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Effect of Postharvest Transport and Storage on Color and Firmness Quality of Tomato

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Abstract: Transport duration affects the vibration level generated which has adverse effects on fresh produce during transportation. Furthermore, temperature affects the quality of fresh commodities during storage. This study evaluated physical changes in tomatoes during transportation and storage. Tomatoes were transported at three distances (100, 154, and 205 km) from a local farm and delivered to the Postharvest Laboratory where vibration acceleration was recorded per distance. Tomato was stored at two different temperatures (10 °C and 22 °C) for 12 days. The physical qualities like weight loss and firmness of all tomato samples were evaluated. RGB image acquisition system was used to assess the color change of tomato. The results of vibration showed that over 40% of accelerations occurred in the range of 0.82–1.31 cm/s^2 of all transport distances. Physical quality analyses like weight loss and firmness were highly affected by transportation distance, storage temperature, and storage period. The reduction in weight loss and firmness was the highest in tomatoes transported from the farthest distance and stored at 22 °C. Lightness, yellowness, and hue values showed a high reduction as transport distance increased particularly in tomatoes stored at 22 °C. Redness, total color difference, and color indices increased significantly on tomatoes transported from 205 km and stored at 10 °C and 22 °C. The study indicated that the increase in transportation distance and storage temperature cause higher changes in the physical qualities of tomatoes.

Keywords: quality; vibration; tomato; transportation

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1. Introduction

Consumers prefer high-quality fresh produce, which is primarily assessed based on their appearance and taste [1]. For this reason, the fresh produce provided to the market should meet the international standards of quality for freshness, firmness, and other quality characteristics [2,3]. Throughout postharvest operations like harvesting, handling processing, storing, and transporting, fresh produce is subjected to different external forces. Therefore, this reduces product quality and decreasing sale prices as well as losses to the orchardists and growers [4]. Transportation is an essential process during the postharvest supply chain of any fresh produce [5]. However, transportation could cause postharvest losses leading to high economic losses [6] if it is not probably managed. Several factors lead to postharvest losses during transportation including bad roads, non-refrigerated vehicles [7], the surrounding environment [8], and mechanical and physiological properties of fresh produce [6]. During transport, fruits and vegetables are often exposed to rough handling and transported over bad road conditions resulted in damage and mechanical injuries which could increase the losses over the supply chain [9].

The vibration produced by vehicles (truck beds) during road transportation has a significant effect on the damage process of agricultural products like fruits and vegetables [10]. Furthermore, it is one of the main reasons for causing external and internal damages to the fresh produce during the supply chain [11,12]. Transport distance is one of the essential factors that directly correlate with vibration level where long-distance transportation time resulted in high vibration level. Çakmak et al. [13], Shahbazi et al. [14], and La Scalia et al. [15] recorded high vibration levels and great damage as transit time increased in fig, watermelon, and strawberry respectively. Furthermore, long transport times during fresh produce transportation can accelerate enzymatic and metabolic processes resulted in increasing the mechanical damage risk, therefore, reducing market value [6].

Different physical changes have been investigated on different fresh produce during transportation like an apple [16], fig [13], grape [17], kiwifruit [18], tomato [8,19,20], and strawberry [15]. Most of the results showed that the internal damages produced by vibration during transportation can generate a rapid degradation [21] which can directly affect ripening level and firmness [12]. The vibrated samples of strawberries had a lower shelf life compared to the control (non-vibrated) samples as reported by Dhital et al. [22]. Xu et al. [3] also recorded high color change on lightness in broccoli stressed to two hours vibration.

Fresh produce storage is another essential part of the postharvest supply chain [23]. The majority of microbial, physiological, and biochemical processes contributing to produce quality deterioration are temperature dependence [24]. A high increase in storage temperature rises the rate of respiration [25], transpiration, and the rate of ethylene production. However, a high reduction of storage temperature could be a reason for causing chilling injuries and quality reduction [26].

Tomato (*Solanum lycopersicum* L.) is one of the most widely grown and important fresh produce worldwide. Tomato is a vital source of many nutrients and other healthy minerals that benefit the human body [27]. Weight, firmness, and color are essential quality indicators influenced by postharvest operations [1,25]. These quality aspects affect consumer acceptance and market success [28]. Compared to other fruits and vegetables, tomato is a sensitive produce [29] which is highly perishable due to vibration and impact load during transportation, the market process, and storage temperature [25]. Vibration during transportation causes the tomato to rub and rotate against other products and the packaging containers resulted in softening and other mechanical damages [8,13]. Besides, storage becomes difficult to maintain particularly in high moisture content fresh produce like tomato [23]. Few studies investigated the effect of real-time transportation vibration generated from different distances coupled with varying storage conditions on tomato fruit that can resolve the critical post-harvest losses and problems in perishable commodities. Therefore, this study was performed to investigate the contribution of vibration generated from road transportation of three different distances (100, 154, and 205 km) and storage temperature (10 and 22 °C) in tomato quality aspects including weight, firmness, and color for 12 days storage period.

