, and advance environmentally friendly agricultural practices.

2. Materials and Methods

2.1. Collection of Macadamia Nuts and Oil Extraction. The macadamia nuts were collected at the horticultural unit of Sokoine University of Agriculture, Tanzania (37° 39′47″ E, 6° 50′48″ S). The extraction of oil from macadamia nuts using petroleum ether (Sigma-Aldrich, United States) at 80°C was performed with the Soxhlet extraction method [22]. Briefly, macadamia nuts were finely ground using a blender (Mister Chef 2200W, Amazon) so as to increase the surface area for oil extraction. The macadamia nut powder was placed in a thimble, which was then inserted into the main chamber of the Soxhlet extractor. The petroleum ether was heated to ensure the solvent's vaporization following condensation. This process was repeated for 9 h to ensure exhaustive extraction of the oil from the macadamia nuts. After the extraction process, the petroleum ether–oil mixture was separated by evaporating the solvent using a rotary evaporator (BUCHI Rotavapor R-205, Marshall Scientific, USA), leaving behind the pure mo. The yield of the oil was then stored under refrigeration temperature (4°C) for further study.

2.2. Preparation of Coating Solution. The mo and ch used to prepare the coating solutions were obtained from specific suppliers to ensure quality and consistency. ch was commercial and purchased from Yixing Clean Water Chemicals Co., Ltd., China, while glacial acetic acid for dissolving the ch was sourced from Merck India Ltd. Three primary concentrations of mo, which was extracted from locally sourced macadamia nuts, were prepared at 1% v/v, 2% v/v, and 2.5% v/v. The chosen mo gradient was based on preliminary trials identifying the optimal balance between barrier efficacy and fruit biocompatibility. This range maximizes oil's protective properties while avoiding the negative effects of higher concentrations (>~2.5%), which disrupt film formation, reduce adhesion, and risk impeding fruit respiration. For the ch solution, a 1% w/v concentration was achieved by dissolving 1 g of ch in 100 mL of distilled water and adjusting the pH to around 5.0 using 1% v/v acetic acid, which enhanced its solubility as reported in other studies [23, 24]. Each concentration of mo was then mixed with the 1% w/v ch solution to create a series of coating formulations in a total volume of 100 mL. These formulations included combinations of mo (denoted "mo") and ch (denoted "ch") in varying proportions: "1% v/v mo + 1% w/v ch," "2% v/v mo + 1% w/v ch," and "2.5% v/v mo + 1% w/v ch," alongside controls of each mo concentration without ch. Furthermore, this study also included a coating formulation with 1% w/v ch.

To improve coating properties, each formulation was supplemented with 2 mL of 2% v/v glycerol (CAS 56-81-5, 137028, Merck, Germany) as a plasticizer, enhancing the coating's flexibility. An antioxidant component, ascorbic acid (2% w/v from Foodchem, China), was incorporated to prevent oxidation of mo during storage and application. Furthermore, 3% w/v carboxymethyl cellulose (CHEBI: 85146, Sigma-Aldrich, USA) was used as a thickening agent, dissolved in water, and added to the oil-ch blend to ensure improved viscosity and ease of application. Calcium chloride (≥ 97% anhydrous powder from Sigma-Aldrich, USA) was added at a 1% w/v concentration to stabilize the formulation and prevent ch precipitation. The final mixture was thoroughly blended with a probe-type ultrasonicator (50–400 W, Hielscher, Germany) until a uniform emulsion formed, ensuring stability. The prepared coatings were pasteurized at 75°C for 15 min using a water bath (Model WB-15, INDIAMART, India), cooled, labeled, and stored in airtight containers for subsequent testing. This meticulous preparation ensured that the coating formulations were suitable for further experiments.

2.3. Coatings of Fresh Tomatoes. A total of 240 uniform tomato fruits (Assila F1 variety) were selected from a harvest at Mazimbu farm in Morogoro Municipal, Tanzania, based on physiological maturity, color, and the absence of blemishes or fungal infections. After washing the fruits with distilled water and allowing them to drain for 30 min, the tomatoes were divided into experimental groups. For each storage condition, the 120 tomatoes were allocated into eight treatment groups: uncoated control, 1% ch only, and the six macadamia oil-ch combinations and oil-only controls described in Section 2.2. Each group for both storage conditions consisted of 15 tomato fruits, which were dipped in the edible coating solution for 15 min, ensuring even coating. Excess coating solution was drained off before storage.

Two storage conditions were used for postharvest quality monitoring: refrigeration at 4°C, 97% RH (relative humidity) and ambient postharvest shed conditions (23.8°C–30°C ± 1°C, 65.8%–97.5% ± 1% RH), with physicochemical quality assessments such as pH, total soluble solids (TSS), titratable acidity (TA), ripening index (TSS/TA), total sugar content, lipid peroxidation, total chlorophyll, and carotenoid content that were conducted at 5-day intervals over 20 days so as to evaluate the significant changes in physicochemical qualities that occurred over time [25, 26]. The experimental setup included three independent replicates per treatment. For each replicate of a given treatment, the group of 15 fruits was subdivided into five subgroups of 3 fruits, each assigned to one of the five destructive sampling time points (Days 0, 5, 10, 15, and 20). This resulted in three data points ($n = 3$) for each treatment at each time point. The experimental setup included both coated and uncoated tomatoes, with three replicates for each treatment to strengthen the study's statistical power and validity.

2.4. Analysis of Physicochemical Quality Parameters of Treated Tomato Fruits

2.4.1. TSS, pH, and TA. The pH value was measured according to the method described in the literature [27] using a digital pH meter (Jenway Model 3305, UniGreenScheme, UK). The pH was firstly calibrated using standard buffer solutions of pH 7.0. The TSS content of treated tomato fruits was measured using a portable digital refractometer (PAL-1, ATAGO Co. Ltd., Japan) at 20°C and expressed as °Brix. The refractometer was standardized using distilled water (0°Brix) before measuring the °Brix of the samples. The TSS to TA ratio (TSS/TA) was also calculated to determine the balance between sweetness and acidity, which is a key factor in the sensory quality of the tomato fruits. TA was measured by the titration method according to the procedure described in the literature [28]; the result was expressed as grams of citric acid per 100 g of fresh tomato weight. The calculation of TA was based on the the following formula:

$$\text{titratable acidity}\,(\%\,\text{TA}) = \frac{N \times (Vt - Vb) xVT \times Eqv.wt X100}{W \times 1000}, \quad (1)$$

whereby *Eqv. wt* = equivalent weight and N = Concentration in Normality of NaOH. Vt = Volume of NaOH used for sample titration. Vb = Volume of NaOH used for blank titration. VT = total volume of sample solution made. W = weight or volume of analytical sample. 100 = conversion factor per 100 g (%). 1000 = conversion factor from mg/L to g/100 mg.

2.4.2. Total Chlorophyll and Carotenoid Contents. The total chlorophyll and carotenoid content was determined by a spectrophotometric method as described by other scholars [29]. Briefly, three tomato fruits from each treatment were ground separately using a blender (Mister Chef/2200W, Amazon) to obtain tomato slurry. Two grams of tomato slurry from each treatment was homogenized with 25 mL of an acetone–hexane mixture (2:3) using a homogenizer (UIP1000hdT, Hielscher, Germany) for 2 min. Then the mixture was centrifuged (Thermo Fisher Scientific Inc., USA) at 25°C with a revolution of 1000 rpm for 10 min, and then the absorbance spectrum of each supernatant was measured using a UV–Vis spectrophotometer (Double beam model, X-ma3000 spectrophotometer, Human Corporation, England) at 663 nm, 645 nm, and 470 nm for chlorophyll a, b, and carotenoid, respectively. Equations (4) and (5) were used to quantify total chlorophyll and carotenoid content.

$$\text{chlorophyll}\,''a''\left(\frac{\text{mg}}{\text{g}}\right) = \frac{12.7\,(OD_{663}) - 2.69\,(OD_{645})}{\text{weight of the sample}}, \quad (2)$$

$$\text{chlorophyll}\,''b''\left(\frac{\text{mg}}{\text{g}}\right) = \frac{22.9\,(OD_{645}) - 2.69\,(OD_{663})}{\text{weight of the sample}}, \quad (3)$$

$$\text{total chlorophyll}\,(a + b) = \frac{20.2\,(OD_{645}) + 8.02\,(OD_{663})}{\text{weight of sample}}, \quad (4)$$

$$\text{carotenoids}\left(\frac{\text{mg}}{\text{g}}\right) = \frac{1000\,(OD_{470}) - 3.27\,(\text{chlorophyll}\,A) - 104\,(\text{chlorophyll}\,B)}{227}, \quad (5)$$

where OD = optical density (actual absorbance).

2.4.3. Lipid Peroxidation. Lipid peroxidation was measured by iodometric titration as described in previous studies [30]. Briefly, a 1 g sample was weighed into a 100 mL Erlenmeyer flask and dissolved in the solvent mixture (30 mL) made by (3:2) glacial acetic acid (CAS Number: 64-19-7, Merck Millipore, US) and chloroform (Emerald Scientific, California). Then, 0.5 mL of a potassium iodide solution was added, and the mixture was stirred for 60 s. Subsequently, 30 mL of distilled water was added and titrated with 0.01 N sodium thiosulfate by using the starch indicator to an equivalent point as per the chemistry M11 laboratory manual.

2.4.4. Total Sugar Content. The quantification of sugar content was conducted using a modified spectrophotometric method as modified in a previous study [31]. Briefly, 0.25 g of tomato slurry was added to distilled water to make a total volume of 100, and a 2 mL portion of the solution was diluted to 100 mL and then filtered through filter paper (Whatman No. 1). A 1 mL portion of the diluted solution was mixed with 1 mL of 5% v/v phenol and 1.0 mL of distilled water for 1 min to allow reactions to take place. Subsequently, 5.0 mL of concentrated H_2SO_4 was added and shaken for 3 min. After the mixture settled down for 30 min, the resulting solution was allowed to cool for 20 min, and the absorbance was measured using a UV–Vis spectrophotometer at 490 nm. The blank sample was prepared using the same procedure, then analyzed to trace the source of introduced contamination.

2.4.5. Measurement of the Firmness of Fresh Tomato Fruits. The firmness (N) of fresh tomato fruits was determined by the texture profile analysis method with a texture analyzer (Model CT3 10K, Brookfield Engineering Laboratories, USA). The analysis was conducted using a two-bite compression test, employing a cylinder probe with a 2 g trigger force. The test involved a 10 mm deformation and was performed at a speed of 10 mm/s. The results of the test were displayed and recorded for further analysis.

2.5. Statistical Analysis. The randomized design with two factorials was conducted in this study, and the variables used were coating solutions and storage time as independent variables, while the dependent variables were lipid peroxidation, pH, TA, TSS, TSS/TA, total sugar content, total chlorophyll and carotenoids content, and texture. The data obtained were tested for normality and homogeneity using the Kolmogorov–Smirnov test and the Shapiro test to determine the parametric and nonparametric tests. From this study, all data were found to be normally distributed (KS value > 0.05). Due to the presence of two categorical independent variables, data were subjected to two-way analysis of variance (ANOVA) on SPSS Version 25 at ($p \leq 0.05$). From these findings, all parameters showed significant differences; therefore, post hoc analysis using the least significant difference (LSD) was employed to determine which formulation(s) were significantly different from each other.

