Article

Influence of Nano-Silica/Chitosan Film Coating on the Quality of ‘Tommy Atkins’ Mango

Hazem S. Kassem ^{1,*} , Mohamed E. Tarabih ² , Hamed Ismail ³ and Eman E. Eleryan ² ¹ Department of Agricultural Extension and Rural Society, College of Food and Agriculture Sciences, King Saud University, Riyadh 11451, Saudi Arabia² Fruit Crops Handling Research Department, Horticulture Research Institute, Agricultural Research Center, Giza 12619, Egypt; mohamedtarabih@arc.sci.eg (M.E.T.); emaneleryan@arc.sci.eg (E.E.E.)³ Department of Food Science, Ontario Agricultural College, University of Guelph, Guelph, ON N1G-2W1, Canada; ismailh@uoguelph.ca

* Correspondence: hskassem@ksu.edu.sa; Tel.: +966-581-045-671

Abstract: In this study, we assessed the coating of ‘Tommy Atkins’ mangoes with films containing chitosan and nano-silicon dioxide in terms of the effects on fruit parameters as an indicator of quality. After coating, the fruits were first stored at 13 ± 1 °C and 90–95% RH for 30 days, and then at 20 ± 2 °C and 70–75% RH for 5 days, which corresponds to the marketing period. The results showed that coating treatments significantly decreased the fruits’ weight loss and decay percentage compared to the uncoated control samples over the storage period. Additionally, all coated treatments delayed skin degreening, reduced endogenous ethylene production, suppressed respiration rate, and maintained the firmness, compared to untreated control fruit. Titratable acidity and vitamin C significantly decreased in all samples during storage, but this decrease was less pronounced in the coated fruits. Furthermore, coating can delay the increments in total soluble solids and total sugars while maintaining total phenolics, and high antioxidant content of fruits, thereby extending the effective length of the marketing period of treated fruits compared to the control. It was shown that the coating combination of 2% chitosan plus 1% nano-silicon dioxide was the most successful in maintaining the mango’s quality under cold storage and during marketing.

Keywords: ‘Tommy Atkins’ mango; *Mangifera indica* L.; chitosan; nano-silicon dioxide; postharvest; shelf life; edible coating; nanoparticles

Citation: Kassem, H.S.; Tarabih, M.E.; Ismail, H.; Eleryan, E.E. Influence of Nano-Silica/Chitosan Film Coating on the Quality of ‘Tommy Atkins’ Mango. *Processes* **2022**, *10*, 279. <https://doi.org/10.3390/pr10020279>

Academic Editors: Tobi Fadiji and Pankaj B. Pathare

Received: 13 December 2021

Accepted: 28 January 2022

Published: 30 January 2022

Publisher’s Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The mango (*Mangifera indica* L.) is an ancient fruit grown in many parts of the world, especially in tropical and subtropical regions [1], with an annual global production of over 55 million metric tons in 2018 [2]. Mangoes are exported at a high rate due to their attractive taste and aroma, nutritional value, and economic viability [3,4]. Egypt’s geographical location gives the country a vast advantage in exporting mango to more than 50 countries. Egypt’s mango exports have risen to 53,000 tons annually, making it the second-most exported fruit in Egypt, after the orange [5]. The essence of the fresh fruit trade is to deliver the fruit from the field to the end customer’s table in the shortest possible time. Mangoes are perishable fruits; thus, poor postharvest handling and sensitivity to chilling injuries contribute to high losses and reduce their storage life and marketing period [6].

The shelf life of mango fruits depends on harvest maturity, where the respiration peak of the ripening process occurs at ambient room temperatures on the third or fourth day after harvesting [7,8]. The ripening development of mango fruit includes a sequence of biochemical reactions resulting in higher respiration, water loss, and the degradation of polymers into simpler compounds, thereby leading to the softening of texture, shrinkage, and loss of nutritional value [9,10]. Moreover, mango shelf life, whether for the inner or export market, varies from 5 to 10 days at room temperature and is approximately a

month in cold storage at 13 °C [11]. In this respect, various technologies have been used to preserve the quality of postharvest mangoes and extend their shelf life. These technologies include cold storage, evaporative cooling, modified atmosphere packaging, and storage in a controlled atmosphere, even though these technologies can result in negative effects, such as chilling injuries and environmental pollution [12].

In light of these adverse effects, edible coatings appear to be a superior choice for handling fruit that can extend their marketing period [12]. They consist of natural biodegradable materials that form a thin film as a preservation strategy to protect the coated fruit [13]. An ideal coating can extend the shelf life of fresh fruit and reduce decay while maintaining the fruit's quality. The rates of respiration and weight loss of mango fruits stored at 12 ± 1 °C for 4 weeks were found to be significantly reduced by coating treatments. The mango's freshness was also preserved while significantly increasing total phenol, flavonoid, and antioxidant activity [14].

Moreover, an edible coating regulates gaseous exchange on the surface of the fruit and limits the amount of water loss through transpiration. Currently, the value of the edible coating is being enhanced at the nanoscale. Nanotechnology treatments can be used to advance the material properties as well as the mechanical, thermal, barrier, and physicochemical properties [15].

Chitosan is a high molecular weight cationic polysaccharide typically obtained from the alkaline deacetylation of chitin found in the exoskeleton of crustaceans, fungal cell walls, and other biological materials. Chitosan has great potential for use as a semi-permeable coating on numerous types of fruits to extend their storage life and reduce postharvest decay [16]. Furthermore, it produces a modified atmosphere for controlling weight loss and metabolic activities as well as protects against microbial attacks during cold storage [17]. Moreover, it shows direct antifungal activity against numerous fungi by inhibiting mycelial growth and spore germination and inducing morphological changes in the hyphae [18]. The edible coatings of hydroxypropyl methylcellulose and beeswax in 'Palmer' mangoes were found to control ripening, and maintain peel and pulp colors, firmness, total soluble solids, titratable acidity, sugars, ascorbic acid, phenolic compounds, flavonoids, and antioxidant activity [19]. Moreover, they were found to reduce weight loss, oxidative stress, and the anthracnose incidence when stored for 15 days at 21 °C.

Chitosan nanoparticles have an advantage over common chitosan due to the increased surface-to-volume ratio, resulting in increased particle activity and efficiency [20]. Thus, nano-coatings can delay postharvest aging by protecting cell membrane structures [21]. Chitosan nanoparticles have been applied to improve banana fruit marketing quality, reducing weight loss, and increasing the content of total soluble solids [22]. In comparison to regular bulk chitosan, adding chitosan nanoparticles to strawberries was more effective in reducing weight loss and increasing antioxidant activity after 21 days of cold storage [23]. In addition, chitosan nanoparticles positively retain firmness in tomato fruits, limiting the loss of ascorbic acid and phenolic compounds by increasing antioxidant system activity during storage [24]. The application of chitosan-aloe vera coatings to Anwar Ratol mango reduced weight loss, delayed firmness loss, minimized pH change, maintained total soluble solid contents, and retained free radical scavenging activity and total phenolic contents during storage [25].

Silicon is a component of sand that is found naturally in quartz. Sami, et al. [26] showed that coating mushrooms with nano-silica and chitosan films had beneficial impacts on their quality and oxidation activities. A nano-silica coating can efficiently reduce oxidation activities, respiration, and reactive oxygen species during cold storage. Lately, there has been a growing interest in the applications of nano-films or coatings to extend the shelf life of products such as fresh fruits. Cantaloupe pieces coated with chitosan/nano-silicon dioxide films demonstrated improvements in terms of better browning activity of polyphenol oxidase (PPO) (0.26 U/min/g) and lower water activity (A_w) (0.89) compared to their uncoated counterparts. The use of nano-coating films improved both titratable acidity and total soluble solid content [27]. Nanoparticles may exhibit different properties

compared to the bulk material due to their small size, greater surface area-to-weight ratio, and various shapes.

The use of chitosan/nano-silicon dioxide coatings can enhance anti-fungal abilities and extend the shelf life of fresh blueberries by reducing the microbial population during marketing [28]. A chitosan/nano-silica coating has been shown to be efficient in raising the chilling tolerance and prolonging storage life of loquat fruit, which also had satisfactory quality [29]. Therefore, the objective of this research was to examine the effect of edible coatings made of chitosan (CTS), chitosan nanoparticles (CTS/N), and nano-silicon dioxide (NSD) on the postharvest quality of ‘Tommy Atkins’ mangoes during cold storage and marketing.