2. Materials and Methods

2.1. Field Experiments

To compare the influence of vibration level and distance during transit on the quality of fresh produce, a total of 27 wooden boxes (400 × 300 × 110 mm) of bright red color tomatoes with calyx ("Miral" variety) of one harvest were purchased from a farm located in Al-Suwaiq, Sultanate of Oman. Tomato boxes were then transported to three different distances (100 km, 154 km, and 205 km) using 1692 kg non-refrigerated pickup (Model: Hilux, Toyota, Samut Prakan, Thailand) to Postharvest Laboratory, College of Agricultural and Marine Sciences at Sultan Qaboos University, Oman. For each distance, the time required to transport tomato fruit boxes per distance was 75 min, 120 min, and 180 min for 100 km, 154 km, and 205 km, respectively. Tomato wooden boxes were covered by a blue plastic sheet to avoid direct exposure to the sun. This study was carried out during the summer season of June 2020.

2.2. Vibration

In this study, a three-axis USB vibration/acceleration data logger (Model: OM-VIB-101, Spectris plc, Connecticut, Norwalk, CT, USA) was used to record the data of obtained vibration during transportation. This sensor has a −16 to 16 g acceleration range, 0 to 60 Hz frequency range, and ±0.5 g accuracy. This sensor was attached in the top position of the tomato fruit container and was positioned vertically to get more vibration [30] inside tomato boxes. For sampling rate, vibration data were recorded every 1 s of road travel.

The generated signals were simplified on the sensor and then transferred to a personal computer to be later analyzed by shock application (vibration data logger, v2.3). Thousands of vibration signals were recorded in each distance during transit in milligal (mGal) which were later converted to cm/s^2. Moreover, vibration analysis was applied to evaluate the number of obtained accelerations (time-domain) for each distance that occurs during transit. Subsequently, all time-domain signals above 0.13 cm/s^2 were calculated using a histogram which was performed to identify the number of peaks of acceleration during transit for each distance.

2.3. Sample Preparation and Laboratory Experiment

A total of 195 tomato fruits from three distances with similar color, firmness, weight (0.487 ± 0.1 kg), and free from defects were selected for the study analysis. For each distance, tomato fruits were divided into two groups, where the first group stored at ambient room temperature (22 ± 1 °C with 65 ± 5% RH) and the other at refrigerated temperature (10 ± 0.5 °C with 95 ± 1% RH). Each storage condition consists of seven sub-groups where each group consists of five replicates to undergo some physical quality analysis (weight loss percentage, color, and firmness) for the evaluation of their postharvest changes due to transport vibration and storage for 12 days at 2 days interval. Daily monitoring of temperature and relative humidity in the laboratory were measured using a temperature meter (Model: TES 13604, TES Electrical Corp., Taipei, Taiwan).

2.3.1. Tomato Weight Loss %

Weight loss (%) of tomato fruit transported from each distance stored at both conditions was determined for two days intervals to an accuracy of ±0.01 g by using an electric weight balance (Model: GX-4000, A & D Company, Tokyo, Japan). The results were calculated as a percentage of the initial recorded weight of the tomato group from the first day of the experiment.

2.3.2. Tomato Color Change

A total of twenty-five external color readings (per one color parameter) were taken from 5 tomato samples per group at 2 days interval using RGB (Red, Green, Blue) image acquisition system (Figure 1). In this system, a cardboard box was used to cover the whole system to avoid backscattering effects. Furthermore, a white background (stage) was placed to provide high contrast between the tomato sample and the background. Tomato samples were illuminated using two 36 W long fluorescent tubes (Model: Dulux L, OSRAM, Milano, Italy) to provide light with uniform intensity over the sample. Light sources were fixed to be parallel to the tomato platform. Moreover, the image of tomato samples was captured using an RGB color camera (Model: EOS FF0D, Canon Inc., Tokyo, Japan) placed vertically in the center of the cardboard box at a distance of 0.26 m from the tomato sample. The digital camera was connected to the USB port of a personal computer where the images were stored for subsequent processing. A remote shooting software EOS Utility included in the camera was performed to acquire the image in the maximum possible resolution [31]. The captured images were stored in JPG format. Each sample was placed and oriented manually. For image processing, ImageJ software (v. 1.53, National Institute of Health, Bethesda, MD, USA) was applied. RGB mean values were obtained by using the histogram tool (Analyze/Histogram menu). RGB values were later converted to CIEL*a*b* color space which was chosen as it is mostly applied in food quality studies [32]. Total color differences