3. Results and Discussion

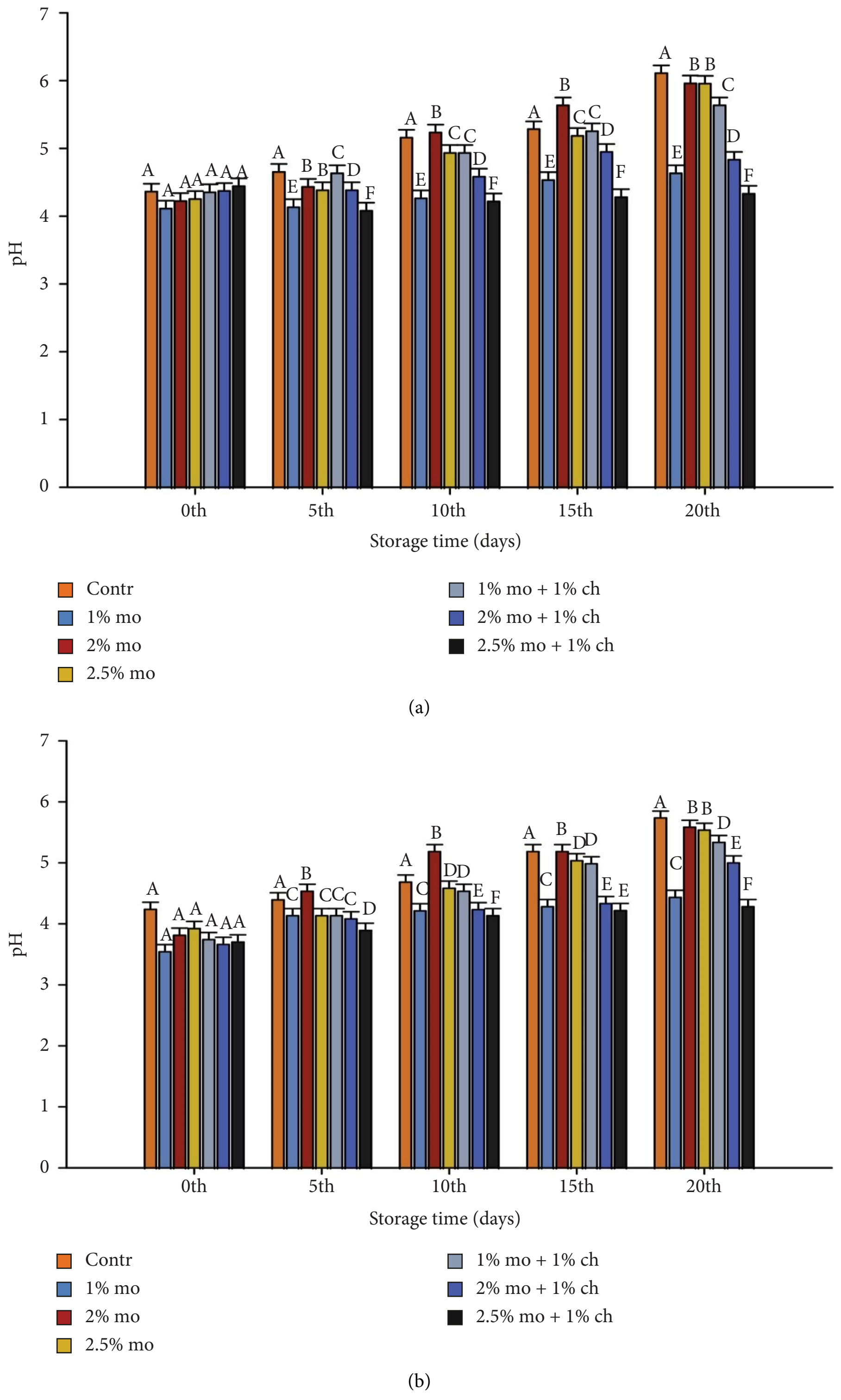
3.1. pH. The results of pH changes of tomatoes that were monitored over 20 days were depicted in Figures 1(a) and 1(b). The different concentrations of coating solutions showed that significantly ($p < 0.05$) influenced the pH of tomato fruits. The formulations consisting of the combination of mo and ch with 2.5% v/v mo and 1% w/v ch had significant lowest changes in pH of tomatoes ($p < 0.05$) compared to all other treatments for both storage conditions throughout the entire 20 days. In the postharvest shed, the pH of tomatoes started at 4.1 on the 5th day and gradually increased to 4.35 on the 20th day. In the refrigeration condition, the pH of tomato fruits was 3.95 on the 5th day and increased slightly to 4.3 on the 20th day. In contrast, the formulations with only mo 1% v/v also showed the smallest increases in pH of tomato fruits under both conditions. The treatment showed the higher pH changes of tomato fruits along 20 days in both conditions. The pH of tomato fruits stored under a postharvest shed also changed from 4.15 on the 5th day to 4.65 on the 20th day, while for tomatoes stored under refrigeration, their pH also changed from 4.15 on the 5th day to 4.45 on the 20th day. Thus, this showed the synergistic effects of treatment made by 2.5% v/v mo and 1% v/v ch over the coating solution made by only mo.

Generally, the acidic nature of fruits is determined by free hydrogen ions that can be associated with respiration [32]. The higher pH value of tomatoes implies higher ripening, and such fruits are likely to be vulnerable to pathogens due to decreases in the acid medium. The finding from this study implies the effectiveness of ch as a preservative, and this could be due to buffering capacity enhanced by ch in lowering the pH [33]. The change in the acid is likely to be associated with the formation of a protective organic layer that reduces the respiration rate and degradation of organic acids in the tomatoes [34]. Similar findings were previously reported whereby essential oils from sweet basil (*Ocimum basilicum*) maintained the pH of tomatoes [35]. Thus, the presence of fatty acids such as oleic oil in mo and film formed by ch could form a barrier for gas exchanges into the inner atmosphere of the tomato fruit. Moreover, *Aloe vera* coatings have been shown to reduce pH changes and extend shelf life by forming a semipermeable barrier that limits gas exchange, similar to the effects observed with ch and mo. This could be due to the presence of ch’s positively charged amino groups that interact with negatively charged microbial cell membranes, disrupting their integrity. By reducing microbial activity, ch minimizes the breakdown of organic acids and other compounds that contribute to pH changes. Wax-based coatings, on the other hand, often provide a more rigid barrier but may lack the antimicrobial and antioxidant properties of ch and mo.

3.2. TA. The changes in TA of tomato samples stored under refrigeration and shed conditions over a 20-day period are shown in Figures 2(a) and 2(b). The formulations used in this study exhibited a significant effect on TA changes ($p < 0.05$) in tomato fruits. Under both storage conditions, the coating solution containing mo with 1% v/v resulted in the highest TA levels of the tomato fruits ($p < 0.001$) throughout the 20-day storage period. For tomatoes stored under postharvest shed conditions, the TA ranged from 0.64 g/L on Day 5 to 0.13 g/L on Day 20, while under refrigeration, the TA ranged from 0.52 g/L on Day 5 to 0.08 g/L on Day 20. In contrast, tomatoes coated with 2.5% v/v mo and 1% w/v ch exhibited lower TA levels. For postharvest shed storage, the TA ranged from 0.455 g/L on Day 5 to 0.05 g/L on Day 20, while under refrigeration, the TA decreased from 0.51 g/L on Day 5 to 0.03 g/L on Day 20. This indicates that ch formulations, whether alone or combined with mo, resulted in a greater decrease in TA compared to mo alone, suggesting that mo is more effective in maintaining the TA of tomatoes.

The mo comprises the oleic acid, which inhibits the activity of ethylene gas, thereby slowing down the ripening of tomatoes. Higher TA observed in this study implies less degradation of organic acid (substrate of respiration) and a lower pH that provides the acidic medium for the defense mechanism of fruit against microbial attack [36]. On the contrary, the lowest TA implies the high respiration rate and ripening, and such fruit is prone to deterioration due to vulnerability from microbes [37].

Moreover, the plant extracts like banana peel and neem that were used as fruit preservatives contain phenolic compounds with hydroxyl groups (–OH) that play a key role in preserving TA [38]. These –OH groups act as antioxidants by donating hydrogen atoms (H^+) to neutralize free radicals, thereby reducing oxidative stress and preventing the degradation of organic acids. Additionally, the –OH groups can inhibit enzymes like polyphenol oxidase (PPO) and peroxidase (POD), which are involved in the breakdown of organic acids [39]. While this established mechanism is supported by our results, our findings specifically advance the understanding of mo as a novel edible coating component. By binding to these enzymes, plant extracts slow down the degradation process, helping to maintain the fruit’s acidity. Furthermore, the –OH groups contribute to the buffering capacity of the coating, stabilizing the pH and creating an environment that favors the preservation of organic acids. The observed results match those observed in our study since mo contains oleic acid and other fatty acids with –OH groups, which provide antioxidant activity and form a hydrophobic barrier on the fruit surface. This barrier could reduce the oxygen penetration, slowing down the oxidative degradation of organic



(a)

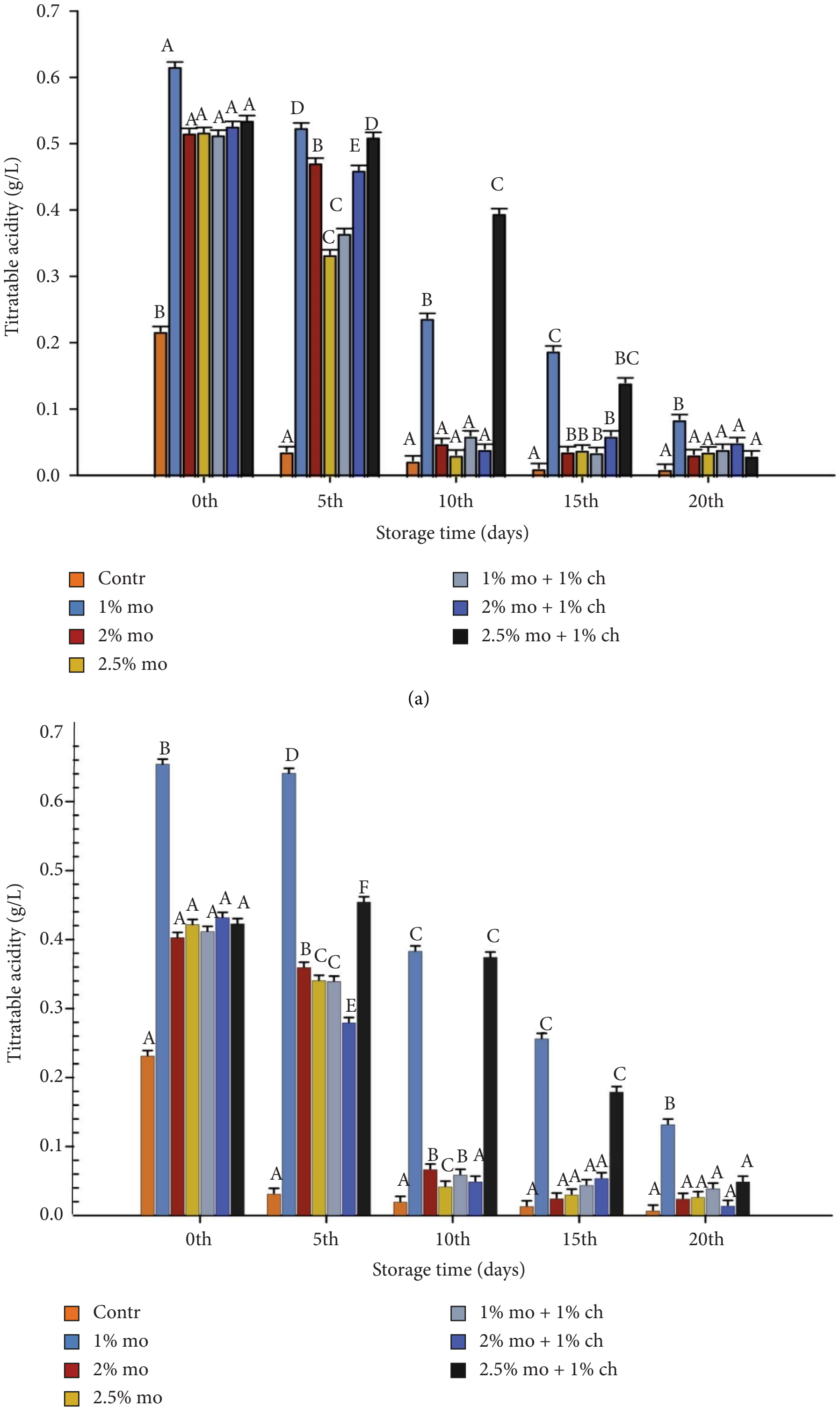
(b)

Figure 1: (a, b): Effect of macadamia nut oil (mo) and chitosan (ch) formulations on pH value of tomatoes along 20 days stored at (a) postharvest shed and (b) refrigeration. Vertical bars show ± percentage error of means for three replicates. Different letters on the same storage day imply significant differences ($p < 0.05$) among formulations.

acids. ch, on the other hand, contains amino groups ($-NH_2$) that protonate to $-NH_3^+$ in acidic environments, offering buffering capacity to stabilize pH. It also forms a semipermeable film that limits gas exchange (O_2 and CO_2), reducing respiration rates and the breakdown of organic acids.