2. Materials and Methods

2.1. Fruit Material

The ‘Tommy Atkins’ mangoes were harvested at physiological maturation (external appearance of the fruit being 75% green and 25% purple) between 125 and 135 days of flowering [30], throughout the 2018 and 2019 seasons, from a commercial confidential orchard located in the New Salheya region (30.629774° N 31.941019° E), Al-Sharqia Governorate, Egypt. The fruits were harvested from 8-year-old trees grown in sandy soil and planted in a 2 m × 5 m plot. Fruits of uniform size and without deformities were chosen and then transported to the postharvest laboratory in the fruit handling department of the Horticulture Research Institute. The fruits were cleaned with water and air dried. A sample of 15 fruits was used to establish their initial characteristics. Mature, uniformly sized mango fruits, free of mechanical damage, were selected for coating application.

2.2. Chemicals

Chitosan (85% deacetylation), nano-silicon dioxide (purity > 99 wt%; 15 nm), acetic acid, and glycerol were supplied by Sigma–Aldrich (St. Louis, MO, USA). Ethanol (C₂H₅OH, 100%), sodium chloride (NaCl, 99.8%), sodium hypochlorite (NaClO/H₂O, 12/13%), hydrogen chloride (HCl), phenolphthalein, methanol, and 2,6-dichlorophenolindophenol were purchased from the El-Gomhorya Company for Chemicals and Pharmaceuticals, Cairo, Egypt.

2.3. Preparation of Edible Coatings Film

Coating solutions were prepared according to Rokayya, et al. [31]. The chitosan film coating component was prepared by dissolving 2% chitosan (85% deacetylation) in 1% acetic acid and 0.5% glycerol solution in deionized water. The coating film was stirred overnight at 300 rpm for 10 h, then centrifuged at 4 °C for 30 min to separate the supernatant and strip insoluble particles.

Nano chitosan particles were prepared by the addition of 1 mL aqueous tri polyphosphate solution (0.25%, *w/v*) to 1 mL of chitosan solution under magnetic stirring. The nano chitosan particle size has been characterized and described by Qi, et al. [32].

Silicon was used as a form of silicate and to purify nano-silicon [33], the synthesized nano-silicon was treated with various methods such as reflux in an acid environment, resulting in nano-silicon bundles with ~99% purity. In the next stage, nano-silicon 8–15 nm in diameter and >10 µm long were suspended in water by sonicating the silicon bundles using an ultrasonicator at 10 mhz for ~30 min resulting in a partially homogeneous solution. A silica solution film (nano-silicon dioxide) was prepared by dissolving 1% nano-silicon dioxide in water. Chitosan/nano-silicon dioxide (CTS/NSD) film was prepared by blending 1% nano-silicon dioxide in 2% chitosan solution.

The structure and properties of the key elements used for preparing chitosan and nano-silicon dioxide are included in Table 1 [34,35].

Table 1. The structure and properties of the key elements used for preparing chitosan (a) and nano-silicon dioxide (b).

<p>(a) CAS Registry Number: 9012-76-4 Mol weight: 50,000–190,000 Da (based on viscosity) Viscosity: 20–300 cP, 1 wt.% in 1% acetic acid (25 °C, Brookfield)(lit.) Solubility: Dilute aqueous acid: soluble</p>	<p>(b) CAS Registry Number: 7631-86-9 Chemical formula: SiO₂ Molar mass: 60.08 g/mol Density: 2.648 (α-quartz), 2.196 (amorphous) g cm^{−3} Melting point: 1.713 °C (Amp) Thermal conductivity: 12 (c-axis), 6.8 (⊥ axis), 1.4 (am.) W/(m·K)</p>

2.4. Treatment and Coating Application

Using a completely randomized design, mango fruits were divided into 5 groups (3 replicates, 20 fruits each, with 60 fruits in each storage period). Based on the concentrations used in previous studies, different concentrations were used in the pre-study (0.5, 1, 1.5, 2, and 2.5%). The best concentrations that gave a favorable result on the fruits were selected in the experiment. The fruits were dipped into various coating solution film for 10 min (2% chitosan, 1% chitosan nanoparticles, and 1% nano-silicon dioxide each alone) while, chitosan/nano-silicon dioxide film was prepared by blending 1% nano-silica in 2% chitosan solution, then dried by an electric fan to lose excess moisture at the ambient temperature compared with the control samples, which were treated with distilled water as follows:

T1	2% Chitosan
T2	1% Chitosan nanoparticles
T3	1% Nano-silicon dioxide
T4	2% Chitosan + 1% Nano-silicon dioxide
T5	Control (dipping fruits with distilled water)

2.5. Storage Conditions

The fruits were spread on a nylon net and air dried until completely dry and then stored in single-layer carton boxes at 13 ± 1 °C and 90–95% relative humidity (RH) for 30 days. Afterward, the fruits were stored at 20 ± 2 °C and 70–75% RH for 5 days, which represents the conditions of the marketing period. At the end of the storage period, the fruits were analyzed in terms of their physical and chemical characteristics.

2.6. Fruit Quality Attributes

2.6.1. Weight Loss Percentage

The weight loss was determined by application of Equation (1):

$$\text{Weight loss \%} = \frac{\text{Initial fruit weight} - \text{Final fruit weight}}{\text{Initial fruit weight}} \times 100\% \quad (1)$$

2.6.2. Decay Percentage

All decayed fruits were calculated by Equation (2) as follows:

$$\text{Decay \%} = \frac{a \times 100}{b} \quad (2)$$

where a = number of decayed fruits; b = number of initial fruits.

2.6.3. Hue Angle Skin Color (h°)

Peel color was determined using a Chroma Meter model CR-410[®]k colorimeter (Konica-Minolta, Japan). Determinations were performed utilizing the arrangement of CIEL, a^* , b^* , and the color tone was assessed utilizing the techniques outlined by McGuire [36] by Equation (3) as follows:

$$(h^\circ) = \tan^{-1} \left(\frac{b}{a} \right) \quad (3)$$

where a = color intervals among green (−) and red (+); b = color intervals among blue (+) and yellow (−).

2.6.4. Fruit Firmness (lb inch^{-2})

Fruit firmness was assessed using a Magness Taylor penetrometer (pressure tester). Readings were recorded at three different places in Newtons (N).

2.6.5. Ethylene Production

The ethylene production was measured according to Pristijono, et al. [37], where mangoes were transferred to a sealed 1500 mL hermetic glass jar with a septum in the lid at 20 °C. After one hour, a gas sample (1 mL) was collected in a syringe, and the ethylene content was analyzed. Ethylene was measured by injecting a gas sample into a flame ionization gas chromatograph (Gow-Mac 580, Bridgewater, NJ, USA) fitted with a stainless steel column (2 m × 3.2 mm outer diameter (OD) × 2.2 mm internal diameter (ID)) packed with Porapak Q (80–100 mesh) (Altech, Sydney, Australia), with 110, 90, and 70 °C as the operating temperature of the detector, column, and the injector, respectively. Nitrogen, hydrogen, and air were used as carrier and combustion gases at flow rates of 60, 30, and 300 mL min^{−1}, respectively. The ethylene concentration was calculated with reference to the concentration of an ethylene standard. The ethylene production rate was calculated by Equation (4) and expressed as $\mu\text{L C}_2\text{H}_4 \text{ kg}^{-1} \text{ h}^{-1}$.

$$\text{Ethylene production } \mu\text{L C}_2\text{H}_4 \text{ kg}^{-1} \text{ h}^{-1} = \frac{\text{C}_2\text{H}_4 \mu\text{L} \times \text{volume of container (L)}}{\text{Initial produce weight (kg)} \times \text{time (h)}} \quad (4)$$

2.6.6. Respiration Rate

A gas sample (5 mL) was obtained for analysis 1 h after sealing the glass jars as previously described for ethylene production, and carbon dioxide concentration was measured to within 0.1% using an ICA40 series low-volume gas analysis system (International Controlled Atmosphere Ltd., Kent, UK). Respiration rate was calculated by Equation (5) and expressed as mL CO₂ kg^{−1} h^{−1} [37].

$$\text{Respiration Rate mL CO}_2 \text{ kg}^{-1} \text{ h}^{-1} = \frac{\text{CO}_2\% \times \text{Volume of container (mL)}}{\text{Initial produce weight (kg)} \times 100 \times \text{time (h)}} \quad (5)$$

2.6.7. Total Soluble Solid (TSS) %

One milliliter of mango juice was dissolved in 40 mL distilled water. TSS (%) was calculated with a Carl Zeiss hand refractometer in the Brix scale [38].

2.6.8. Titratable Acidity (TA) %

Titrateable acidity was determined according to A.O.A.C. [39]. The outcomes were conveyed as a fraction of citrus acid (g citrus extract/100 g new weight).

2.6.9. Vitamin C Content ($\text{mg } 100 \text{ g}^{-1} \text{ FW}$)

Vitamin C was determined by the oxidation of ascorbic acid with 2,6-dichlorophenolindophenol, and the results were articulated as mg 100 g^{−1} fresh weight (FW) according to A.O.A.C. [39].