($\Delta E*$) that indicate the magnitudes of color change in the stored tomato (Equation (1)), chroma that represents the color intensity of stored (Equation (2)), a hue which indicates the purity of tomato color (Equation (3)), color index (CI) (Equation (4)), and tomato color index (COL) (Equation (5)) were also calculated to track red color development of stored tomato fruit transported from different distances using the following equations [33]:

$$\Delta E = \sqrt{\Delta a*^2 + \Delta b^2 + \Delta L*^2} \quad (1)$$

$$Chroma = \sqrt{a*^2 + b*^2} \quad (2)$$

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

$$CI = a^*/b^* \quad (4)$$

$$COl = \left(\frac{2000 \times a^*}{L^* \times Chroma}\right) \quad (5)$$

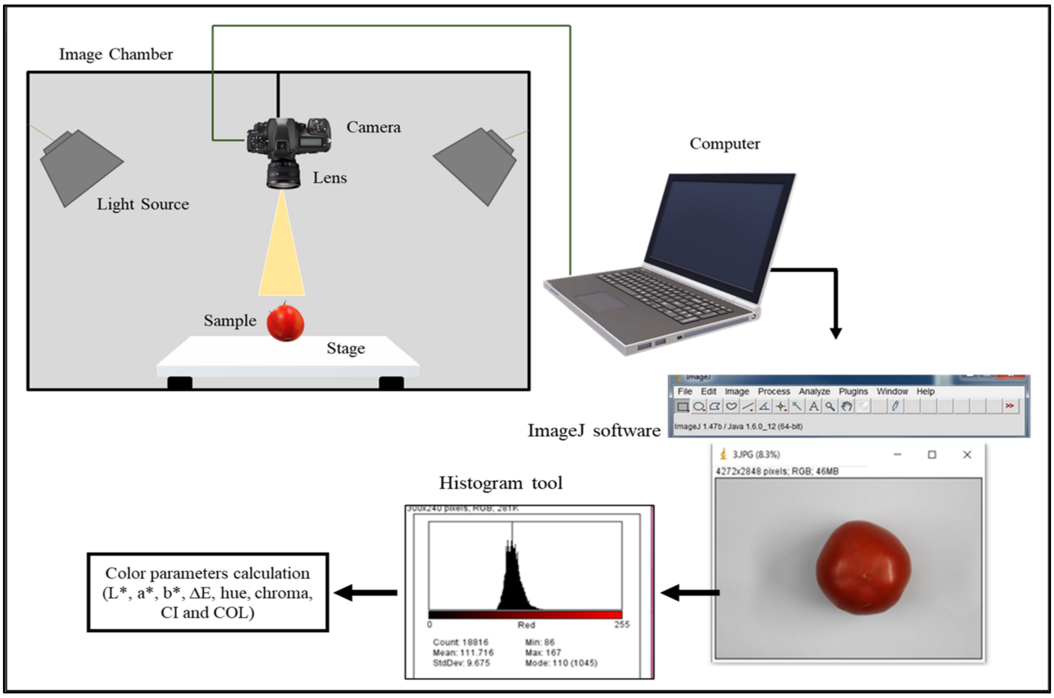

Figure 1. A schematic of a typical RGB image acquisition system.

2.3.3. Tomato Firmness

The firmness of tomato fruit was determined by a digital fruit firmness tester (Model: FHP-803, L.L.C., Franklin, ME, USA) [34] using an appropriate stainless-steel cylinder probe with a 3 mm diameter. Two measurements were taken at opposite positions on each tomato using a total of 5 samples from (10 readings per group) tomato fruit transported from each distance stored at both conditions and was expressed as N.

2.4. Statistical Analysis

SPSS 20.0 (International Business Machine Crop., New York, NY, USA) was used to study the impact of experimental variables, i.e., transport distance (100 km, 154 km, and 205 km), storage condition (10 ± 0.5 °C and 22 ± 1 °C), and storage duration on the physical (weight loss, color, and firmness) quality parameters of tomato by performing three-way analysis of variance (ANOVA) and the mean values were considered at 5% significance level ($p < 0.05$). Mean and standard deviation (S.D) were also reported for all measured parameters. Tukey's range (HSD) test was applied to determine the significant differences between treatment means. Construction of all graphs was performed using GraphPad Prism software version 9.0.0 (GraphPad Software, Inc., San Diego, CA, USA).