3.3. *TSS.*

The changes in TSS of tomato samples stored under refrigeration and shed conditions over 20 days were depicted in Figures 3(a) and 3(b). The findings showed that the 1% v/v mo treatment led to a significantly minimum TSS value ($p < 0.05$) of tomato fruits along storage days in both storage conditions.

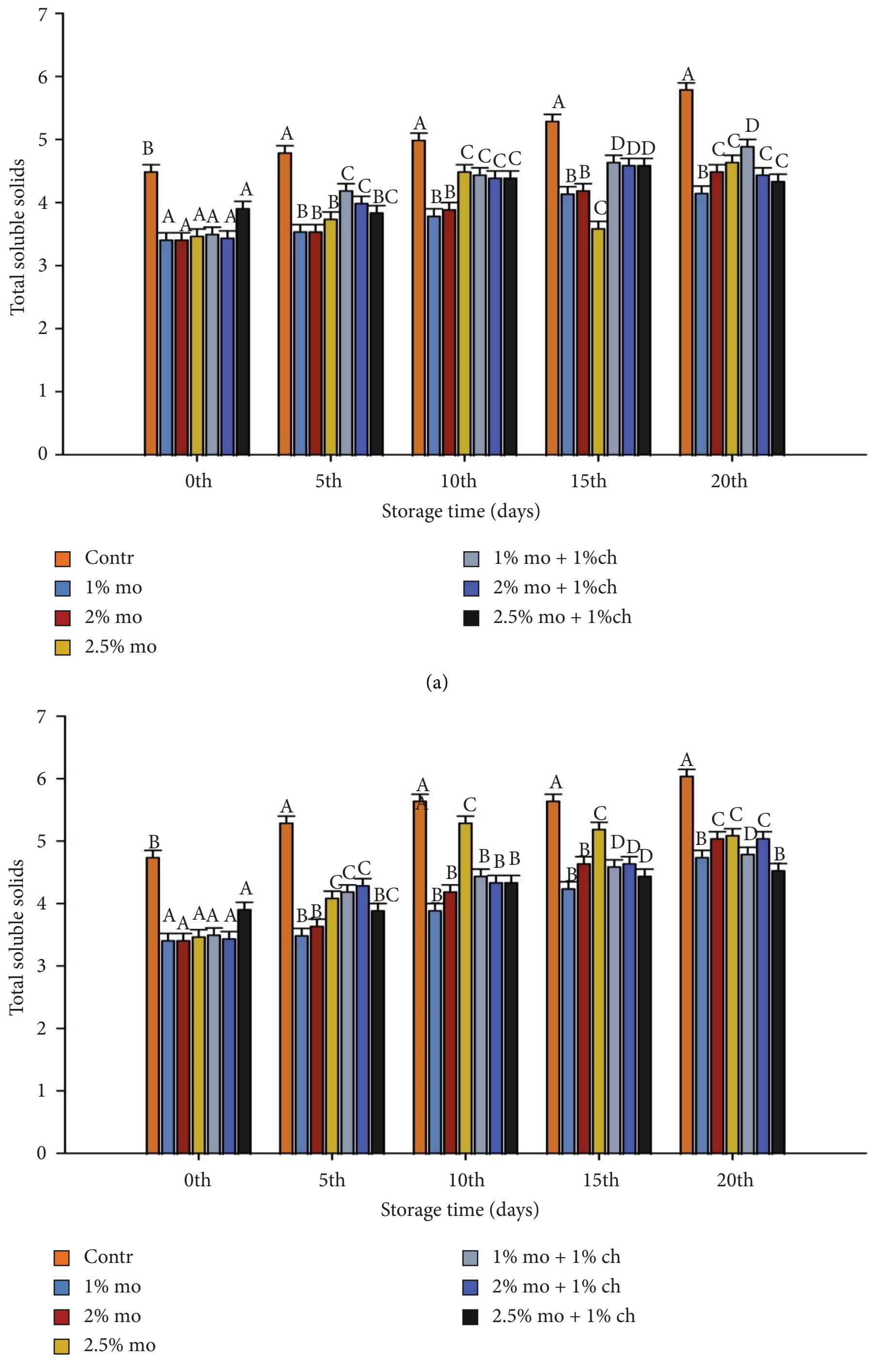


(a)

(b)

Figure 2: (a, b): Effect of macadamia nut oil (mo) and chitosan (ch) formulations on titratable acidity value of tomatoes along 20 days stored at (a) postharvest shed and (b) refrigeration. Vertical bars show ± percentage error of means for three replicates. Different letters on the same storage day imply significant differences ($p < 0.05$) between formulations.

The sample of tomatoes treated with 1% v/vmo exhibited the lowest TSS, ranging from 3.55 °Brix on the 5th day to 4.16 °Brix on the 20th day under the shed condition, while under the refrigeration condition, the TSS varied from 3.5 °Brix on the 5th day to 4.75 °Brix on the 20th day. The tomatoes treated with combined formulations of mo and ch showed higher TSS



(a)

(b)

Figure 3: (a, b): Effect of macadamia nut oil (mo) and chitosan (ch) formulations on TSS value of tomatoes along 20 days stored at (a) postharvest shed and (b) refrigeration. Vertical bars show ± percentage error of means for three replicates. Different letters on the same storage day imply significant differences ($p < 0.05$) among formulations.

value∗s∗ throughout the storage days. This indicates that 1% v/v mo alone was more effective in maintaining lower TSS levels compared to formulations containing 1% ch or the combination of mo and ch.

This result aligns with the findings from previous studies concerning apricot jam (*Prunus armeniaca*) [40] that showed an increase in TSS along the storage time. Another study supports this, as TSS increased along the storage time, and application of ch diminished the elevation of TSS and maintained it for up to 30 days [41]. These recent findings reveal the superior efficacy of mo alone. The preservation observed was possibly attributed to the presence of tocopherol in the oil, which inhibits metabolic reactions within the tomato fruits. Consequently, the inhibition minimizes the conversion of polymeric compounds like polysaccharides into simpler sugar forms. Soluble solids in fruits primarily encompass sugars and a minor proportion of amino acids, organic acids, vitamins, and minerals [42]. mo is rich in fatty acids like oleic and palmitoleic acid, which confer antioxidant properties that reduce oxidative stress and slow the breakdown of sugars and organic acids [43]. Furthermore, these compounds form a semipermeable barrier on the fruit surface, limiting oxygen availability and reducing respiration rates. Therefore, this study advances the application of edible coatings by identifying a novel, lipid-based coating that outperforms a common biopolymer (ch) in maintaining TSS stability. This suggests a dual mechanism of action, both biochemical and physical barrier, by providing a more effective method for delaying postharvest senescence through metabolic inhibition.

3.4. *TSS/TA.*

The formulations of coating solution made by mo alone and its combination have significantly ($p \leq 0.05$) lowered the TSS/TA of tomatoes compared to uncoated tomatoes, as illustrated in Figures 4(a) and 4(b). The study showed that the utilization of 1% v/v mo treatment resulted in the lowest value of the TSS/TA of tomato fruits across both storage conditions (postharvest shed and refrigeration) throughout the 20-day storage time. The value observed ranged from 5.78 on the 5th day to 79.54 on the 20th day and 6.96 on the 5th day to 84.74 on the 20th day at refrigeration and shed conditions, respectively. The observed TSS/TA differences between refrigeration and postharvest shed at the 20th day are depicted in Figures 5(a) and 5(b). Tomato fruits treated with coating solutions comprising 2% v/v mo and 1% w/v ch recorded significantly higher TSS/TA values. On the postharvest shed, the value ranged from 13.8 on the 5th day to 264.7 on the 20th day. This finding highlights that mo alone performs better in slowing down the ripening of tomatoes than when it is in combination with ch or ch alone.

The TSS/TA in fruit postharvest handling determines ethylene production, fruit acidity, and starch and sugar content changes. The higher the TSS/TA value, the higher the respiration rate that deteriorates the qualities of tomatoes [44]. The application of mo introduces chemical compounds, such as oleic acid, which display inhibitory effects on microbial activity. This inhibition arises from the interaction of these compounds with bacterial cell membranes [45]. This interaction disrupts the electron transport chain related to respiration, subsequently blocking enzyme activity within bacterial cells [46]. This phenomenon can potentially be attributed to the influence of a protective oil layer on the tomato's surface. This layer likely hinders the exchange of respiratory gases, thereby reducing the enzymatic conversion of polysaccharides into simple sugars, thereby raising the TSS value [47]. In contrast, a lower TSS/TA value indicates diminished TSS content, potentially due to reduced respiration rate. Consequently, this implies an extended shelf life for the tomatoes. Similar results reported concerning the gum arabic edible coating have delayed ripening and maintained the quality of persimmon fruits [48].

The TSS/TA, which reflects ethylene production, acidity, and sugar content changes, is a critical parameter in postharvest quality management. Higher TSS/TA values correlate with increased respiration rates, leading to the deterioration of tomato quality. The application of mo introduces compounds like oleic acid, which exhibit inhibitory effects on microbial activity by disrupting bacterial cell membranes and interfering with the electron transport chain, thereby blocking enzyme activity [45, 46]. This antimicrobial action, combined with the formation of a protective oil layer on the tomato surface, likely reduces gas exchange, slowing the enzymatic conversion of polysaccharides into simple sugars and moderating TSS levels [47]. A lower TSS/TA ratio indicates reduced respiration and extended shelf life, aligning with findings from other edible coatings like gum arabic, which delays ripening in persimmon fruits [48]. Comparatively, *Aloe vera* coatings reduce respiration rates and ethylene production through polysaccharide-based barriers but lack the active antimicrobial properties of mo-ch coatings. Wax-based coatings, while effective at forming hydrophobic barriers, do not inherently possess antioxidant or antimicrobial functionalities unless supplemented with additives. mo provides a superior hydrophobic barrier and intrinsic antimicrobial activity via its fatty acid profile. The superior performance of mo alone over the mo-ch combination indicates that the optimal coating formulation is not always a complex composite. Specifically, for modulating the ripening-related metabolism in tomatoes, a simple, well-formulated lipid layer can be more effective than a composite that may alter the fruit's gas exchange environment less efficiently. At the molecular level, the interactions between mo and ch enhance their synergistic effects: ch's cationic nature disrupts microbial membranes, while mo's fatty acids inhibit enzyme activity, creating a dual-action antimicrobial mechanism. Additionally, ch scavenges water-soluble free radicals, and mo neutralizes lipid-soluble radicals, providing robust antioxidant protection. These interactions, along with the optimized formulation of 1% mo, highlight the coating's superior ability to maintain fruit quality compared to other edible coatings, offering a sustainable solution for extending shelf life and preserving nutritional value.