2.6.10. Total Sugar (%)

Total sugar was assessed using the Lane and Eynon titration method, according to James [40]. Five grams of the sample was placed into a beaker and 100 mL of warm water was added. The solution was stirred until all the soluble matter was dissolved, then filtered through Whatman filter paper into a 250 mL volumetric flask. After that, 100 mL of the solution was pipetted into a conical flask, and then mixed with 10 mL of diluted hydrogen chloride and boiled for 5 min. On cooling, the solution was neutralized to phenolphthalein with 10% NaOH and added to a 250 mL volumetric flask. This solution was used for titration against Fehling's solution, and readings were considered as follows in Equation (6):

$$\text{Total sugar \%} = \frac{\text{factor (4.95)} \times \text{dilution (250)} \times 2.5}{\text{titer} \times \text{weight of sample} \times 10} \times 100 \quad (6)$$

2.6.11. Total Phenolic Content (mg g⁻¹ FW)

Total phenolics were estimated according to [41]. The absorbance was estimated at 750 nm as mg g⁻¹ FW gallic acid equivalent.

2.6.12. Antioxidant % (DPPH Radical Assay of Fruit Peel)

The DPPH (2,2-diphenyl-1-picryl-hydrazyl-hydrate) free radical activity of the methanol extract of fruit peel was determined according to the methods of [42]. Methanol extract (0.1 mL) was added to 0.9 mL of freshly prepared DPPH methanol solution (0.1 mM). The activity of DPPH % was determined as follows in Equation (7):

$$\text{DPPH radical scavenging (\%)} = \left[\left(\frac{\text{Absorbance of control} - \text{Absorbance of sample}}{\text{Absorbance of control}} \right) \times 100 \right] \quad (7)$$

The inhibition absorption (IC₅₀) is defined as µg of the phenolics of the test sample that causes a decrease to 50% of the initial radical compounds. The IC₅₀ values were measured from the dose–response curves.

2.6.13. Sensory Evaluation/Organoleptic Test of Fruits

Organoleptic evaluation of ripe fruits was carried out by a panel of semi-trained judges [43]. The sensory characteristics, such as skin color, pulp color and appearance, pulp texture, taste and flavor, and overall acceptability, were evaluated on a 9-point Hedonic scale using the score card, as mentioned in Table 2. The mean of scores given by the judges was used for statistical analysis.

Table 2. Hedonic scale rating for various sensory attributes.

Scale	Peel Color and Appearance	Pulp Color and Appearance	Pulp Texture	Pulp Taste and Flavor	Overall Acceptability
1	Poor	Poor	Poor	Poor	Poor
3	Fair	Fair	Fair	Fair	Fair
5	Good	Good	Good	Good	Good
7	Very good	Very good	Very good	Very good	Very good
9	Excellent	Excellent	Excellent	Excellent	Excellent

2.7. Statistical Analysis

The experiment was carried out with a completely randomized design. The normality of data distribution was evaluated using the Shapiro–Wilk test. A one-way ANOVA test was performed to test the differences between treatments within the same storage period, and specific differences between pairs of means were measured using Duncan's multiple range test at ($p \leq 0.05$) [44] using the statistical software program, CoStat (version 6.4). The results were plotted as the mean $\pm$ standard error (SE) using Sigma Plot (version 14.0, Systat Software, Inc., San Jose, CA, USA).

3. Results

3.1. Weight Loss %

According to the results in Figure 1, the weight loss percentage of the ‘Tommy Atkins’ fruits increased significantly during cold storage and marketing. Weight loss was significantly lower in all treatments when compared to the control sample. The greatest weight loss percentage was observed in the control (6.71%) after 30 days of cold storage, while 8.31% was lost after 5 days of marketing at 20 °C. Conversely, the fruits coated with chitosan 2% + nano-silicon dioxide 1% showed a decrease in weight loss values (3.73%) after 30 days of cold storage, as well as a loss of 4.16% after 5 days of marketing at 20 °C.

Figure 1. Weight loss percentage as a mean of ‘Tommy Atkins’ mangoes from two seasons, stored at 13 ± 1 °C and 90–95% RH for 30 days. Afterward, the fruits were stored at 20 ± 2 °C and 70–75% RH for 5 days as the marketing period. Vertical bars indicate the standard error (SE) of the mean ($n = 5$). The superscript letters followed by the same letters are not significantly different according to Duncan’s multiple range test at 0.05 level.

3.2. Decay Percentage

The results in Figure 2 demonstrate that all the treatments reduced the decay percentage of the ‘Tommy Atkins’ fruits during storage compared to the control. Regardless of the storage intervals, no decayed fruits were recorded before 15 days of cold storage in any of the treatments. After 30 days of cold storage, the mangoes coated with chitosan 2% + nano-silicon dioxide 1% demonstrated the least percentage of decay (5.0%). After the same time period, the control fruits had the highest percentage of decay (14.0%). On the other hand, the mango fruits coated with chitosan 2% + nano-silicon dioxide 1% had the lowest decay (8.04%) during marketing, after 5 days at 20 °C. Furthermore, the control fruits had the highest decay (32.90%) at the end of the marketing period for both seasons.

3.3. Skin Hue Color (h°)

The data in Figure 3 indicate that all treatments slowed the evolution of fruit skin color compared with the untreated fruits. During the storage period, the green hue of the mangoes gradually disappeared. On the other hand, green color values in the fruits were nearly as low during marketing as in cold storage. In untreated fruits, the values of hue color were rapidly reduced, which indicated a loss of green color at the end of cold storage (80.0 h°) and at 5 days of marketing (69.0 h°). Furthermore, chitosan 2% + nano-silicon dioxide 1% retained a darker skin color following cold storage (105.0 h°) and marketing (92.0 h°) than the other treatments or the control.

Figure 2. Decay percentage as a mean of ‘Tommy Atkins’ mangoes from two seasons, stored at 13 ± 1 °C and 90–95% RH for 30 days. Afterward, the fruits were stored at 20 ± 2 °C and 70–75% RH for 5 days as the marketing period. Vertical bars indicate the standard error (SE) of the mean ($n = 5$). The superscript letters followed by the same letters are not significantly different according to Duncan’s multiple range test at 0.05 level.

Figure 3. Skin color hue angle (h°) as a mean of ‘Tommy Atkins’ mangoes from two seasons, stored at 13 ± 1 °C and 90–95% RH for 30 days. Afterward, the fruits were stored at 20 ± 2 °C and 70–75% RH for 5 days as the marketing period. Vertical bars indicate the standard error (SE) of the mean ($n = 5$). The superscript letters followed by the same letters are not significantly different according to Duncan’s multiple range test at 0.05 level.

3.4. Fruit Firmness (N/cm)

As displayed in Figure 4, fruit firmness was influenced by the duration of storage periods and the treatments used. The applied treatments significantly increased the solidity of the fruits compared to the untreated fruits, regardless of the storage period. Fruit firmness, on the other hand, drastically decreased as storage duration increased. In this respect, the highest firmness (8.54 N/cm) was attained for chitosan 2% + nano-silicon dioxide 1% after cold storage and at the end of marketing (6.75 N/cm).

Figure 4. Fruit firmness (N/cm) as a mean of ‘Tommy Atkins’ mangoes from two seasons, stored at 13 ± 1 °C and 90–95% RH for 30 days. Afterward, the fruits were stored at 20 ± 2 °C and 70–75% RH for 5 days as the marketing period. Vertical bars indicate the standard error (SE) of the mean ($n = 5$). The superscript letters followed by the same letters are not significantly different according to Duncan’s multiple range test at 0.05 level.

3.5. Ethylene Production ($\mu\text{L C}_2\text{H}_4 \text{ kg}^{-1} \text{ h}^{-1}$)

As displayed in Figure 5, the ethylene production rates of mango fruits showed that coated treatments suppressed ethylene production during storage. It means that the coated treatments significantly delayed fruit ripening by inhibiting ethylene production during storage compared to the untreated fruits, regardless of the storage period. The results showed that stored mango fruit treated with chitosan 2% + nano-silicon dioxide 1% slowed endogenous ethylene production than all coated treatments or the control after 30 days of cold storage ($0.013 \mu\text{L C}_2\text{H}_4 \text{ kg}^{-1} \text{ h}^{-1}$) and after 5 days at marketing ($0.010 \mu\text{L C}_2\text{H}_4 \text{ kg}^{-1} \text{ h}^{-1}$).

3.6. Respiration Rate $\text{mL CO}_2 \text{ kg}^{-1} \text{ h}^{-1}$

The data in Figure 6 indicate that mango respiration rate was increased during ripening. In this respect, respiration rates across all treatments and storage periods ranged from 41.40 to 69.80 $\text{mL CO}_2 \text{ kg}^{-1} \text{ h}^{-1}$. After 30 days of cold storage and 5 days at marketing, the untreated fruit had significantly higher respiration rates than coated fruits. These results suggest that chitosan 2% + nano-silicon dioxide 1% treatment maintained mango fruit quality by reducing the respiration rate after 30 days of cold storage ($48.5 \text{ mL CO}_2 \text{ kg}^{-1} \text{ h}^{-1}$) and after 5 days at marketing ($51.20 \text{ mL CO}_2 \text{ kg}^{-1} \text{ h}^{-1}$).