3. Results and Discussions

3.1. Vibration Level Analysis during Transit

To determine vibration levels during transportation, continuous vertical, longitudinal, and lateral accelerations were measured. Minimum and maximum values of acceleration were the same in all three travel distances due to the continuous measurements of the same instrument during transportation. The results of the transport experiment showed that the vertical direction (Z) gave the maximum acceleration value in all three distances with 2.694 cm/s^2 followed by lateral (X) (1.314 cm/s^2) and longitudinal (Y) (1.123 cm/s^2). Therefore, all subsequent analysis was done using vertical vibration level data. Similar findings were observed by Soleimani and Ahmadi [35] who reported that vertical direction can generate high vibration compared to lateral and longitudinal directions.

A histogram of all time-domain vibration data higher than 0.13 g was used to identify the number of acceleration peaks that occurred per distance (Figure 2). The measured time-domain vibration signals were divided into intervals of 0.17 (0.13–2.69 cm/s^2). The maximum number of peaks was highly found in the acceleration interval of 0.99–1.17 cm/s^2 with 1607, 2864, and 4121 peaks for 100, 154, and 205 km, respectively. It was followed by the acceleration interval of 1.17–1.34 cm/s^2 which was also higher during transit of the longest distance with 2505 peaks compared to medium (1935) and short (1365) distances.

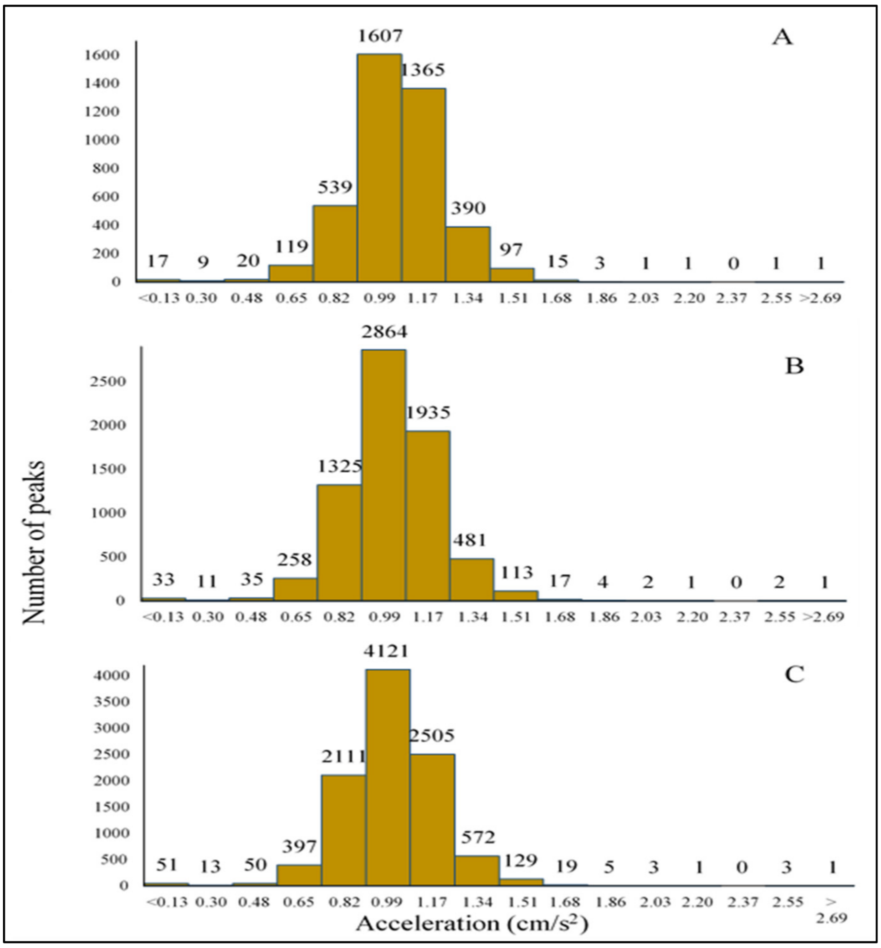

Figure 2. The number of peaks (signals) generated during transport for each acceleration interval (cm/s^2) from (**A**) 100 km (**B**) 154 km and (**C**) 205 km distances using a histogram.

Figure 3 indicates that over 40% of accelerations occurred in the range of 0.82–1.31 cm/s^2 of all transport distances. The percentage of this highest acceleration range was higher in the longest distance with 41% followed by medium 40% and short 38% distance. The maximum accelerations observed during transit (2.96 cm/s^2) showed only 0.03% of acceleration occurrence in all three distances, particularly the shortest distance (100 km). Generally, increasing distance is responsible to increase the acceleration occurrence during transport. The result of the acceleration value measured in the research is close to that reported by Shahbaz et al. [14] who reported that the accelerations of over 97% of vibrations recorded on the transported bins had values below 2 g. They also reported that the intervals of 0.25–0.50 g and 0.50 0.75 g had the highest distribution percentages of vibration accelerations, where the values in these intervals were 35.06 and 23.59% respectively. Besides, increasing the vibration period to 60 min during simulated in-transit vibration resulted in a greater percentage of damage for watermelon with 0.7 g acceleration vibration compared with 0.3 g by 30 min. Wu and Wang [19] observed damage in tomatoes during simulated transit due to vibration when exposed to more than 1 g acceleration.