3.5. *Total Chlorophyll and Carotenoid Contents.*

The changes of total chlorophyll content of tomato samples held under refrigeration and shed conditions throughout a 20-day period are shown in Figures 6(a_1) and 6(b_2). The treatment consisting of 2.5% v/v mo combined with 1% w/v ch showed the highest chlorophyll content of tomatoes under both storage conditions throughout the entire 2 days. On the 5th day of storage, the 2.5% v/v mo+ 1% w/v ch exhibited the highest total chlorophyll content of tomatoes,

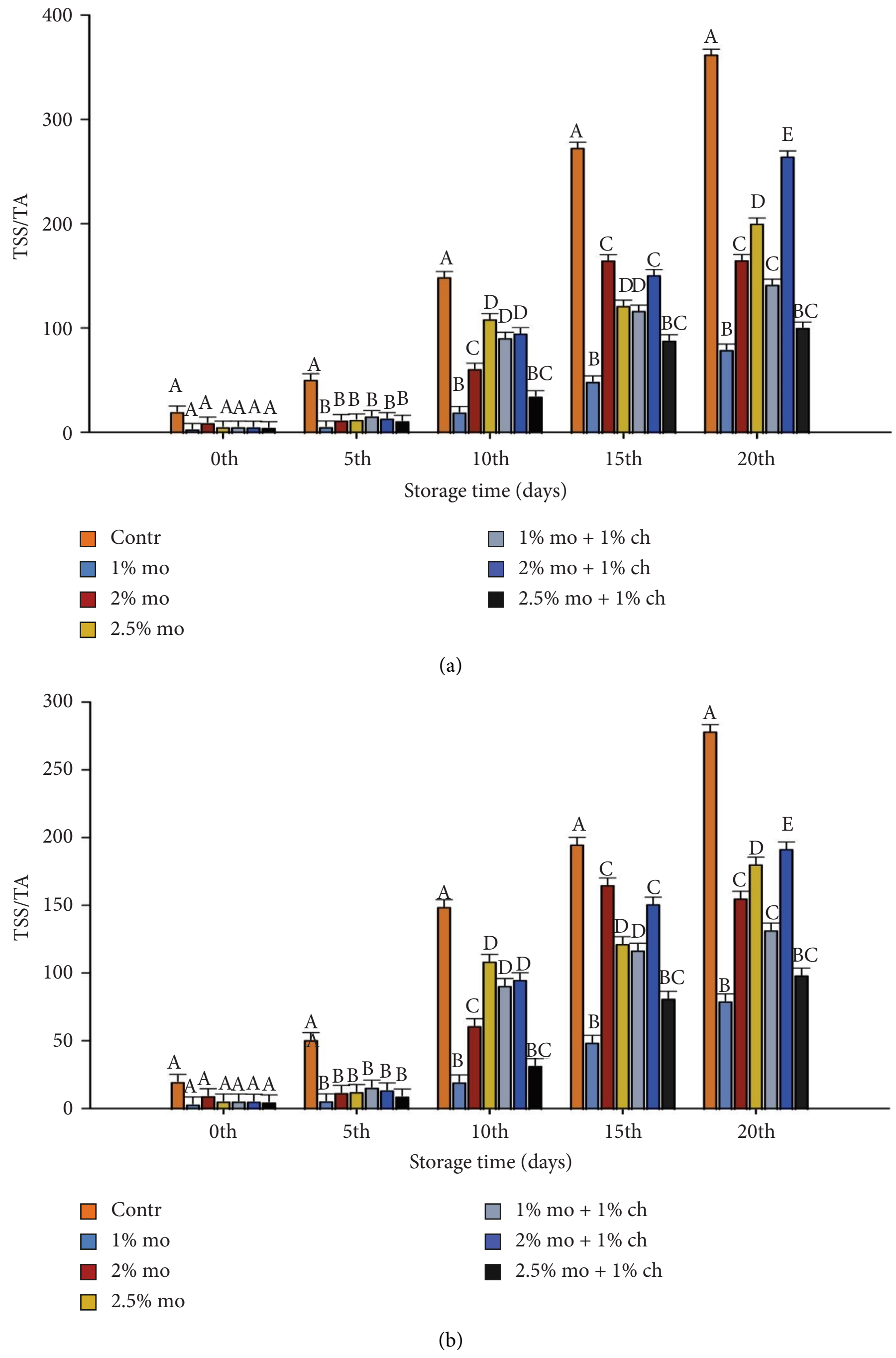


Figure 4: (a, b): Effect of macadamia nut oil (mo) and chitosan (ch) formulations on ripening index value of tomatoes along 20 days stored at (a) postharvest shed and (b) refrigeration. Vertical bars show ± percentage error of means for three replicates. Different letters on the same storage day imply significant differences ($p < 0.05$) among formulations.

measuring 0.19 and 0.12 mg/100 mL for shed and refrigeration conditions, respectively. On the 15th day of storage, the values read 0.035 and 0.04 mg/100 mL for the shed and refrigeration conditions, respectively. The tomatoes treated with 2.5% v/v mo had significantly lower total chlorophyll content on the 20th day; their values observed were 0.017 mg/100 mL on the 5th day to 0.005 mg/100 mL on the 15th day under the postharvest shed, while the total chlorophyll content ranged from 0.05 mg/100 mL on the 5th day to 0.01 mg/100 mL on the 20th day. This showed the synergistic effect of mo when in combination with ch. The higher reductions of total chlorophyll observed on uncoated tomatoes were decreased values of 0.04, 0.0009, and 0.00001 mg/100 mL on the 5th, 10th, and 15th days, respectively. Similarly, under refrigeration, the decreasing trends were observed as 0.12, 0.0004, and 0.0003 mg/100 mL on the 5th, 10th, and 15th days, respectively.

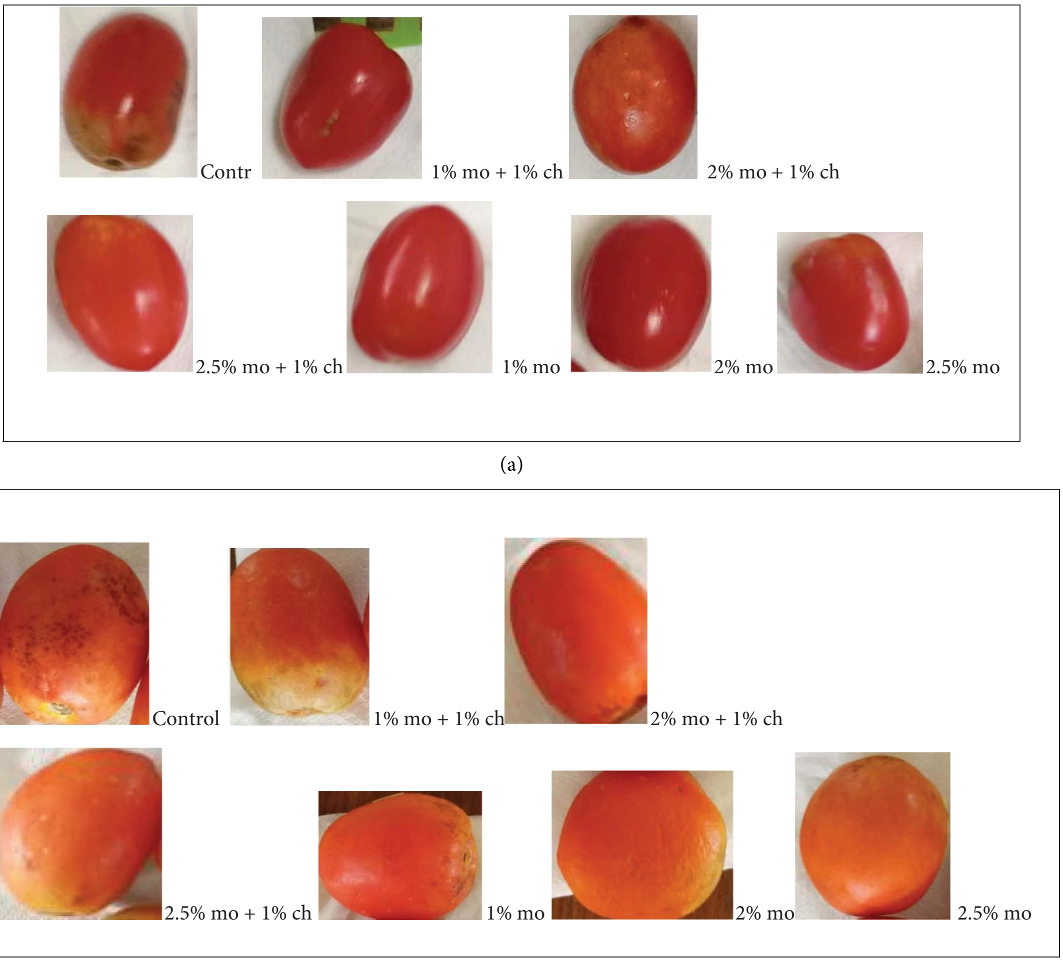


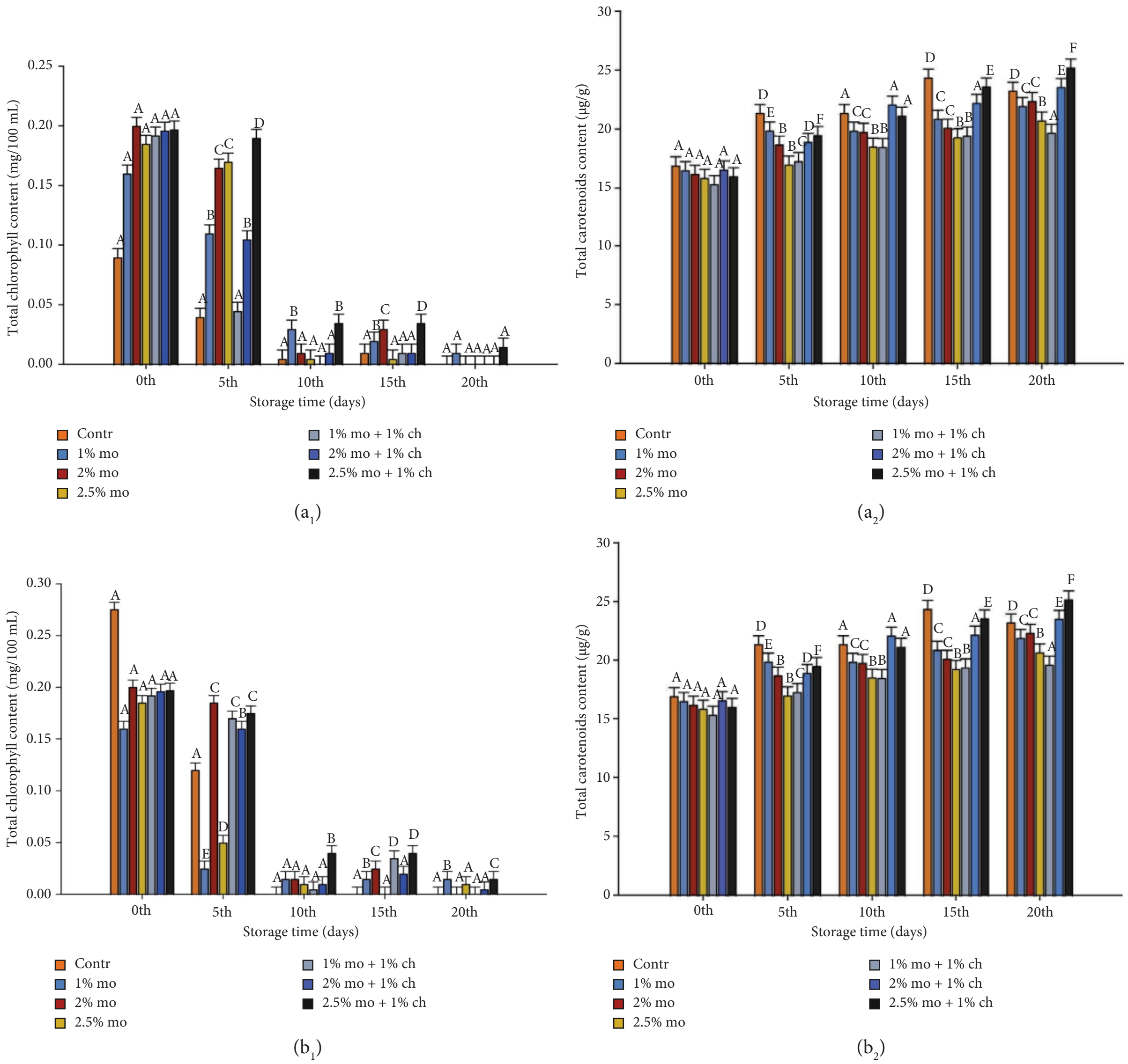
Figure 5: (a, b): Tomatoes' appearance on the 20th day of storage for both (a) postharvest shed and (b) refrigeration conditions.

mo, with its rich fatty acid composition including oleic acid, might function as an effective surface barrier for gas exchanges. This leads to a slowdown in metabolic reactions. Furthermore, the incorporation of 1% w/v ch into mo enhances this effect synergistically. ch can delay enzyme activities, including those of chlorophyllase—an enzyme responsible for catalyzing the conversion of chlorophyll to chlorophyllide by eliminating the phytol side [49]. This study is coherent with the reported finding that showed higher chlorophyll content of tomatoes coated with edible coating compared to the control [50].