Figure 5. Ethylene production ($\mu\text{L C}_2\text{H}_4 \text{ kg}^{-1} \text{ h}^{-1}$) as a mean of ‘Tommy Atkins’ mangoes from two seasons, stored at $13 \pm 1^\circ \text{C}$ and 90–95% RH for 30 days. Afterward, the fruits were stored at $20 \pm 2^\circ \text{C}$ and 70–75% RH for 5 days as the marketing period. Vertical bars indicate the standard error (SE) of the mean ($n = 5$). The superscript letters followed by the same letters are not significantly different according to Duncan’s multiple range test at 0.05 level.

Figure 6. Respiration rate $\text{mL CO}_2 \text{ kg}^{-1} \text{ h}^{-1}$ as a mean of ‘Tommy Atkins’ mangoes from two seasons, stored at $13 \pm 1^\circ \text{C}$ and 90–95% RH for 30 days. Afterward, the fruits were stored at $20 \pm 2^\circ \text{C}$ and 70–75% RH for 5 days as the marketing period. Vertical bars indicate the standard error (SE) of the mean ($n = 5$). The superscript letters followed by the same letters are not significantly different according to Duncan’s multiple range test at 0.05 level.

3.7. Total Soluble Solid (TSS %)

Figure 7 demonstrates that all storage periods and treatments had a significant effect on TSS %. Similarly, as storage progressed, the percentage of TSS increased, whereas the rate of TSS in the coated treatments was lower than in the untreated samples. Control fruits exhibited a higher TSS percentage than all treatments after 30 days of cold storage (14.30%) and 5 days of shelf life (15.60%). The smallest TSS % was observed for mangoes treated with chitosan 2% + nano-silicon dioxide 1%, since it scored 12.50% after cold storage and 13.80% during marketing.

Figure 7. Total soluble solid (TSS) % as a mean of ‘Tommy Atkins’ mangoes from two seasons, stored at 13 ± 1 °C and 90–95% RH for 30 days. Afterward, the fruits were stored at 20 ± 2 °C and 70–75% RH for 5 days as the marketing period. Vertical bars indicate the standard error (SE) of the mean ($n = 5$). The superscript letters followed by the same letters are not significantly different according to Duncan’s multiple range test at 0.05 level.

3.8. Titratable Acidity (TA)

Figure 8 shows that prolonging the cold storage duration and applying postharvest treatments had a substantial impact on TA in mangoes. All treatments demonstrated a progressive decline in titratable acidity during the storage period and at the end of marketing. Furthermore, when compared to all coated fruits, there was a decrease in TA in the control sample. In this regard, the mangoes treated with chitosan 2% + nano-silicon dioxide 1% had a greater TA (1.08%) after cold storage and during marketing (0.88%).

3.9. Vitamin C ($\text{mg } 100 \text{ g}^{-1} \text{ FW}$)

Compared with the control, all the applied treatments significantly slowed down the reduction of vitamin C until the end of the storage periods, as demonstrated in Figure 9, during either 30 days of cold storage or 5 days of marketing. While vitamin C levels in the control fruits decreased significantly as storage progressed, they ranged between $21.30 \text{ mg } 100 \text{ g}^{-1} \text{ FW}$ after cold storage and $16.0 \text{ mg } 100 \text{ g}^{-1} \text{ FW}$ at the end of marketing. The highest amount of vitamin C was obtained using chitosan 2% + nano-silicon dioxide 1%, which recorded $29.70 \text{ mg } 100 \text{ g}^{-1} \text{ FW}$ after cold storage and $22.0 \text{ mg } 100 \text{ g}^{-1} \text{ FW}$ at the end of marketing.

Figure 8. Titratable acidity (TA) % as a mean of ‘Tommy Atkins’ mangoes from two seasons, stored at 13 ± 1 °C and 90–95% RH for 30 days. Afterward, the fruits were stored at 20 ± 2 °C and 70–75% RH for 5 days as the marketing period. Vertical bars indicate the standard error (SE) of the mean ($n = 5$). The superscript letters followed by the same letters are not significantly different according to Duncan’s multiple range test at 0.05 level.

Figure 9. Vitamin C mg 100 g⁻¹ FW as a mean of ‘Tommy Atkins’ mangoes from two seasons, stored at 13 ± 1 °C and 90–95% RH for 30 days. Afterward, the fruits were stored at 20 ± 2 °C and 70–75% RH for 5 days as the marketing period. Vertical bars indicate the standard error (SE) of the mean ($n = 5$). The superscript letters followed by the same letters are not significantly different according to Duncan’s multiple range test at 0.05 level.

3.10. Total Sugar ($\text{mg } 100 \text{ g}^{-1} \text{ FW}$)

Total sugar levels gradually increased during cold storage, as shown in Figure 10. The control fruits had the greatest total sugar content (9.75%) after 30 days of cold storage, and it reached 11.50% during marketing. The nano-silicon dioxide 1% treatment produced the lowest significant sugar level (8.75%) after 30 days of cold storage, and it reached 10.56% at the end of marketing.

Figure 10. Total sugar % as a mean of ‘Tommy Atkins’ mangoes from two seasons, stored at 13 ± 1 °C and 90–95% RH for 30 days. Afterward, the fruits were stored at 20 ± 2 °C and 70–75% RH for 5 days as the marketing period. Vertical bars indicate the standard error (SE) of the mean ($n = 5$). The superscript letters followed by the same letters are not significantly different according to Duncan’s multiple range test at 0.05 level.

3.11. Total Phenolic Contents ($\text{mg } 100 \text{ g}^{-1} \text{ FW}$)

The data in Figure 11 show the interaction effects of the storage periods and applied treatments on the total phenolics. In this regard, all of the treatments used decreased the loss of total phenolics in the ‘Tommy Atkins’ mangoes considerably during storage. The data also reveal that the fruits treated with chitosan 2% + nano-silicon dioxide 1% had the greatest amounts of phenolic compounds over the storage period. Total phenolics in this treatment reached 19.85 mg g^{-1} after cold storage and 17.87 mg g^{-1} after 5 days of marketing.

3.12. Antioxidant % (DPPH Radical Scavenging Assay)

As shown in Figure 12, the major antioxidant percentage of the fruit was scaled using the DPPH method (IC₅₀ values). At the end of cold storage, untreated fruits exhibited a lower rate of antioxidant capacity (higher IC₅₀ values), reaching $10.80 \mu\text{g}$, whereas at the end of marketing, the value was $9.60 \mu\text{g}$. The extreme rate (lower IC₅₀ value) of antioxidant capacity was noticed after cold storage in fruits coated with chitosan 2% + nano-silicon dioxide 1% ($7.05 \mu\text{g}$), and it reached $6.20 \mu\text{g}$ at the end of marketing.

Figure 11. Total phenolics mg g⁻¹ FW as a mean of 'Tommy Atkins' mangoes from two seasons, stored at 13 ± 1 °C and 90–95% RH for 30 days. Afterward, the fruits were stored at 20 ± 2 °C and 70–75% RH for 5 days as the marketing period. Vertical bars indicate the standard error (SE) of the mean (n = 5). The superscript letters followed by the same letters are not significantly different according to Duncan's multiple range test at 0.05 level.

Figure 12. Antioxidant % (DPPH radical assay of fruit peel) as a mean of 'Tommy Atkins' mangoes from two seasons, stored at 13 ± 1 °C and 90–95% RH for 30 days. Afterward, the fruits were stored at 20 ± 2 °C and 70–75% RH for 5 days as the marketing period. Vertical bars indicate the standard error (SE) of the mean (n = 5). The superscript letters followed by the same letters are not significantly different according to Duncan's multiple range test at 0.05 level.

3.13. Sensory Evaluation/Organoleptic Test (Taste, Aroma, Texture, Flavor)

Organoleptic scores for peel color and appearance (Table 3) were at a maximum in the treatment chitosan 2% + nano-silicon dioxide 1% as a mean of both seasons after 5 days of marketing (7.80). The minimum score for peel color was associated with the control (4.43). The pulp color of mango, which was observed visually, obtained a maximum score in the treatment chitosan 2% + nano-silicon dioxide 1% (8.20) as a mean of both seasons after 5 days of marketing. The subsequent best scoring treatment was 1% nano-silicon dioxide (6.84) after 5 days of marketing. The control scored the least for pulp color and appearance (4.86) after 5 days of marketing. Mango texture revealed high scores for the treatment chitosan 2% + nano-silicon dioxide 1% (8.55) as a mean of both seasons after 5 days of marketing. This treatment was followed by 1% nano-silicon dioxide and 1% chitosan nanoparticles (6.92 and 6.77), respectively. The lowest score for texture was noted in the control (4.57) throughout the investigation. The taste and flavor of mango fruits recorded maximum scores in the treatment chitosan 2% + nano-silicon dioxide 1% (8.35). Throughout the investigation, the lowest score for taste and flavor was noted in the control (4.33). The results also revealed that the chitosan 2% + nano-silicon dioxide 1% treatment continued to score higher values for overall acceptability (8.22), registering significant differences among the rest of the treatments. The control's lowest score for overall acceptability was observed (4.55).