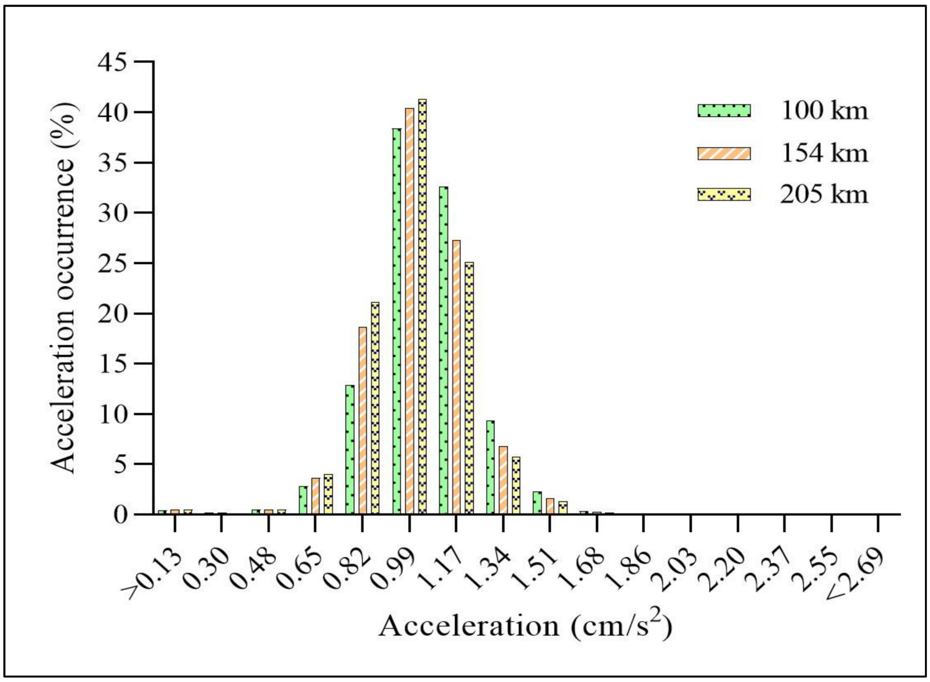

Figure 3. The occurrence percentage of the acceleration intervals (cm/s^2) for 100, 154, and 205 km distances in the vehicle during transportation.

3.2. *Effect on Physical Quality Characteristics of Tomato*

3.2.1. Weight Loss (%)

Figure 4 shows that the weight loss of tomato fruit was affected by transport distance ($p < 0.0001$), storage temperature ($p = 0.0052$), and storage duration ($p < 0.0072$). An increasing trend in weight loss was observed in all tomato fruits transported from different distances stored at 10 and 22 °C for 12 days storage period. However, weight reduction percentage was significantly higher in tomato transported from the longest distance and stored at 22 °C with 6.91% followed by tomato transported from middle and shortest distances with 6.31% and 5.96%, respectively (Figure 4). Nevertheless, the weight loss of tomatoes transported from the long, medium, and short transport distances and subjected to cold temperature (10 °C) was 3.5%, 3.3%, and 3.09%, respectively over 12 days. Generally, increasing transportation distance and temperature storage at (22 °C) increased the weight reduction of tomato samples during storage. However, low-temperature storage reduced the effect of transportation distance on the weight loss of tomato fruit.