Conversely, the decline in chlorophyll content corresponds to a significant ($p \leq 0.05$) increase in carotenoid pigments, as presented in Figures 6(a_2) and 6(b_2). The uncoated tomatoes exhibit significantly higher carotenoid content ($p \leq 0.05$) than other treatments under both storage conditions throughout the 20 days. Its value reads from 35.57 μg/g on the 5th day to 44.15 μg/g on the 20th day for postharvest shed, while at refrigeration the values read 19.9 μg/g on the 5th day to 21.94 μg/g on the 20th day. The treatment consisting of 1% v/v mo demonstrated a significant lowest total carotenoid content ($p < 0.05$) compared to other treatments. The values range from 16.04 μg/g on the 5th day to 27.53 μg/g on the 20th day and 16.54 μg/g on the 5th day to 21.94 μg/g on the 20th day for postharvest shed and refrigeration conditions, respectively. Additionally, the highest total carotenoid content observed on tomatoes treated by 2.5% v/v mo and 1% w/v ch stored under postharvest shed and refrigeration conditions was 42.81 and 25.21 μg/g on the 20th day, respectively. This finding presents a key advancement from prior edible coating research, which typically notes a general rise in carotenoids during storage. Crucially, we demonstrate that mo alone is uniquely effective at suppressing the rapid conversion of chlorophyll to carotenoids, thereby better preserving the fruit's initial physiological state compared to the composite coating. This increase in carotenoid content in other treatments could be attributed to accelerated metabolic reactions resulting in the conversion of total chlorophyll content into beta carotenoids [51, 52].

3.6. Lipid Peroxidation.

The synergistic effect of mo with ch on the lipid peroxidation of tomatoes stored under shed and refrigeration conditions is investigated in this current study. The findings demonstrated that the use of mo and ch showed significant differences ($p \leq 0.05$) in lipid peroxidation between coated and uncoated tomatoes as depicted in



(a_1) (a_2)

(b_1) (b_2)

Figure 6: (a_1, b_1, a_2 & b_2): Effect of macadamia nut oil (mo) and chitosan (ch) formulations on total chlorophyll and carotenoid value of tomatoes along 20 days stored at (a) postharvest shed and (b) refrigeration. Vertical bars show ± percentage error of means for three replicates. Different letters on the same storage day imply significant differences ($p < 0.05$) among formulations.

Figure 7(a) and 7(b), respectively. The utilization of 2.5% v/v mo and 1% w/v ch treatment had the lowest value of lipid peroxidation across both storage conditions. The formulation consisting of 2.5% v/v mo and 1% w/v ch exhibited the significantly lowest lipid peroxidation, as the value read from 17.5 meq/kg on the 5th day to 24.44 meq/kg on the 20th day at shed storage, while at refrigeration the value read 13.5 meq/kg on the 5th day to 19.71 meq/kg on the 20th day. On the other hand, the 2% mo treatment yielded the highest lipid peroxidation in comparison to other formulations. On the 20th day their value reads 37.14 and 19.93 meq/kg for both shed and refrigeration conditions, respectively. This implies that there is a synergistic effect when MNO is combined with ch compared with the oil alone. The control sample resulted in substantially increased lipid peroxidation since the value approached 55.415 and 25.835 meq/kg (20th day) for postharvest shed and refrigeration, respectively, thus highlighting the higher oxidation of untreated tomatoes. A previous study done on rosemary and eucalyptus extracts (*Eucalyptus* spp.) had effectively decreased the lipid peroxidation of apple (*M. domesticus*) and pear fruits (*Pyrus pyrifolia*) [53]. Also, this result indicated that the formulation of 2.5% v/v mo and 1% w/v ch exhibited lower lipid peroxidation than the other formulations. Using ch integrated with mo might induce antifungal properties and activate the defense enzymes such as chitinase and chitosanase, which are associated with induced systemic resistance of fruits against oxidation [54]. ch-coated fruits maintain high anti-oxidative enzyme activities such as POD, catalase (CAT), superoxide dismutase (SOD), and ascorbate peroxidase (APX) activities [55]. These enzymes scavenge overproduced reactive oxygen species (ROS) in tomatoes, retard peroxidation of membrane lipids, alleviate fruit oxidative stress, and therefore control senescence during storage of tomatoes.

3.7. Total Sugar Level. The changes of total sugar level of coated and uncoated tomato fruits are illustrated in Figure 8(a), 8(b). The findings indicate that the application of a 1% v/v mo treatment resulted in significantly lower ($p \leq 0.05$) total sugar levels of tomatoes under both storage conditions throughout the entire 20-day storage duration. The observed increase in total sugar content ranged from 30.375 mg/mL on the 5th day to 37.5 mg/mL on the 20th day for postharvest shed, while the values recorded were 28.72 mg/mL on the 5th day to 60.2 mg/mL on the 20th day for refrigeration condition. In addition, the formulation made of a composite of 2% v/v mo and 1% w/v ch showed the higher total sugar content throughout the storage conditions. This value range is 29.95 to 71.285 mg/mL on the 20th day at the postharvest shed, while the value range is from 39.96 mg/mL on the 5th day to 80.1 mg/mL on the 20th day. This finding highlights that mo alone performs better in slowing the conversion of polysaccharides into simple sugars and is the more promising coating solution as compared to when in combination with ch.

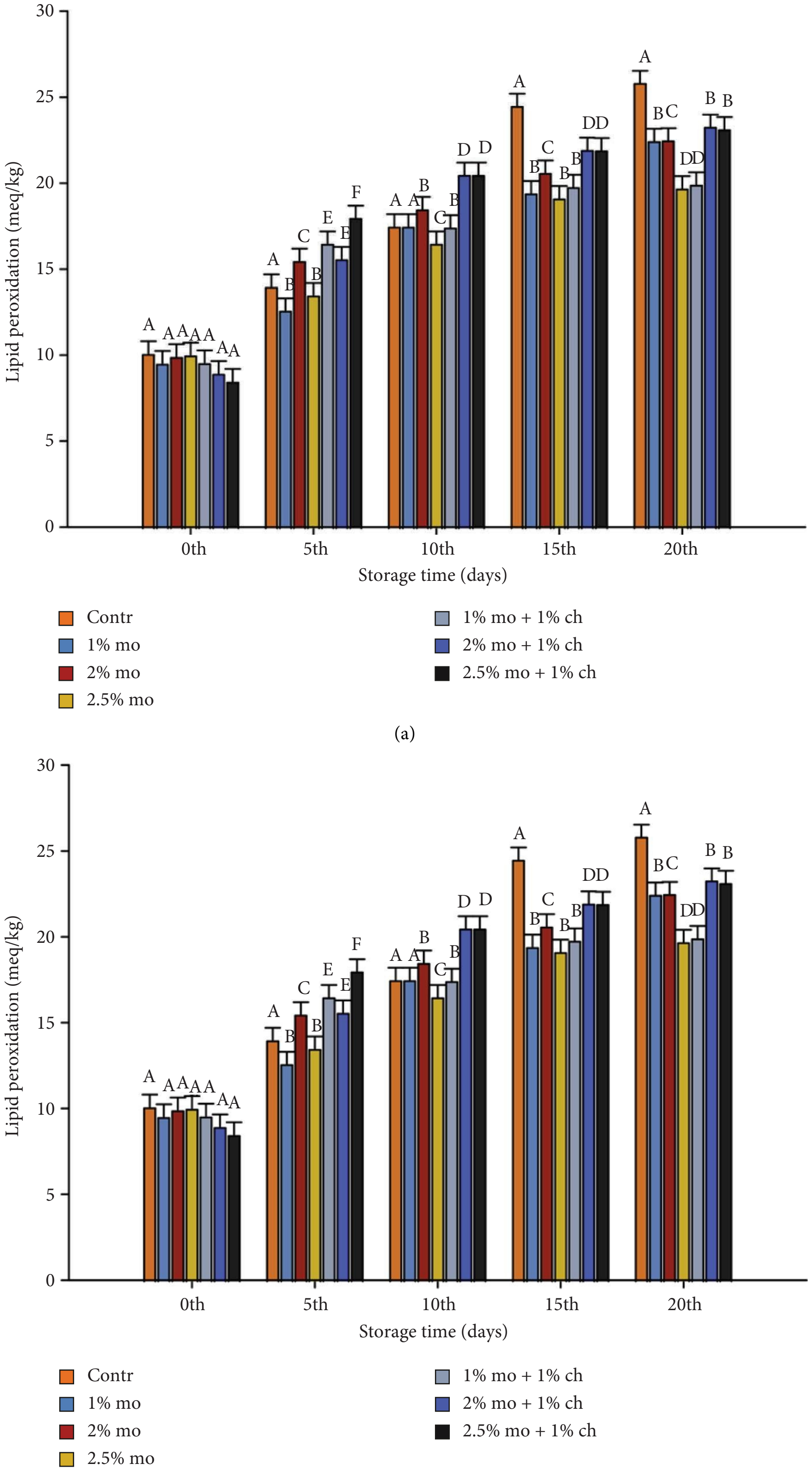
The gradual rise in total sugar content can be attributed to the higher respiration rate, which facilitates the decomposition of polysaccharides into simple sugars (oligosaccharides). This finding aligns with the study that applied neem leaf extract, *Aloe vera* gel, and $CaCl_2$ formulations, which delayed the rise in total sugar content of tomatoes [56]. The mo contains oleic acid that forms a film layer on the surface of tomatoes, thereby reducing the O_2 gas inside the tomatoes and accumulating CO_2. The elevated concentration of CO_2 imparts an inhibitory effect on auto-induced ethylene production in climacteric fruits, as CO_2 and ethylene compete for the same active sites [57].

The gradual rise in total sugar content, attributed to higher respiration rates and polysaccharide breakdown, was effectively delayed by mo, which forms a hydrophobic film layer on the fruit surface. This reduces O_2 ingress and accumulates CO_2, inhibiting ethylene production, a mechanism consistent with findings from other edible coatings like *Aloe vera* gel and wax-based formulations. However, mo's oleic acid content provides additional antioxidant and antimicrobial benefits, surpassing the limitations of traditional wax coatings that lack bioactive properties. When combined with ch, a biopolymer known for its antimicrobial and antioxidant effects, the synergistic interactions at the molecular level further enhance the coating's functionality. ch stabilizes the oil emulsion, improves film cohesion, and scavenges ROS, while mo reduces gas permeability and contributes lipophilic antioxidants. Together, they create a dual mechanism for ethylene inhibition and microbial control, offering comprehensive protection against oxidative stress and spoilage. These findings underscore the superiority of combining mo and ch over standalone coatings, providing a promising strategy to extend the shelf life and maintain the physicochemical quality of tomatoes during storage.

3.8. Firmness. The results of firmness of coated and uncoated tomato fruits are depicted in Figures 9(a) and 9(b) when stored under refrigeration and shed conditions over 20 days. The result showed a significant difference ($p \leq 0.05$) in firmness between the coated and uncoated tomatoes for the 20-day storage period. These findings demonstrate that the utilization of a 1% v/v mo treatment led to the slight decreases in hardness across both storage conditions throughout the entire 20-day storage duration. A coating solution of 1% v/v mo showed the decrease of firmness from 355 N on the 5th day to 172.5 N on the 20th day for tomatoes stored under a postharvest shed, while the value changes from 241 N on the 5th day to 130 N on the 20th under refrigeration temperature. Conversely, the combination of 2% v/v mo and 1% ch treatment yielded the lowest hardness for both storage environments on 20-day storage. The formulation showed the decrease from 120.5 N on the 5th day to 82 N on the 20th day for tomatoes stored under a postharvest shed, while the value changes from 202 N on the 5th day to 105 N on the 20th day under refrigeration temperature. These findings indicate that ch and mo do not offer the synergistic effect on preserving the firmness of tomatoes. Figures 5(a), 5(b) showed that tomatoes appear pale and shriveled when stored in refrigeration compared to tomatoes stored in a postharvest shed that appear bright in color; however, for some treatments, the sample is likely to deteriorate. This can be due to the presence of an enzyme in tomatoes that reacts to the cold, causing cell membranes to break down. As a result, the fruit becomes mushy and mealy.