Table 3. Hedonic scale rating for various sensory attributes as a mean of ‘Tommy Atkins’ mangoes from two seasons, after stored for 5 days as the marketing period.

Treatments	Peel Color and Appearance	Pulp Color and Appearance	Pulp Texture	Pulp Taste and Flavor	Overall Acceptability
2% Chitosan	5.40 bc	5.71 bc	5.87 bc	5.89 bc	5.72 bc
1% Chitosan nanoparticles	6.40 b	6.54 b	6.77 b	6.51 b	6.55 b
1% Nano-silicon dioxide	6.74 b	6.84 b	6.92 b	6.44 b	6.73 b
2% Chitosan + 1% Nano-silicon dioxide	7.80 a	8.20 a	8.55 a	8.35 a	8.22 a
Control (dipped fruits with distilled water)	4.43 c	4.86 c	4.57 c	4.33 c	4.55 c

Values within the column with the same letter are not significantly different by Duncan multiple range test at $p \leq 0.05$.

4. Discussion

4.1. Weight Loss %

The results obtained in the present study show that the weight loss percentage of the ‘Tommy Atkins’ fruits increased during cold storage and marketing. The percentage of weight loss for all coated fruits was much lower than in the control sample. This demonstrates that the reduction in metabolic activity and moisture evaporation from skin led to the decreased loss in fruit weight [34]. A major factor that causes weight loss in fruit is water loss due to transpiration. Furthermore, the loss of a carbon atom through each cycle of the respiration process might also cause weight loss in fruit [16]. Coating substances prevent water loss from fruits by acting as a barrier for moisture between a fruit and its environment at ambient temperature, and nanoparticle films can reduce fruit transpiration and preserve the stiffness of cell walls in fresh fruits [45]. It has been found that chitosan helps maintain the quality of fruits and vegetables by preventing moisture and odor loss, and reducing transpiration, respiration rates, and ethylene production [17].

4.2. Decay Percentage

The findings also show that both weight reduction and decay incidence significantly increased during cold storage. Mangoes are climacteric fruits with higher levels of metabolic action, ethylene production, and respiration that hasten ripening after harvest. These procedures correspond with the occurrence of fruit weight loss, rapid softening due to decay, and browning of peels that shorten storability [46]. The ability of the chitosan coating to delay the ripening of mango fruits could improve their protection against pathogen infection during storage. Likewise, chitosan nanoparticles contain powerful

abiotic factors for plant resistance to the attacks from various pathogens. In addition, the enhanced resistance in fruits coated with chitosan may be related to the increment activities of defensive enzymes, such as chitinase, β -1,3-glucanase, and phenylalanine ammonia-lyase [47].

4.3. Skin Hue Color (h°)

The findings revealed that all of the treatments resulted in the retention of a darker fruit skin color compared to the untreated fruits. The pulp tissues of coated fruits have synergistic effects on slowing color pigment degradation; this preservation may be attributed to a decrease in respiration, slowing down the metabolic and enzymatic activities in the fruits during storage [38]. In this respect, Wongmetha and Ke [34] noted that water loss could improve the β -carotene pigmentation of mangoes during cold storage.

4.4. Fruit Firmness ($lb\ inch^{-2}$)

Regardless of the storage period, the applied treatments increased the solidity of the fruits considerably when compared to untreated fruits. Generally, fruit ripening is associated with softening and cell wall changes, resulting in increased pectin solubility. Therefore, the coating could maintain the firmness of fruits by reducing the activity of cell walls, and degrading enzymes, such as polygalacturonase, galactosidase, and pectin methylesterase [14].

4.5. Ethylene Production ($\mu L\ C_2H_4\ kg^{-1}\ h^{-1}$)

Mango is a climacteric fruit with a fast metabolism after harvest [48]. It means that CO_2 and ethylene production increase throughout the postharvest period. It is generally known that ethylene production during climacteric ripening drives signal transduction, which, in turn, activates the expression of genes that encode enzymes that catalyze ripening changes, such as color, flavor, texture, and scent, among others [49]. The ability of chitosan to delay ripening and senescence processes most likely reduces the development of latent infection indirectly. These effects could also be connected to lower internal oxygen levels, resulting in lower rates of ethylene synthesis and respiration [50].

4.6. Respiration Rate $mL\ CO_2\ kg^{-1}\ h^{-1}$

The mango has a short shelf life when stored at room temperature due to the rapid respiration rate and consequent ripening, limiting the marketing period in remote locations [19]. Edible coatings act as a physical barrier to O_2 , reducing the rate of fruit respiration. Thus, the decrease in the respiration rate diminished the activities of hydrolysis enzymes and impeded fruit softening [48]. Chitosan-based coatings act as a barrier film on the surface of the fruit, preserving the non-enzymatic antioxidant content during storage by altering the atmosphere around the fruit, and acting as semi-permeable barriers that limit gas exchange (C_2H_4 , CO_2 , and O_2). A low oxygen permeability in chitosan-coated fruits leads to the inhibition of the enzymes' activity in oxidative reactions of bioactive substances, resulting in significant alterations in respiratory pathway metabolism and a slowing of the ripening process due to the suppression of ethylene production [51].

4.7. Total Soluble Solid (TSS %)

Fruit softening is associated with systems that solubilize pectinic substances, such as starch and dissolvable sugars, and their involvement in the loss of water from the peel [52]. An edible coating delays fruit ripening as a reaction to a change in internal levels of CO_2 , O_2 , and ethylene in the fruits. Due to this delay, chitosan can form a semi-porous film that modifies the interior climate of the fruit by acting as a barrier for oxygen uptake and, thus, slowing the metabolic action and ripening process. Subsequently, the respiratory pace of the fruits can be slowed, and the storage life is prolonged by the amassed CO_2 and diminished O_2 in the fruits as a result of semi-permeability of the chitosan coating [53]. During cold storage, the total sugar levels gradually increased. The activities of the enzymes, in this

regard, were responsible for starch hydrolysis in the dissolvable sugars, which might have resulted in a raised TSS %. In addition, during the respiration process, a decline in carbohydrates, pectin, and the partial hydrolysis of protein occurred, which led to the increase in the TSS % [54]. The variation in the total soluble solid percentage during storage may be due to the hydrolysis of complex carbohydrates in the cell wall. Likewise, the reduction in the TSS % in coated fruits was probably due to the decelerated metabolic activities as a result of respiration and evaporation [55]. On the other hand, a highly negative correlation with pulp firmness and a strongly positive correlation with the total sugar content were observed in the mango fruits coated with chitosan [53].

4.8. Titratable Acidity (TA)

The findings indicated that all treatments exhibited a continuous decrease in titratable acidity during storage and at the end of marketing. Thus, fruits coated in higher concentrations had inhibited respiration and, therefore, the rate of utilization of the respiratory substrates, such as organic acids, was minimal. Likewise, lower fruit acidity was also attributable to postharvest treatments that delayed respiration and slowed metabolic response mechanisms, reducing the usage of respiratory substrates, such as organic acids [56]. The declining trend in fruit acidity is associated with a reduction in organic acids as a result of respiration reactions. Therefore, coating the fruits led to limiting of organic acid turnover into sugars [53]. On the other hand, the inverse relationship between TSS and TA percentages was observed due to the decrement in acidity through the metabolic process until the end of storage [57]. Likewise, apple fruits coated with 1.5% chitosan were firmer, had higher titratable acidity and ascorbic acid, as well as lower weight loss and TSS [57]. The chitosan–pullulan composite edible coating maintained total soluble solids (TSS), acidity, and pH of coated mango fruits [16].

4.9. Vitamin C ($\text{mg } 100 \text{ g}^{-1} \text{ FW}$)

Vitamin C significantly declined as the storage prolonged because of the actions of phenol oxides and ascorbic acid oxidase enzymes through cold storage [58]. Vitamin C degrades quickly at ambient temperatures because there are numerous respective enzymes that are present. This could be due to the involvement of multiple metabolic pathways, such as the synthesis of ethylene, oxalate, and tartrate [59]. Nano-coating combination films may protect the ascorbic acid contents by limiting gas exchange and respiration rates with the environment, inhibiting the ascorbic acid exposure to O_2 and concentrating it in the fruit [60].