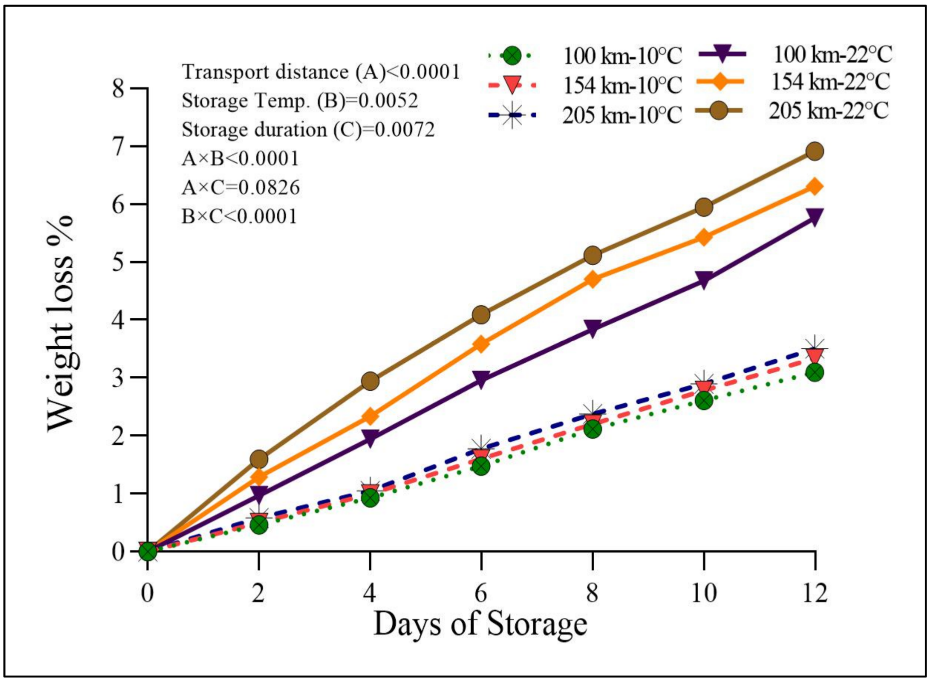

Figure 4. Weight loss (%) of tomatoes from three different distances stored at (A) 10 ± 0.5 °C (95 ± 1%RH) and (B) 22 ± 1 °C (65 ± 5%RH) for 12 days.

These results suggested that tomato fruit transported from the longest distance were stressed due to multiple vibrations compared to others. Exposure to external vibration resulted in a higher respiration rate leading to more weight reduction during storage [16]. Furthermore, Wei et al. [12] reported that fresh produce experienced high weight reduction due to the increment in transport vibration which accelerates water reduction of fresh produce as well as shriveling resulted from intracellular damage. Regarding storage, Endalew [36] stated that storage time and storage temperature had a great effect on the weight loss of tomatoes. Storage at ambient temperature increased the tomato weight loss due to transpiration, respiration [37], and dehydration [38] resulted in water loss leading to an increase in the physical barriers between a fresh produce with the surrounded air [36]. Transpiration occurs in response to the vapor pressure deficit of water that is a function of pressure, air temperature, and relative humidity. Moreover, respiration can prompt weight loss increment due to the alteration of carbon (C) atoms to atmospheric carbon dioxide (CO_2) [7]. In tomato, a higher transpiration rate resulted from higher temperature storage condition compared to lower temperatures lead to shriveling and wilting, thus, reduce consumer acceptability and market-level [36]. Low relative humidity at ambient temperature can also reduce water quantity in the produce which accelerates water reduction [39]. In this study, low temperature storge at 10 °C declined weight reduction of tomato due to the direct impact on vapor pressure and water retention enhancement.

Similarly, Jung et al. [17] experienced 15% and 9% weight loss in the grape group exposed to vibration and control group during 30 days storage. Furthermore, Çakmak et al. [13] found higher mass loss of fig when affected by high vibration frequency and acceleration (16 Hz~2.54 m s^{-2}) compared to fig exposed to 3 Hz~0.56 m s^{-2} at different storage conditions. Wei et al. [12] also revealed a significant weight loss and shrinkage on kiwifruit affected by simulated vibration compared to the non-vibrated kiwifruit after 12 days storage at 25 °C and 75% RH. A progressive increase in weight loss was also reported during storage for 10 days at 34 °C [40] and 8 °C, 12 °C, 20 °C for 20 days [41]. The findings of this study were also in agreement with the findings of Pathare and Al-Dairi [42] who recorded a high percentage of weight reduction in tomato for 10 days storage at room temperature.

3.2.2. Color Change

A significant difference was observed between tomato color lightness (L*) values and transport distance (p = 0.0445), storage temperature (p = 0.0047), and storage duration (p = 0.0025) (Figure 5). During storage, tomato transported from 205 km and stored at 22 °C showed the highest decrease on L* value from 44.30 to 18.10 on Days 0 and 12 respectively. This was followed by tomato transported from 154 km and 100 km from 44.57 and 45.50 to 18.23 and 24.62 respectively (Figure 5). The same scenario was observed on tomato fruit stored at 10 °C, where the highest L* value reported on tomato transported from long followed by medium and short distances. On Day 12, the study reported a 45.88%, 59.08%, and 59.13% reduction in tomato lightness transported from short, medium, and long distances stored at 22 °C compared to only 23.44%, 34.80%, and 35.95% at 10 °C. This indicated that storage at 10 °C slowed down the lightness reduction of tomatoes that could be affected by vibration during different transportation distances. This could be attributed to the repeated vibration stresses during long-distance transportation of tomato resulted in increasing lightness reduction and alteration. Furthermore, the L* value reduction during storage at 22 °C indicated the increment of tomato fruit darkening during storage due to carotenoids synthesis [36]. The slow reduction in lightness (L*) at low storage temperature can occur due to normal ripening resulted from the inhibition of enzymatic activities [43]. The effect of transportation on the fresh produce was also studied by La Scalia et al. [15], where lightness was reduced during storage with no significant effect on vibration duration. Zhou et al. [44] confirmed that pears suffered from transport vibration during long transit time showed high changes on L* stored at ambient temperature. Endalew [36] also stated that the lightness value of tomatoes decreased with the storage time.