The decrease in firmness is due to a higher respiration rate that facilitates the ripening of tomatoes, thereby reducing cell-to-cell adhesion and weakening of the parenchyma cell wall [22]. The presence of phenolic compounds in mo might provide the antioxidant properties that retain firmness retention [58, 59]. Along the storage days, the degradation of insoluble protopectin to soluble pectic acid and pectin can be facilitated by the polygalacturanase enzyme that softens the surface of fruits [60, 61]. The mo contains tocopherol that could provide the inhibitory effect on the polygalacturanase activity, thus retaining the firmness of tomatoes. This observation correlates with the study that applied Candelilla Wax Edible and *Flourensia cernua* to extend the firmness of tomatoes during storage [62, 63].

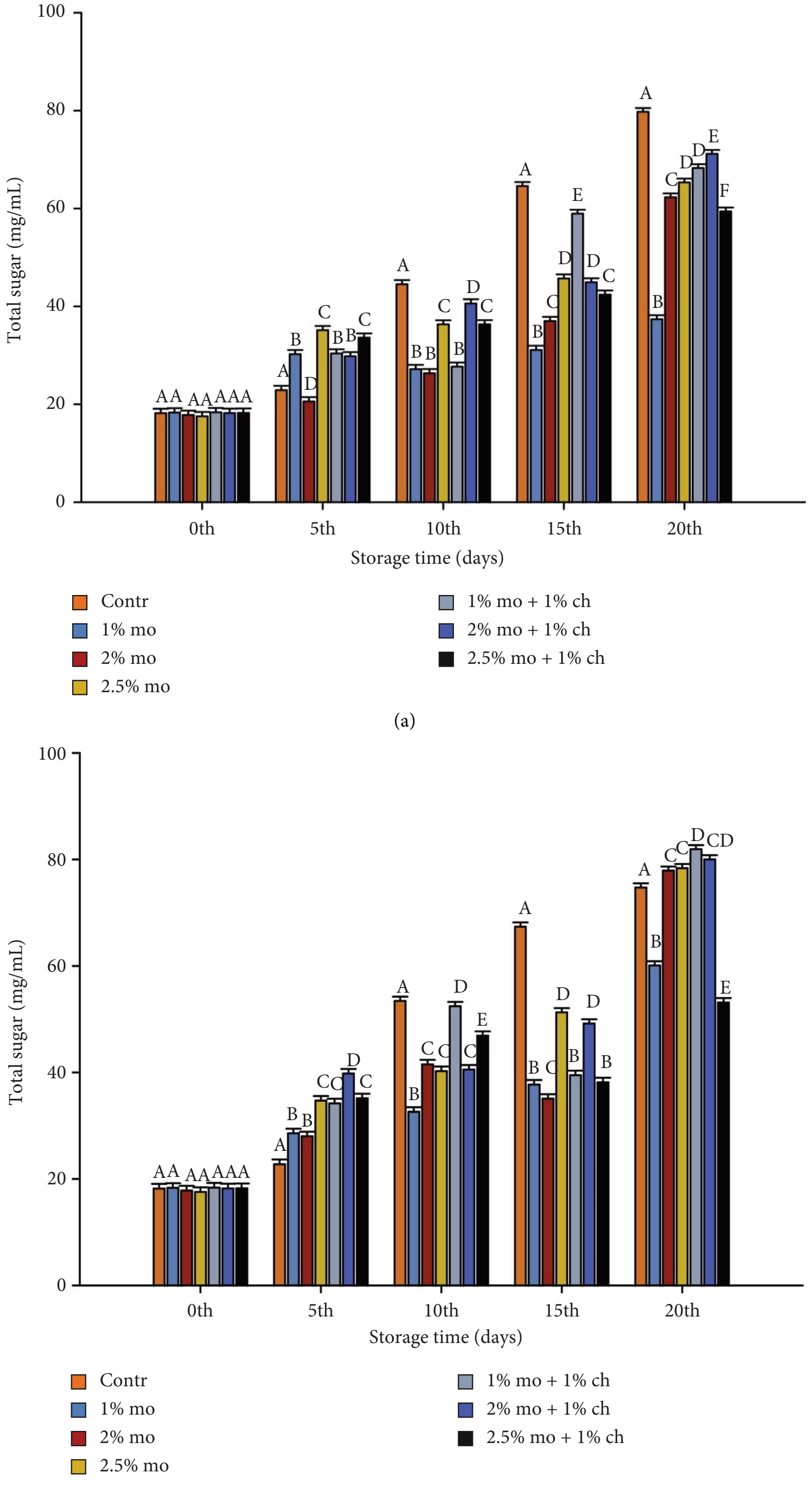
The findings demonstrate that a 1% mo and ch coating outperforms other formulations in maintaining the physicochemical characteristics of tomatoes during storage. Compared to *Aloe vera*-based coatings, which rely on polysaccharides for firmness retention and mild antioxidant activity, the mo-ch coating offers superior oxidative stability due to its tocopherol content and monounsaturated fatty acids. Unlike wax-based coatings, which act as passive barriers and lack active functional properties, the mo-ch coating provides inherent antioxidant and antimicrobial benefits, making it more effective in extending shelf life while remaining biodegradable. Additionally, compared to



(a)

(b)

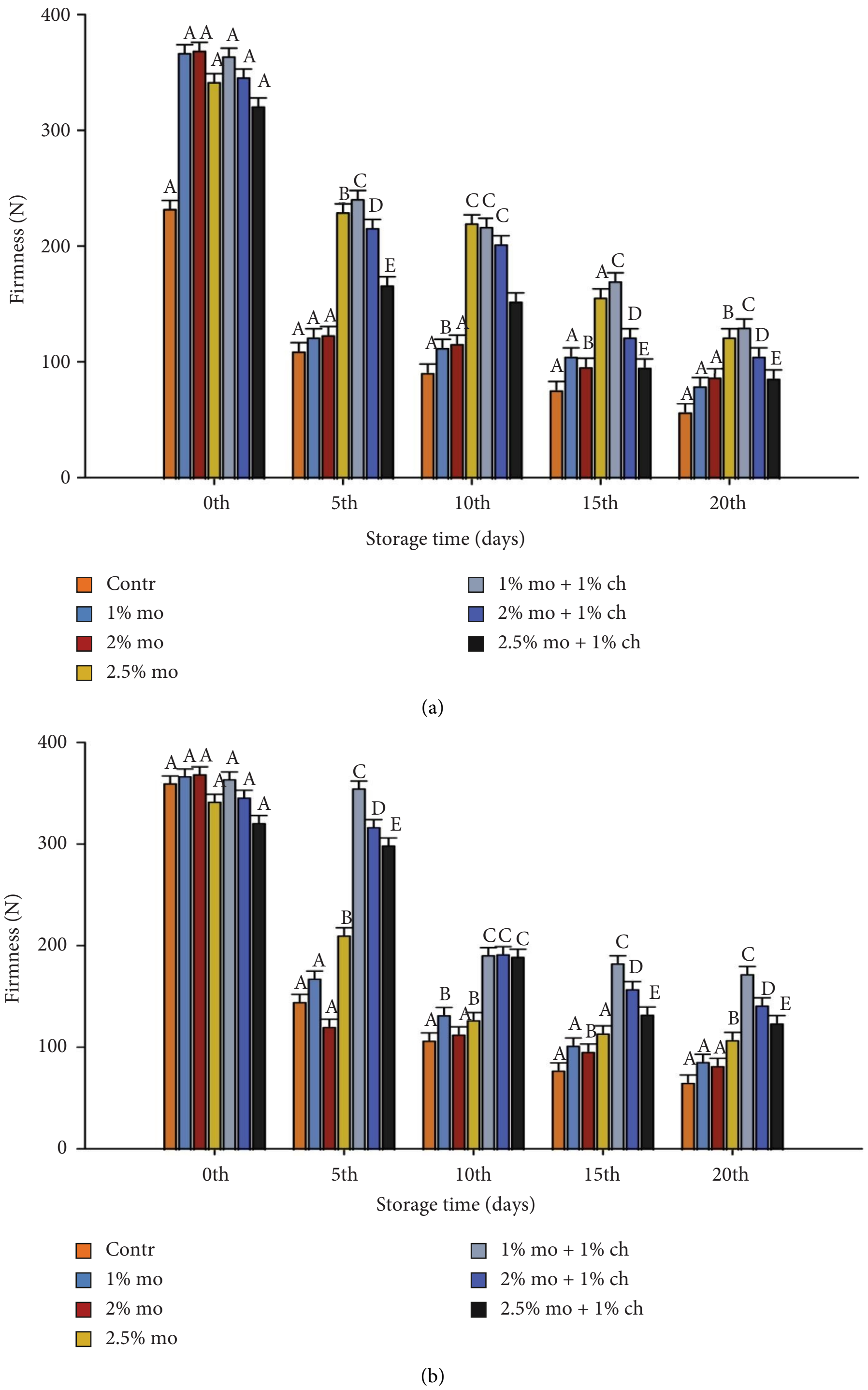
Figure 7: (a, b): Effect of macadamia nut oil (mo) and chitosan (ch) formulations on lipid peroxidation value of tomatoes along 20 days stored at (a) postharvest shed and (b) refrigeration. Vertical bars show ± percentage error of means for three replicates. Different letters on the same storage day imply significant differences ($p < 0.05$) among formulations.



(a)

(b)

Figure 8: (a, b): Effect of macadamia nut oil (mo) and chitosan (ch) formulations on total sugar contents of tomatoes along 20 days stored at (a) postharvest shed and (b) refrigeration. Vertical bars show ± percentage error of means for three replicates. Different letters on the same storage day imply significant differences ($p < 0.05$) among formulations.



(a)

(b)

Figure 9: (a, b): Effect of macadamia nut oil (mo) and chitosan (ch) formulations on firmness of tomatoes along 20 days stored at (a) postharvest shed and (b) refrigeration. Vertical bars show ± percentage error of means for three replicates. Different letters on the same storage day imply significant differences ($p < 0.05$) among formulations.

other oil-based coatings, the unique fatty acid profile of mo, particularly its high oleic acid content, enhances hydrophobicity and oxidative stability, with the optimized 1% concentration striking an ideal balance. At the molecular level, hydrogen bonding and electrostatic interactions between mo and ch ensure uniform distribution and stability. It offers the synergistic antioxidant mechanisms where ch targeting water-soluble radicals and mo neutralizing lipid-soluble radicals thereby reducing oxidative stress. The antimicrobial efficacy of the coating arises from ch's cationic nature disrupts microbial membranes and mo's fatty acids inhibiting enzyme activity, by creating a dual-action effect

Table 1: Post hoc analysis of 2.5% mo + 1% ch and 1% mo with control.

Parameter	Mean for the treatment group (j) versus control	Mean difference ($i - j$)	Sig.
Lipid peroxidation	1% mo	14.6508*	0.000
	2.5% mo + 1% ch	7.6299*	0.000
Total sugar content	1% mo	14.9094*	0.000
	2.5% mo + 1% ch	8.0273*	0.000
pH	1% mo	1.4533*	0.000
	2.5% mo + 1% ch	1.6855*	0.000
TA	1% mo	−0.1974*	0.000
	2.5% mo + 1% ch	−0.1335*	0.000
TSS	1% mo	2.1316*	0.000
	2.5% mo + 1% ch	1.9800*	0.000
Ripening index	1% mo	268.3501*	0.000
	2.5% mo + 1% ch	179.8736*	0.000
Total chlorophyll content	1% mo	0.1376*	0.000
	2.5% mo + 1% ch	0.1149*	0.000
Total carotenoid content	1% mo	6.6058*	0.000
	2.5% mo + 1% ch	3.2920*	0.000
Texture	1% mo	165*	0.000
	2.5% mo + 1% ch	143*	0.000

Note: Vertical bars show ± percentage error of means for three replicates.
*Specify the significant difference.

against bacteria and fungi. Furthermore, the tocopherols in mo inhibit polygalacturonase activity, slowing pectin degradation and preserving tomato firmness. These findings underscore the advantages of the 1% mo-ch coating over other edible coatings, highlighting its potential as a sustainable and multifunctional solution for fresh produce preservation.