4.10. Total Sugar ($\text{mg } 100 \text{ g}^{-1} \text{ FW}$)

The ripening of mango fruits is characterized by changes in textural softening, sugar content, and surface color. The results showed that nano-silicon dioxide successfully deferred the ripening of the mangoes, as specified by the preservation of firmness, delay in color change, total sugar increase, and inhibition of respiration rates [61]. The data also revealed that the sugar content negatively correlated with titratable acidity (TA) and fruit firmness. The increment in the total sugars of the control fruits during storage can be demonstrated as a result of the changes in biochemical activity through the respiratory process, while the coating treatments slowed ripening processes and increased the fruit shelf life [53].

4.11. Total Phenolic Contents ($\text{mg } 100 \text{ g}^{-1} \text{ FW}$)

The results also showed that the phenolic components in mango fruits rapidly decreased during cold storage. The decrease in these phenols might be due to the action of polyphenol oxidase, which led to the breakdown of cell structures during ripening. Phenolic compounds are affected by diverse biotic and abiotic stresses, including chilling injuries [62]. The capacity of total phenolics is a determinant to retain the nutritional quality of fruits, including astringency, color, bitterness, and flavor, enhance resistance, and

limit disease growth. Additionally, phenolic compounds are essential in the scavenging of reactive oxygen species (ROS) to boost the antioxidant activity of fruits [14]. In this respect, chitosan nanoparticles could prevent the increase in PPO activity in treated fruit by activating the antioxidant enzymes and preserving the stability of the cell membrane [34]. Moreover, fruit treated with nano-SiO₂/chitosan showed a lower amount of PPO activity compared to the chitosan treatment alone [34]. The current findings were similarly in line with those of [28], who found that chitosan, gum Arabic, and alginate coatings improved the preservation of total phenolics in carambola fruit during storage [55].

4.12. Antioxidant % (DPPH Radical Scavenging Assay)

Fruit antioxidant activities increase with age, and these increases may be linked to changes in lipophilic antioxidant activity. Similarly, the increment in the antioxidant capacity (lower IC₅₀ values) during storage supports the findings of Kondo, et al. [63], who found that the DPPH activity (IC₅₀ values) of mangoes increased over 10 days at 6 and 12 °C. Furthermore, antioxidant enzymes, such as peroxidase (POD), superoxide dismutase (SOD), and ascorbate peroxidase (APX), were important in preventing postharvest oxidative stress [64]. Antioxidants in fruits must be kept throughout storage to maintain the overall attributes required for quality. The chitosan coating increases antioxidants in various fruits by raising the potential of reactive oxygen species. Moreover, coating fruits can also keep their antioxidant properties by removing oxygen-free radicals and decreasing respiration during storage [65]. The findings of this study indicate that coating mango fruits with chitosan/nano-silicon dioxide to extend their freshness is a viable alternative for the future.

4.13. Sensory Evaluation/Organoleptic Test

Sensory evaluation is critical in determining a fruit's suitability for consumption, which is especially significant for mangoes, where the color of the fruit is one of the essential quality indicators. Color variations in mangoes are principally connected with the breakdown and synthesis of various chemicals, including carotenoids in fruit. Thus, mangoes' peel color changes from green to yellow during ripening [66]. Flavor is the sensory impression of a food or other substance and is mainly determined by the chemical senses of taste and smell. Variations in mango flavor could be attributed to a variety of components (cisocimene and myrcene) that affect the unripe mango's characteristic green scent. During mango ripening, transformational changes in fatty acid composition, particularly from palmitic to palmitoleic acid, may be linked to changes in aroma and flavor qualities [67]. Furthermore, fruit sensory attributes, including freshness, color, flavor, and texture, have been found to be retained by chitosan composite edible coating [16]. The human perception of flavor is mainly attributed to organic acids and sugar ratio. Furthermore, pH, acidity, and TSS are highly linked to sourness and astringency [68]. Previous studies have shown the change in mango flavor to be attributed to storage duration. In this context, Abbasi, et al. [69] found that after four weeks of storage, the mango taste score increased from 3.54 to 8.42. Another study conducted by Kaswija, et al. [70] found that the degree of ripeness of the fruit is critical in determining its sensory attributes and acceptance. In general, changes in respiration, ethylene production, structural polysaccharides, chlorophyll degradation, and the synthesis of carotenoids, carbohydrates, organic acids, lipids, phenolics, and a number of volatile compounds are all involved in the ripening process of mango fruit. These variables mainly contribute to the development of the mango fruit's overall sensory profile [66].

5. Conclusions

Traditionally, cold storage has been the most preferred strategy for extending the life of postharvest fruits. Edible nanoparticle coatings were investigated to protect the freshness and prolong the shelf life of mangoes and their potential for preserving fruit quality. Coating 'Tommy Atkins' mangoes with nano-silica dioxide and chitosan combina-

tion films successfully delayed ripening, as shown by reducing weight loss, endogenous ethylene production, suppressed respiration rate, and preserving fruit firmness. All coated treatments slowed the rate of the rise in total soluble solids and total sugars when compared to the control at the end of cold storage and marketing. Therefore, we assume that mango growers could efficiently utilize chitosan/nano-silicon dioxide coatings in the future to prolong the freshness of fruits, maintain sensory evaluation and reduce deterioration, and increase profitability.

Author Contributions: Conceptualization, H.S.K.; data curation and validation, M.E.T.; methodology, H.S.K. and M.E.T.; formal analysis, M.E.T.; writing—original draft preparation, M.E.T. and E.E.E.; writing—review and editing, H.I. and E.E.E. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Researchers Supporting Project Number (RSP-2021/403), King Saud University, Riyadh, Saudi Arabia.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Akurugu, G.K.; Olympio, N.S.; Ninfaa, D.A.; Karbo, E.Y. Evaluation of Post Harvest Handling and Marketing of Mango (*Mangifera indica*) in Ghana (a Case Study in Northern Region). *J. Res. Agric. Anim. Sci.* **2016**, *4*, 4–9.
2. FAO. *Major Tropical Fruits—Statistical Compendium 2018*; FAO: Rome, Italy, 2019.
3. Sivakumar, D.; Jiang, Y.; Yahia, E.M. Maintaining mango (*Mangifera indica* L.) fruit quality during the export chain. *Food Res. Int.* **2011**, *44*, 1254–1263. [[CrossRef](#)]
4. Jahurul, M.; Zaidul, I.; Ghafoor, K.; Al-Juhaimi, F.Y.; Nyam, K.-L.; Norulaini, N.; Sahena, F.; Omar, A.M. Mango (*Mangifera indica* L.) by-products and their valuable components: A review. *Food Chem.* **2015**, *183*, 173–180. [[CrossRef](#)] [[PubMed](#)]
5. FAOSTAT. *Mango Production and Exports in Egypt*; FAOSTAT, FAO: Rome, Italy, 2018.
6. Cárdenas-Coronel, W.G.; Velez-de la Rocha, R.; Siller-Cepeda, J.H.; Osuna-Enciso, T.; Muy-Rangel, M.D.; Sañudo-Barajas, J.A. Changes in the composition of starch, pectins and hemicelluloses during the ripening stage of mango (*Mangifera indica* cv. Kent). *Rev. Chapingo Ser. Hortic.* **2012**, *18*, 05–19.
7. Narayana, C.; Pal, R.; Roy, S. Effect of pre-storage treatments and temperature regimes on shelf-life and respiratory behaviour of ripe Baneshan mango. *J. Food Sci. Technol. Mysore* **1996**, *33*, 79–82.
8. Ali, S.; Anjum, M.A.; Khan, A.S.; Nawaz, A.; Ejaz, S.; Khaliq, G.; Iqbal, S.; Ullah, S.; Rehman, R.N.U.; Ali, M.M. Carboxymethyl Cellulose Coating Delays Ripening of Harvested Mango Fruits by Regulating Softening Enzymes Activities. *Food Chem.* **2021**, *168*, 131804. [[CrossRef](#)]
9. Lalel, H.J.; Singh, Z.; Tan, S.C. Aroma volatiles production during fruit ripening of ‘Kensington Pride’ mango. *Postharvest Biol. Technol.* **2003**, *27*, 323–336. [[CrossRef](#)]
10. Zheng, X.; Ye, L.; Jiang, T.; Jing, G.; Li, J. Limiting the deterioration of mango fruit during storage at room temperature by oxalate treatment. *Food Chem.* **2012**, *130*, 279–285. [[CrossRef](#)]
11. Carrillo-Lopez, A.; Ramirez-Bustamante, F.; Valdez-Torres, J.; Rojas-Villegas, R.; Yahia, E. Ripening and quality changes in mango fruit as affected by coating with an edible film. *J. Food Qual.* **2000**, *23*, 479–486. [[CrossRef](#)]
12. Maina, B.; Ambuko, J.; Hutchinson, M.J.; Owino, W.O. The Effect of Waxing Options on Shelf Life and Postharvest Quality of “ngowe” Mango Fruits under Different Storage Conditions. *Adv. Agric.* **2019**, *2019*, 5085636. [[CrossRef](#)]
13. McHugh, T.; Senesi, E. Apple wraps: A novel method to improve the quality and extend the shelf life of fresh-cut apples. *J. Food Sci.* **2000**, *65*, 480–485. [[CrossRef](#)]
14. Rastegar, S.; Atrash, S. Effect of alginate coating incorporated with Spirulina, Aloe vera and guar gum on physicochemical, respiration rate and color changes of mango fruits during cold storage. *J. Food Meas. Charact.* **2021**, *15*, 265–275. [[CrossRef](#)]
15. Sorrentino, A.; Gorrasi, G.; Vittoria, V. Potential perspectives of bio-nanocomposites for food packaging applications. *Trends Food Sci. Technol.* **2007**, *18*, 84–95. [[CrossRef](#)]
16. Kumar, N.; Petkoska, A.T.; AL-Hilifi, S.A.; Fawole, O.A. Effect of Chitosan–Pullulan Composite Edible Coating Functionalized with Pomegranate Peel Extract on the Shelf Life of Mango (*Mangifera indica*). *Coatings* **2021**, *11*, 764. [[CrossRef](#)]
17. Tripathi, P.; Dubey, N. Exploitation of natural products as an alternative strategy to control postharvest fungal rotting of fruit and vegetables. *Postharvest Biol. Technol.* **2004**, *32*, 235–245. [[CrossRef](#)]
18. Bautista-Baños, S.; Hernández-López, M.; Bosquez-Molina, E.; Wilson, C. Effects of chitosan and plant extracts on growth of *Colletotrichum gloeosporioides*, anthracnose levels and quality of papaya fruit. *Crop Prot.* **2003**, *22*, 1087–1092. [[CrossRef](#)]