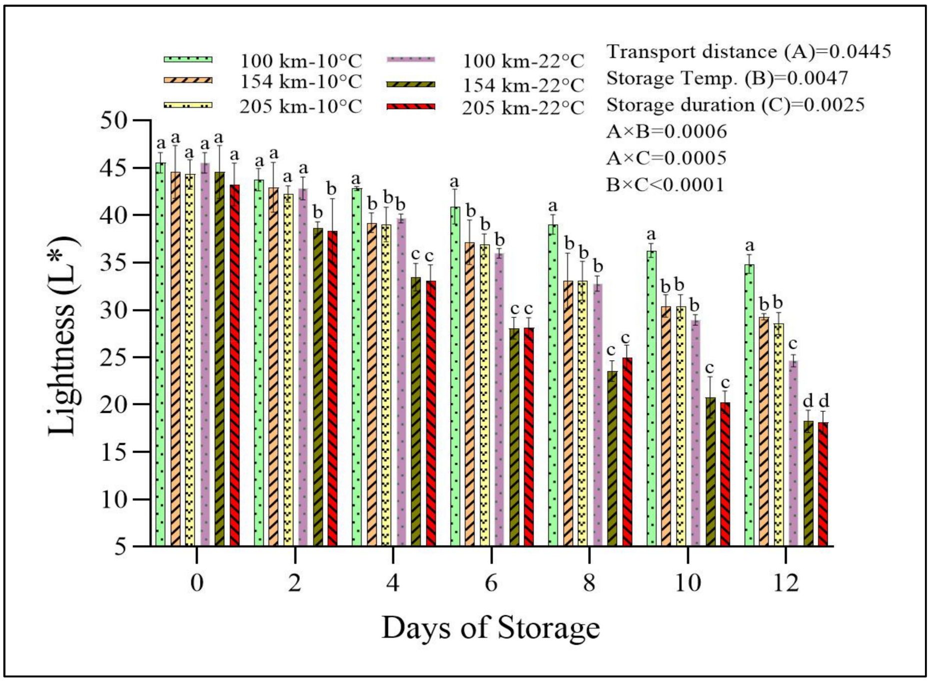

Figure 5. L* value of tomatoes from three different distances stored at (A) 10 ± 0.5 °C (95 ± 1% RH) and (B) 22 ± 1 °C (65 ± 5% RH) for 12 days. Error bars represent standard error (SE) of the mean values ±S.E. of 25 measurements (readings) of 5 tomato replicates. Bars with different letters (per day) are significantly different ($p < 0.05$) performed by the Tukey HSD test and numerical values of A, B, and C are p-values.

The increase of 'redness' and decrease of 'greenness' in tomato fruit was associated with the increment in a* value. The results revealed that the red color (a*) of tomato fruit was influenced by the independent variables like transport distance (p = 0.0343), storage temperature (p = 0.0093), and storage duration (p = 0.0014) (Figure 6). Tomato transported from the longest distance and then stored at 22 °C recorded the highest alternation of a* value from 20.94 on Day 0 to 33.39 on the last day of storage. However, the a* value of tomato transported from the shortest distance increased from 20.05 to 32.21 on Day 0 and Day 12, respectively (Figure 6). Tomatoes stored at 10°C after being transported from 100 km showed the least degree of red color development during storage from 20.05 to 25.74 on Days 0 and 12, respectively, while that from longest distance increased from 20.94 to 28.76 for 12 days storage (Figure 6). In the case of transportation distance, the repeated acceleration occurrence which was recorded from the longest distance could lead to an increase in the ripping process that accelerates redness development in tomato fruit. Tomato kept at room temperature can provide an optimal environment for the tomato to ripe resulted in increasing redness (a*) compared to cold storage conditions [7]. Storage at 22 °C can cause an increase in a* value of tomato due to chlorophyll degradation, lycopene accumulation, and ethylene biosynthesis [45]. Tigist et al. [46] also stated that high temperature tends to increase the red color of tomato compared to low temperature due to the increase in the ripening state of tomato during storage. Regarding transport, La Scalia et al. [15] recorded a small but significant influence of vibration duration on a* value of strawberries. Similarly, Wu and Wang [19] found that tomatoes became redder when exposed to higher acceleration vibration during 60 min of simulated transport. An increase in a* value was obtained during storage, particularly, at 20 °C with a delay in redness development recorded in tomato stored at 2 and 5 °C (Pinheiro et al., 2013). The same scenario was found by Guillén et al. [47], who reported a slow development on a* value of tomato stored for 28 days storage.