3.9. Comparative Analysis of Coating Formulations Provided Optimum Physicochemical Properties of Tomato Fruits. Two formulations in particular, 1% v/v mo and a combination of 2.5% v/v mo and 1% w/v ch, offered the desired effect on the physicochemical quality of the tomato fruits investigated in this study. Multiple comparisons were performed to determine the most efficient coating solution among these two formulations in reference to uncoated tomatoes, and the results of least square differences are presented in Table 1. Parameters including lipid peroxidation, pH, TSS, TA, TSS/TA, total chlorophyll content, firmness, and total carotenoid content were examined. The results showed significant mean differences ($p < 0.05$) between coated and uncoated tomatoes for all parameters investigated under this study. However, the formulation with 1% v/v mo has higher mean differences than that of a combination with 2.5% v/v mo and 1% w/v ch. These findings highlight that a formulation with 1% v/v mo revealed a highly significant effect on maintaining the physicochemical quality of tomato fruits compared to a combined formulation with 2.5% v/v mo and 1% w/v ch. This finding coincides with the study done on tomato preservation that used tomatoes coated with ch and vanillin during storage days [64–66].

4. Conclusion

The study demonstrated that the combined application of 2.5% v/v mo and 1% w/v ch synergistically improved the postharvest quality of tomatoes by significantly reducing pH changes, chlorophyll degradation, and lipid peroxidation compared to individual coatings. However, mo alone (1% v/v) was more effective in preserving TSS, total sugars, TA, carotenoids, TSS/TA, and firmness. The findings suggest that while ch enhances certain protective effects of mo, the oil alone may be more beneficial for maintaining most physicochemical properties. Further research should focus on optimizing these coatings for commercial scalability and cost-effectiveness.

Data Availability Statement

The data are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Tlehema Gwandu Umbayda: conceptualization, methodology, validation, formal data analysis, and writing the manuscript.

Anthony Daniel Funga and Alinanuswe Joel Mwakalesi: methodology, formal data analysis, review, and manuscript editing.

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References

[1] E. Karagiannis, "Postharvest Physiology of Climacteric and Nonclimacteric Fruits and Vegetables, in Oxygen, Nitrogen and Sulfur Species," in *Post-Harvest Physiology of Horticultural Crops*, ed. V. Ziogas and F. J. Corpas (Academic Press, 2024), 1–21.

[2] S. Bodbodak and M. Moshfeghifar, "Advances in Controlled Atmosphere Storage of Fruits and Vegetables," in *Eco-Friendly Technology for Postharvest Produce Quality*, ed. M. W. Siddiqui (Academic Press, 2016), 39–76.

[3] L. Mwankemwa, M. P. Mhina, P. Mamiro, and J. Ambuko, "Tomato Post-Harvest Losses as Influenced by Improper Handling Facilities in Morogoro, Tanzania," *Tanzania Journal of Agricultural Sciences* 22, no. 2 (2023): 394–403.

[4] N. Firdous, "Post-Harvest Losses in Different Fresh Produces and Vegetables in Pakistan with Particular Focus on Tomatoes," *Journal of Horticulture and Postharvest Research* 4, no. 1 (2021): 71–86.

[5] A. Farooq, B. Niaz, F. Saeed, et al., "Exploring the Potential of Aloe Vera Gel-Based Coating for Shelf Life Extension and Quality Preservation of Tomato," *International Journal of Food Properties* 26, no. 2 (2023): 2909–2923, https://doi.org/10.1080/10942912.2023.2263661.

[6] M. Sheikh, S. Mehnaz, and M. B. Sadiq, "Prevalence of Fungi in Fresh Tomatoes and Their Control by Chitosan and Sweet Orange (*Citrus sinensis*) Peel Essential Oil Coating," *Journal of the Science of Food and Agriculture* 101, no. 15 (2021): 6248–6257, https://doi.org/10.1002/jsfa.11291.

[7] B. Zewdie, T. T. Shonte, and K. Woldetsadik, "Shelf Life and Quality of Tomato (*Lycopersicon esculentum Mill.*) Fruits as Affected by Neem Leaf Extract Dipping and Beeswax Coating," *International Journal of Food Properties* 25, no. 1 (2022): 570–592, https://doi.org/10.1080/10942912.2022.2053709.

[8] P. Mohammadi-Benaruiyeh and G. R. Sharifi-Sirchi, "Grape Seed and Skin Extracts as Natural Preserving Agents on Strawberry Fruit," *International Journal of Horticultural Science and Technology* 8, no. 4 (2021): 415–429.

[9] A. Fatiqin, H. Amrulloh, I. Apriani, et al., "A Comparative Study on Phytochemical Screening and Antioxidant Activity of Aqueous Extract From Various Parts of Moringa oleifera," *Indonesian Journal of Natural Pigments* 3, no. 2 (2021): 43–47, https://doi.org/10.33479/ijnp.2021.03.2.43.

[10] Y.-y. Ren, P. p. Sun, X. x. Wang, et al., "Degradation of Cell Wall Polysaccharides and Change of Related Enzyme Activities With Fruit Softening in Annona squamosa During Storage," *Postharvest Biology and Technology* 166 (2020): https://doi.org/10.1016/j.postharvbio.2020.111203.

[11] C. Chen, Q. Huang, X. Peng, et al., "Alleviatory Effects of Salicylic Acid on Postharvest Softening and Cell Wall Degradation of 'Jinshayou'Pummelo (*Citrus Maxima Merr.*): A Comparative Physiological and Transcriptomic Analysis," *Food Chemistry* 424 (2023): https://doi.org/10.1016/j.foodchem.2023.136428.

[12] M. D. Mira-Sánchez, J. Castillo-Sánchez, and J. M. Morillas-Ruiz, "Comparative Study of Rosemary Extracts and Several Synthetic and Natural Food Antioxidants. Relevance of Carnosic acid/carnosol Ratio," *Food Chemistry* 309 (2020): https://doi.org/10.1016/j.foodchem.2019.125688.

[13] M. R. Wylie and D. S. Merrell, "The Antimicrobial Potential of the Neem Tree *Azadirachta indica*," *Frontiers in Pharmacology* 13 (2022): https://doi.org/10.3389/fphar.2022.891535.

[14] M. L. Flores-López, J. M. Vieira, C. M. R. Rocha, et al., "Postharvest Quality Improvement of Tomato (*Solanum lycopersicum L.*) Fruit Using a Nanomultilayer Coating Containing Aloe vera," *Foods* 13, no. 1 (2023): 83, https://doi.org/10.3390/foods13010083.

[15] A. Arakkal, I. Aazem, G. Honey, A. Vengellur, S. G. Bhat, and G. C. Sailaja, "Antibacterial Polyelectrolytic Chitosan Derivatives Conjugated Natural Rubber Latex Films With Minimized Bacterial Adhesion," *Journal of Applied Polymer Science* 138, no. 1 (2021): https://doi.org/10.1002/app.49608.

[16] M. Abdel Salam, "Study the Effect of Chitosan and Aloe vera Coating on Mango (*Mangifera indica L.*)," *Assiut Journal of Agricultural Sciences* 52, no. 5 (2021): 6–129, https://doi.org/10.21608/ajas.2022.106005.1065.

[17] M. S. Aboryia, S. F. El-Gioushy, R. Sami, et al., "Synergistic Effect of Dipping in Aloe vera Gel and Mixing with Chitosan or Calcium Chloride on the Activities of Antioxidant Enzymes and Cold Storage Potential of Peach (*Prunus persica L.*) Fruits," *Coatings* 12, no. 4 (2022): 498, https://doi.org/10.3390/coatings12040498.

[18] A. Sarker, A. Deltsidis, and T. E. Grift, "Effect of Aloe Vera Gel-Carboxymethyl Cellulose Composite Coating on the Degradation Kinetics of Cucumber," *Journal of Biosystems Engineering* 46, no. 2 (2021): 112–128, https://doi.org/10.1007/s42853-021-00092-z.

[19] T. Kaseke, O. A. Fawole, and U. L. Opara, "Chemistry and Functionality of cold-pressed Macadamia Nut Oil," *Processes* 10, no. 1 (2021): 56, https://doi.org/10.3390/pr10010056.

[20] N. El Alami El Hassani, A. Baraket, and C. Alem, "Recent Advances in Natural Food Preservatives: a Sustainable Solution for Food Safety and Shelf Life Extension," *Journal of Food Measurement and Characterization* 19, no. 1 (2025): 293–315, https://doi.org/10.1007/s11694-024-02969-x.

[21] T. G. Umbayda, A. D. Funga, and A. J. Mwakalesi, "Novel Edible Coating Based on Macadamia Nut Oil and Chitosan to Maintain the Antioxidant and Physical Properties of Tomato Fruits," *Applied Food Research* 4, no. 1 (2024): https://doi.org/10.1016/j.afres.2024.100434.

[22] P. Kalaitzis, E. Giannoutsou, and A. Konkina, "Role of the Cell Wall in the Regulation of Fruit Ripening," in *Plant Cell Walls* (CRC Press, 2023).

[23] A. Ronte, J. Chalitangkoon, E. J. Foster, and P. Monvisade, "Development of a pH-responsive Intelligent Label Using Low Molecular Weight Chitosan Grafted with Phenol Red for Food Packaging Applications," *International Journal of Biological Macromolecules* 266 (2024): https://doi.org/10.1016/j.ijbiomac.2024.131212.

[24] J. F. G. Motta, J. C. C. Santos, J. de Abreu Figueiredo, et al., "Development of Chitosan-based Films with Invertase Enzyme for Active Packaging: Physicochemical Parameters, Structure, Application, and Storage," *International Journal of Biological Macromolecules* 298 (2025): https://doi.org/10.1016/j.ijbiomac.2025.139902.

[25] V. NeysariFam, E. Motamedi, M. Sarshar, and A. Rafati, "Effect of Potato Starch/Guar Gum/Nanoclay/Needle Pine Leaf Essential Oil Packaging Films on Button Mushroom Postharvest Quality," *Food and Bioprocess Technology* (2024): 1–12.

[26] P.-H. Huang, C. H. Jian, Y. W. Lin, D. W. Huang, W. Chen, and L.-J. Wang, "Impact of *Premna microphylla* Turcz Leaf Water Extracts on the Properties of Gelatin-Carrageenan Edible Film and Its Application in Cherry Tomatoes Storage," *Food Chemistry X* 25 (2025): https://doi.org/10.1016/j.fochx.2025.102186.

[27] F. N. Nkede, A. A. Wardana, N. T. H. Phuong, et al., "Preparation and Characterization of chitosan/lemongrass oil/cellulose Nanofiber Pickering Emulsions Active Packaging and Its Application on Tomato Preservation," *Journal of Polymers and the Environment* 31, no. 11 (2023): 4930–4945, https://doi.org/10.1007/s10924-023-02885-z.

[28] O. S. Darwish, M. R. Ali, E. Khojah, B. N. Samra, K. M. A. Ramadan, and M. M. El-Mogy, "Pre-Harvest Application of Salicylic Acid, Abscisic Acid, and Methyl Jasmonate Conserve Bioactive Compounds of Strawberry Fruits During Refrigerated Storage," *Horticulturae* 7, no. 12 (2021): 568, https://doi.org/10.3390/horticulturae7120568.

[29] J. Branisa, K. Jomova, M. Porubska, V. Kollar, M. Simunkova, and M. Valko, "Effect of Drying Methods on the Content of Natural Pigments and Antioxidant Capacity in Extracts from Medicinal Plants: a Spectroscopic Study," *Chemical Papers* 71, no. 10 (2017): 1993–2002, https://doi.org/10.1007/s11696-017-0193-9.