19. Sousa, F.F.; Junior, J.S.P.; Oliveira, K.T.; Rodrigues, E.C.; Andrade, J.P.; Mattiuz, B.-H. Conservation of ‘palmer’ mango with an edible coating of hydroxypropyl methylcellulose and beeswax. *Food Chem.* **2021**, *346*, 128925. [\[CrossRef\]](#) [\[PubMed\]](#)
20. Eshghi, S.; Hashemi, M.; Mohammadi, A.; Badii, F.; Mohammadhoseini, Z.; Ahmadi, K. Effect of nanochitosan-based coating with and without copper loaded on physicochemical and bioactive components of fresh strawberry fruit (*Fragaria x ananassa* Duchesne) during storage. *Food Bioprocess Technol.* **2014**, *7*, 2397–2409. [\[CrossRef\]](#)
21. Nasr, F.; Pateiro, M.; Rabiei, V.; Razavi, F.; Formanek, S.; Gohari, G.; Lorenzo, J.M. Chitosan-Phenylalanine Nanoparticles (Cs-Phe Nps) Extend the Postharvest Life of Persimmon (*Diospyros kaki*) Fruits under Chilling Stress. *Coatings* **2021**, *11*, 819. [\[CrossRef\]](#)
22. Lustriane, C.; Dwivany, F.M.; Suendo, V.; Reza, M. Effect of chitosan and chitosan-nanoparticles on post harvest quality of banana fruits. *J. Plant Biotechnol.* **2018**, *45*, 36–44. [\[CrossRef\]](#)
23. Resende, N.; Gonçalves, G.; Reis, K.; Tonoli, G.; Boas, E. Chitosan/cellulose nanofibril nanocomposite and its effect on quality of coated strawberries. *J. Food Qual.* **2018**, *2018*, 1727426. [\[CrossRef\]](#)
24. Meena, M.; Pilania, S.; Pal, A.; Mandhania, S.; Bhushan, B.; Kumar, S.; Gohari, G.; Saharan, V. Cu-chitosan nano-net improves keeping quality of tomato by modulating physio-biochemical responses. *Sci. Rep.* **2020**, *10*, 21914. [\[CrossRef\]](#) [\[PubMed\]](#)
25. Amin, U.; Khan, M.K.I.; Khan, M.U.; Akram, M.E.; Pateiro, M.; Lorenzo, J.M.; Maan, A.A. Improvement of the Performance of Chitosan–Aloe vera Coatings by Adding Beeswax on Postharvest Quality of Mango Fruit. *Foods* **2021**, *10*, 2240. [\[CrossRef\]](#) [\[PubMed\]](#)
26. Sami, R.; Elhakem, A.; Alharbi, M.; Benajiba, N.; Fikry, M.; Helal, M. The combined effect of coating treatments to nisin, nano-silica, and chitosan on oxidation processes of stored button mushrooms at 4 C. *Sci. Rep.* **2021**, *11*, 6031. [\[CrossRef\]](#)
27. Eldib, R. Application of Nano-coating and Chitosan Combination Films on Cantaloupe Preservation. *Pak. J. Biol. Sci. PJB* **2020**, *23*, 1037–1043. [\[CrossRef\]](#)
28. Li, Y.; Rokayya, S.; Jia, F.; Nie, X.; Xu, J.; Elhakem, A.; Almatrafi, M.; Benajiba, N.; Helal, M. Shelf-life, quality, safety evaluations of blueberry fruits coated with chitosan nano-material films. *Sci. Rep.* **2021**, *11*, 55. [\[CrossRef\]](#)
29. Song, H.; Yuan, W.; Jin, P.; Wang, W.; Wang, X.; Yang, L.; Zhang, Y. Effects of chitosan/nano-silica on postharvest quality and antioxidant capacity of loquat fruit during cold storage. *Postharvest Biol. Technol.* **2016**, *119*, 41–48. [\[CrossRef\]](#)
30. Cardoso-Almeida, F.D.A.; Figueiredo-Neto, A.; Lucena-Cavalcante, Í.H. Physical and mechanical parameters correlated to the ripening of mangoes (*Mangifera indica* L.) cv. ‘Tommy Atkins’. *Acta Agron.* **2017**, *66*, 186–192.
31. Rokayya, S.; Khojah, E.; Elhakem, A.; Benajiba, N.; Chavali, M.; Vivek, K.; Iqbal, A.; Helal, M. Investigating the nano-films effect on physical, mechanical properties, chemical changes, and microbial load contamination of white button mushrooms during storage. *Coatings* **2021**, *11*, 44. [\[CrossRef\]](#)
32. Qi, L.; Xu, Z.; Jiang, X.; Hu, C.; Zou, X. Preparation and antibacterial activity of chitosan nanoparticles. *Carbohydr. Res.* **2004**, *339*, 2693–2700. [\[CrossRef\]](#)
33. Haghighi, M.; Pessarakli, M. Influence of silicon and nano-silicon on salinity tolerance of cherry tomatoes (*Solanum lycopersicum* L.) at early growth stage. *Sci. Hortic.* **2013**, *161*, 111–117. [\[CrossRef\]](#)
34. Zhu, Y.; Li, D.; Belwal, T.; Li, L.; Chen, H.; Xu, T.; Luo, Z. Effect of nano-SiO_x/chitosan complex coating on the physicochemical characteristics and preservation performance of green Tomato. *Molecules* **2019**, *24*, 4552. [\[CrossRef\]](#) [\[PubMed\]](#)
35. Sami, R.; Khojah, E.; Elhakem, A.; Benajiba, N.; Helal, M.; Alhuthal, N.; Alzahrani, S.A.; Alharbi, M.; Chavali, M. Performance study of nano/SiO₂ films and the antimicrobial application on cantaloupe fruit shelf-life. *Appl. Sci.* **2021**, *11*, 3879. [\[CrossRef\]](#)
36. McGuire, R.G. Reporting of objective color measurements. *HortScience* **1992**, *27*, 1254–1255. [\[CrossRef\]](#)
37. Pristijono, P.; Golding, J.B.; Bowyer, M.C. Postharvest UV-C treatment, followed by storage in a continuous low-level ethylene atmosphere, maintains the quality of ‘Kensington pride’ mango fruit stored at 20 C. *Horticulturae* **2019**, *5*, 1. [\[CrossRef\]](#)
38. Ranganna, S. *Handbook of Analysis and Quality Control for Fruit and Vegetable Products*; Tata McGraw-Hill Education: New York, NY, USA, 1986.
39. Association of Official Analytical Chemists. *Official Methods of Analysis*, 16th ed.; Association of Official Analytical Chemists: Washington, DC, USA, 2005; Volume 16.
40. James, C.S. *Analytical Chemistry of Food*; University of Plymouth: Plymouth, UK, 1995; pp. 96–97.
41. Chun, O.K.; Kim, D.-O.; Lee, C.Y. Superoxide radical scavenging activity of the major polyphenols in fresh plums. *J. Agric. Food Chem.* **2003**, *51*, 8067–8072. [\[CrossRef\]](#)
42. Ao, C.; Li, A.; Elzaawely, A.A.; Xuan, T.D.; Tawata, S. Evaluation of antioxidant and antibacterial activities of *Ficus microcarpa* L. fil. extract. *Food Control* **2008**, *19*, 940–948. [\[CrossRef\]](#)
43. Manasa, B. Evaluation of sensory attributes of mango fruits CV ‘Alphonso’ as influenced by pre-harvest treatments. *J. Pharmacogn. Phytochem.* **2019**, *8*, 2475–2480.
44. Duncan, D.B. Multiple range and multiple F tests. *Biometrics* **1955**, *11*, 1–42. [\[CrossRef\]](#)
45. Gardesh, A.S.K.; Badii, F.; Hashemi, M.; Ardakani, A.Y.; Maftoonazad, N.; Gorji, A.M. Effect of nanochitosan based coating on climacteric behavior and postharvest shelf-life extension of apple cv. Golab Kohanz. *LWT* **2016**, *70*, 33–40. [\[CrossRef\]](#)
46. Zaharah, S.S.; Singh, Z.; Symons, G.M.; Reid, J.B. Role of brassinosteroids, ethylene, abscisic acid, and indole-3-acetic acid in mango fruit ripening. *J. Plant Growth Regul.* **2012**, *31*, 363–372. [\[CrossRef\]](#)
47. Romanazzi, G.; Nigro, F.; Ippolito, A.; Divenere, D.; Salerno, M. Effects of pre-and postharvest chitosan treatments to control storage grey mold of table grapes. *J. Food Sci.* **2002**, *67*, 1862–1867. [\[CrossRef\]](#)