[30] L. Geng, K. Liu, and H. Zhang, "Lipid Oxidation in Foods and Its Implications on Proteins," *Frontiers in Nutrition* 10 (2023): https://doi.org/10.3389/fnut.2023.1192199.

[31] A. A. Albalasmeh, A. A. Berhe, and T. A. Ghezzehei, "A New Method for Rapid Determination of Carbohydrate and Total Carbon Concentrations Using UV Spectrophotometry," *Carbohydrate Polymers* 97, no. 2 (2013): 253–261, https://doi.org/10.1016/j.carbpol.2013.04.072.

[32] S. Brizzolara, G. A. Manganaris, V. Fotopoulos, C. B. Watkins, and P. Tonutti, "Primary Metabolism in Fresh Fruits During Storage," *Frontiers of Plant Science* 11 (2020): 80, https://doi.org/10.3389/fpls.2020.00080.

[33] S. Affes, I. Aranaz, N. Acosta, et al., "Chitosan Derivatives-based Films as pH-sensitive Drug Delivery Systems With Enhanced Antioxidant and Antibacterial Properties," *International Journal of Biological Macromolecules* 182 (2021): 730–742, https://doi.org/10.1016/j.ijbiomac.2021.04.014.

[34] X. Gong, J. Huang, Y. Xu, et al., "Deterioration of Plant Volatile Organic Compounds in Food: Consequence, Mechanism, Detection, and Control," *Trends in Food Science & Technology* 131 (2023): 61–76, https://doi.org/10.1016/j.tifs.2022.11.022.

[35] M. E. Ionica, F. Tutulescu, and A. Bita, "Development of Basil Essential Oil (BEO) as a Novel Alternative to Prolong the Storage of Tomato (*Lycopersicum Esculentum* L.)," *Agriculture* 12, no. 12 (2022): 2135, https://doi.org/10.3390/agriculture12122135.

[36] M. Al-Dairi, P. B. Pathare, and R. Al-Yahyai, "Chemical and Nutritional Quality Changes of Tomato During Postharvest Transportation and Storage," *Journal of the Saudi Society of Agricultural Sciences* 20, no. 6 (2021): 401–408, https://doi.org/10.1016/j.jssas.2021.05.001.

[37] A. Njie, W. Zhang, X. Dong, et al., "Effect of Melatonin on Fruit Quality via Decay Inhibition and Enhancement of Antioxidative Enzyme Activities and Genes Expression of Two Mango Cultivars During Cold Storage," *Foods* 11, no. 20 (2022): 3209, https://doi.org/10.3390/foods11203209.

[38] A. Naz, M. Rauf, M. A. Anjum, and K. Razzaq, "Natural Plant Extracts and Postharvest Quality of Fruits and Vegetables," *Sustainable Postharvest Technologies for Fruits and Vegetables* (CRC Press), 418–430.

[39] M. Arnold and A. Gramza-Michałowska, "Enzymatic Browning in Apple Products and Its Inhibition Treatments: a Comprehensive Review," *Comprehensive Reviews in Food Science and Food Safety* 21, no. 6 (2022): 5038–5076, https://doi.org/10.1111/1541-4337.13059.

[40] A. Tantawy, S. Mounir, and W. Eid, "Study of Some Physicochemical and Sensory Properties of Apricot Jam Supplemented with Apricot Kernel Flour," *New Valley Journal of Agricultural Science* 3, no. 10 (2023): 0, https://doi.org/10.21608/nvjas.2023.231054.1240.

[41] A. Basit, S. T. Shah, and I. Ullah, "Quality Indices of Tomato Plant as Affected by Water Stress Conditions and Chitosan Application," *Pure and Applied Biology (PAB)* 9, no. 2 (2020): 1364–1375, https://doi.org/10.19045/bspab.2020.90143.

[42] F. Salehi, "Physicochemical Characteristics and Rheological Behaviour of Some Fruit Juices and Their Concentrates," *Journal of Food Measurement and Characterization* 14, no. 5 (2020): 2472–2488, https://doi.org/10.1007/s11694-020-00495-0.

[43] M. Martinez, H. M. Wallace, C. Searle, B. Elliott, and S. Hosseini Bai, "Understanding Chemical Pathways of Brown Centre Formation in Laboratory Induced and Conventionally Dried nut-in-shell Macadamia Kernels," *Heliyon* 10, no. 3 (2024): https://doi.org/10.1016/j.heliyon.2024.e25221.

[44] H. Xiao-yi, D. Zhen-wen, L. Li, and L. Fei, "Effects of Harvest Ripeness on Storage Quality of Tomato Fruits," *Emirates Journal of Food and Agriculture* 11 (2023): 978–987.

[45] G. Casillas-Vargas, C. Ocasio-Malavé, S. Medina, et al., "Antibacterial Fatty Acids: an Update of Possible Mechanisms of Action and Implications in the Development of the next-generation of Antibacterial Agents," *Progress in Lipid Research* 82 (2021): https://doi.org/10.1016/j.plipres.2021.101093.

[46] R. Chhabra, S. Kaur, L. Vij, and K. Gaur, "Exploring Physiological and Biochemical Factors Governing Plant Pathogen Interaction: a Review," *International Journal of Current Microbiology and Applied Sciences* 9, no. 11 (2020): 1650–1666, https://doi.org/10.20546/ijcmas.2020.911.197.

[47] A. Yadav, N. Kumar, and A. Upadhyay, "Edible Coating as Postharvest Management Strategy for Shelf-Life Extension of Fresh Tomato (*Solanum lycopersicum* L.): an Overview," *Journal of Food Science* 87, no. 6 (2022): 2256–2290, https://doi.org/10.1111/1750-3841.16145.

[48] M. S. Saleem, S. Ejaz, M. A. Anjum, et al., "Postharvest Application of Gum Arabic Edible Coating Delays Ripening and Maintains Quality of Persimmon Fruits During Storage," *Journal of Food Processing and Preservation* 44, no. 8 (2020): https://doi.org/10.1111/jfpp.14583.

[49] C. Pucci, C. Martinelli, A. Degl'Innocenti, A. Desii, D. De Pasquale, and G. Ciofani, "Light-Activated Biomedical Applications of Chlorophyll Derivatives," *Macromolecular Bioscience* 21, no. 9 (2021): https://doi.org/10.1002/mabi.202100181.

[50] F. L. Tchouala Tazo, G. Kanmegne, A. Ngotio Tchinda, O. J. Kenfack, and E. Tafré Phounzong, "Optimization of Edible Coating Formulation Using Response Surface Methodology for Delaying the Ripening and Preserving Tomato (*Solanum lycopersicum*) Fruits," *Journal of Food Quality* 2023, no. 1 (2023): 1–11, https://doi.org/10.1155/2023/7710980.

[51] L. Kapoor, A. J. Simkin, C. George Priya Doss, and R. Siva, “Fruit Ripening: Dynamics and Integrated Analysis of Carotenoids and Anthocyanins,” *BMC Plant Biology* 22, no. 1 (2022): 27, https://doi.org/10.1186/s12870-021-03411-w.

[52] E. H. Algarni, I. A. Elnaggar, A. E. w. N. Abd El-wahed, et al., “Effect of Chitosan Nanoparticles as Edible Coating on the Storability and Quality of Apricot Fruits,” *Polymers* 14, no. 11 (2022): 2227, https://doi.org/10.3390/polym14112227.

[53] P. Xylia, A. Chrysargyris, D. Shahwar, Z. F. R. Ahmed, and N. Tzortzakis, “Application of Rosemary and Eucalyptus Essential Oils on the Preservation of Cucumber Fruit,” *Horticulturae* 8, no. 9 (2022): 774, https://doi.org/10.3390/horticulturae8090774.

[54] N. Abd El-Baky and A. A. A. F. Amara, “Natural Antimicrobial Therapeutic Peptides: Milk Lactoferricin and *Spirulina platensis* Peptides,” in *Antimicrobials in Pharmaceutical and Medicinal Research* (CRC Press, 2023), 19–47.

[55] M. H. Shahrajabian, Y. Kuang, H. Cui, L. Fu, and W. Sun, “Metabolic Changes of Active Components of Important Medicinal Plants on the Basis of Traditional Chinese Medicine Under Different Environmental Stresses,” *Current Organic Chemistry* 27, no. 9 (2023): 782–806, https://doi.org/10.2174/1385272827666230807150910.

[56] J. C. Dhami, D. R. Katuwal, K. R. Awasthi, and K. S. Dhami, “Effect of Different Post-harvest Treatments on Quality and Shelf Life of Tomato (Lycopersicon esculentum Mill.) Fruits During Storage,” *Nepalese Horticulture* 17, no. 1 (2023): 41–48, https://doi.org/10.3126/nh.v17i1.60631.

[57] P. Brat, C. Bugaud, C. Guillermet, and F. Salmon, “Review of Banana Green Life Throughout the Food Chain: from autocatalytic Induction to the Optimisation of Shipping and Storage Conditions,” *Scientia Horticulturae* 262 (2020): https://doi.org/10.1016/j.scienta.2019.109054.

[58] H. Liu, J. Cao, and W. Jiang, “Changes in Phenolics and Antioxidant Property of Peach Fruit During Ripening and Responses to 1-methylcyclopropene,” *Postharvest Biology and Technology* 108 (2015): 111–118, https://doi.org/10.1016/j.postharvbio.2015.06.012.

[59] M. H. Shinga and O. A. Fawole, “*Opuntia Ficus indica* Mucilage Coatings Regulate Cell Wall Softening Enzymes and Delay the Ripening of Banana Fruit Stored at Retail Conditions,” *International Journal of Biological Macromolecules* 245 (2023): https://doi.org/10.1016/j.ijbiomac.2023.125550.

[60] J. Ruiz-Martínez, J. A. Aguirre-Joya, R. Rojas, et al., “Candelilla Wax Edible Coating with *Flourensia cernua* Bioactives to Prolong the Quality of Tomato Fruits,” *Foods* 9, no. 9 (2020): 1303, https://doi.org/10.3390/foods9091303.

[61] Z. S. Safari, P. Ding, J. Juju Nakasha, and S. F. Yusoff, “Combining Chitosan and Vanillin to Retain Postharvest Quality of Tomato Fruit During Ambient Temperature Storage,” *Coatings* 10, no. 12 (2020): 1222, https://doi.org/10.3390/coatings10121222.

[62] S. Shah and M. S. Hashmi, “Chitosan–Aloe Vera Gel Coating Delays Postharvest Decay of Mango Fruit,” *Horticulture, Environment, and Biotechnology* 61, no. 2 (2020): 279–289, https://doi.org/10.1007/s13580-019-00224-7.

[63] J. M. Vieira, M. L. Flores-López, D. J. de Rodríguez, M. C. Sousa, A. A. Vicente, and J. T. Martins, “Effect of chitosan–Aloe Vera Coating on Postharvest Quality of Blueberry (Vaccinium corymbosum) Fruit,” *Postharvest Biology and Technology* 116 (2016): 88–97, https://doi.org/10.1016/j.postharvbio.2016.01.011.

[64] M. Vanaei, M. Kiani, M. Ghasemi, and A. M. Azar, “Effects of Chitosan and Aloe vera Gel Coating on Quality Characters of Pistachio,” *Journal of Nutritional Health & Food Engineering* 2, no. 1 (2015): 17–20, https://doi.org/10.15406/jnhfe.2015.02.00042.

[65] C. Adetunji, A. Fadiji, and O. Aboyeji, “Effect of Chitosan Coating Combined Aloe vera Gel on Cucumber (*Cucumis sativa L.*) Post-harvest Quality During Ambient Storage,” *Journal of Emerging Trends in Engineering and Applied Sciences* 5, no. 6 (2014): 391–397.

[66] Y. Lai, W. Wang, J. Zhao, et al., “Chitosan Na-montmorillonite Films Incorporated with Citric Acid for Prolonging Cherry Tomatoes Shelf Life,” *Food Packaging and Shelf Life* 33 (2022): https://doi.org/10.1016/j.fpsl.2022.100879.