48. Bibi, F.; Baloch, M.K. Postharvest Quality and Shelf Life of Mango (*Mangifera indica* L.) Fruit as Affected by Various Coatings. *J. Food Process. Preserv.* **2014**, *38*, 499–507. [\[CrossRef\]](#)
49. Dautt-Castro, M.; López-Virgen, A.G.; Ochoa-Leyva, A.; Contreras-Vergara, C.A.; Sortillón-Sortillón, A.P.; Martínez-Téllez, M.A.; González-Aguilar, G.A.; Casas-Flores, J.S.; Sañudo-Barajas, A.; Kuhn, D.N. Genome-wide identification of mango (*Mangifera indica* L.) Polygalacturonases: Expression analysis of family members and Total enzyme activity during fruit ripening. *Front. Plant Sci.* **2019**, *10*, 969. [\[CrossRef\]](#) [\[PubMed\]](#)
50. Jitareerat, P.; Paumchai, S.; Kanlayanarat, S.; Sangchote, S. Effect of chitosan on ripening, enzymatic activity, and disease development in mango (*Mangifera indica*) fruit. *N. Z. J. Crop Hortic. Sci.* **2007**, *35*, 211–218. [\[CrossRef\]](#)
51. Adiletta, G.; Di Matteo, M.; Petriccione, M. Multifunctional Role of Chitosan Edible Coatings on Antioxidant Systems in Fruit Crops: A Review. *Int. J. Mol. Sci.* **2021**, *22*, 2633. [\[CrossRef\]](#)
52. Mebratie, M.A.; Woldetsadik, K.; Ayalew, A.; Haji, J. Comparative study of different banana ripening methods. *Sci. Technol. Arts Res. J.* **2015**, *4*, 32–38. [\[CrossRef\]](#)
53. Silva, G.M.C.; Silva, W.B.; Medeiros, D.B.; Salvador, A.R.; Cordeiro, M.H.M.; da Silva, N.M.; Santana, D.B.; Mizobutsi, G.P. The chitosan affects severely the carbon metabolism in mango (*Mangifera indica* L. cv. Palmer) fruit during storage. *Food Chem.* **2017**, *237*, 372–378. [\[CrossRef\]](#)
54. Woolf, A.B.; Cox, K.A.; White, A.; Ferguson, I.B. Low temperature conditioning treatments reduce external chilling injury of ‘Hass’ avocados. *Postharvest Biol. Technol.* **2003**, *28*, 113–122. [\[CrossRef\]](#)
55. Gol, N.B.; Chaudhari, M.L.; Rao, T.R. Effect of edible coatings on quality and shelf life of carambola (*Averrhoa carambola* L.) fruit during storage. *J. Food Sci. Technol.* **2015**, *52*, 78–91. [\[CrossRef\]](#)
56. Tefera, A.; Seyoum, T.; Woldetsadik, K. Effects of disinfection, packaging and evaporatively cooled storage on sugar content of mango. *Afr. J. Biotechnol.* **2008**, *7*, 65–72.
57. Zeb, S.; Sajid, M.; Shah, S.T.; Ali, M.; Ali, S.; Nawaz, Z.; Rauf, K.; Khan, A.; Shah, H.; Shah, S.A.A. 34. Influence of post-harvest application of chitosan on physico-chemical changes of apple fruit during storage. *Pure Appl. Biol. PAB* **2020**, *9*, 2554–2562.
58. Zhu, F.; Yun, Z.; Ma, Q.; Gong, Q.; Zeng, Y.; Xu, J.; Cheng, Y.; Deng, X. Effects of exogenous 24-epibrassinolide treatment on postharvest quality and resistance of Satsuma mandarin (*Citrus unshiu*). *Postharvest Biol. Technol.* **2015**, *100*, 8–15. [\[CrossRef\]](#)
59. Venkatesh, J.; Park, S.W. Role of L-ascorbate in alleviating abiotic stresses in crop plants. *Bot. Stud.* **2014**, *55*, 38. [\[CrossRef\]](#) [\[PubMed\]](#)
60. Sun, Y.; Li, M.; Mitra, S.; Hafiz Muhammad, R.; Debnath, B.; Lu, X.; Jian, H.; Qiu, D. Comparative phytochemical profiles and antioxidant enzyme activity analyses of the southern highbush blueberry (*Vaccinium corymbosum*) at different developmental stages. *Molecules* **2018**, *23*, 2209. [\[CrossRef\]](#) [\[PubMed\]](#)
61. Rao, G.B.; Susmitha, P. Silicon uptake, transportation and accumulation in Rice. *J. Pharmacogn. Phytochem.* **2017**, *6*, 290–293.
62. Lattanzio, V.; Kroon, P.A.; Quideau, S.; Treutter, D. Plant phenolics—Secondary metabolites with diverse functions. *Recent Adv. Polyphen. Res.* **2008**, *1*, 1–35.
63. Kondo, S.; Kittikorn, M.; Kanlayanarat, S. Preharvest antioxidant activities of tropical fruit and the effect of low temperature storage on antioxidants and jasmonates. *Postharvest Biol. Technol.* **2005**, *36*, 309–318. [\[CrossRef\]](#)
64. Valenzuela, J.L.; Manzano, S.; Palma, F.; Carvajal, F.; Garrido, D.; Jamilena, M. Oxidative stress associated with chilling injury in immature fruit: Postharvest technological and biotechnological solutions. *Int. J. Mol. Sci.* **2017**, *18*, 1467. [\[CrossRef\]](#)
65. Yu, Y.; Zhang, S.; Ren, Y.; Li, H.; Zhang, X.; Di, J. Jujube preservation using chitosan film with nano-silicon dioxide. *J. Food Eng.* **2012**, *113*, 408–414. [\[CrossRef\]](#)
66. Akhtar, S.; Mahmood, S.; Naz, S.; Nasir, M.; Sultan, M. Sensory evaluation of mangoes (*Mangifera indica* L.) grown in different regions of Pakistan. *Pak. J. Bot.* **2009**, *41*, 2821–2829.
67. Engel, K.H.; Tressl, R. Studies on the volatile components of two mango varieties. *J. Agric. Food Chem.* **1983**, *31*, 796–801. [\[CrossRef\]](#)
68. Malundo, T.; Shewfelt, R.; Ware, G.; Baldwin, E. Sugars and acids influence flavor properties of mango (*Mangifera indica*). *J. Am. Soc. Hortic. Sci.* **2001**, *126*, 115–121. [\[CrossRef\]](#)
69. Abbasi, N.A.; Iqbal, Z.; Maqbool, M.; Hafiz, I.A. Postharvest quality of mango (*Mangifera indica* L.) fruit as affected by chitosan coating. *Pak. J. Bot.* **2009**, *41*, 343–357.
70. Kaswija, M.; Peter, M.; Leonard, F. Sensory attributes, microbial quality and aroma profiles of off vine ripened mango (*Mangifera indica* L.) fruit. *Afr. J. Biotechnol.* **2006**, *5*, 201–205.