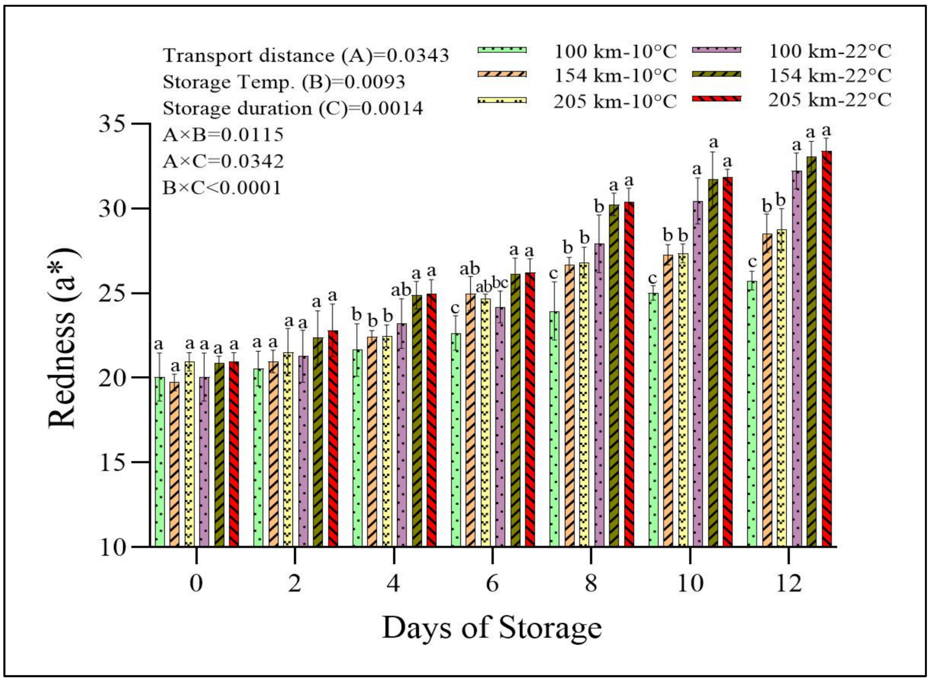

Figure 6. a* value of tomatoes from three different distances stored at (A) 10 ± 0.5 °C (95 ± 1% RH) and (B) 22 ± 1 °C (65 ± 5% RH) for 12 days. Error bars represent standard error (SE) of the mean values ±S.E. of 25 measurements (readings) of 5 tomato replicates. Bars with different letters (per day) are significantly different ($p < 0.05$) performed by the Tukey HSD test and numerical values of A, B, and C are p-values.

As shown in Figure 7, the alteration of tomato color yellowness was significantly affected by all three factors such as transport distance ($p = 0.0100$), storage temperature ($p = 0.0032$), and storage duration ($p = 0.0004$). The b* value of all tomato samples transported from all distances decreased dramatically, particularly, at 22 °C with 58.18% followed by medium and short distances by 58.01% and 49.36% respectively for 12 days storage period. However, the b* value of tomato transported from short, medium, and long distances and stored at 10 °C was significantly lower than those stored at 22 °C with 30.92%, 41.98%, and 41.96%, respectively (Figure 7). The reduction in yellowness (b*) during storage is mostly associated with red color development [36]. As highlighted by Khairi et al. [48], the yellowness (b*) value of tomato was continually decreased as temperature and time increased. The yellow discoloration was also observed on tomato, which reached its minimum b* value after 21 days at 5 and 10 °C [43].

The total color difference is considered as an outcome of alteration in L*, a*, and b* values. Total color differences of tomatoes were statistically significant with transport (p = 0.0435), storage temperature (p = 0.0078), and storage duration (p = 0.0026) (Figure 8). Tomato transported from long distance and stored at ambient temperature had the highest change in total color differences which was ranging between 0 and 32.83 for 12 days storage compared to medium and short distances. Tomato transported from a short distance and stored at 10 °C recorded the lowest range of total color differences from 0 to14.99 (Figure 8).

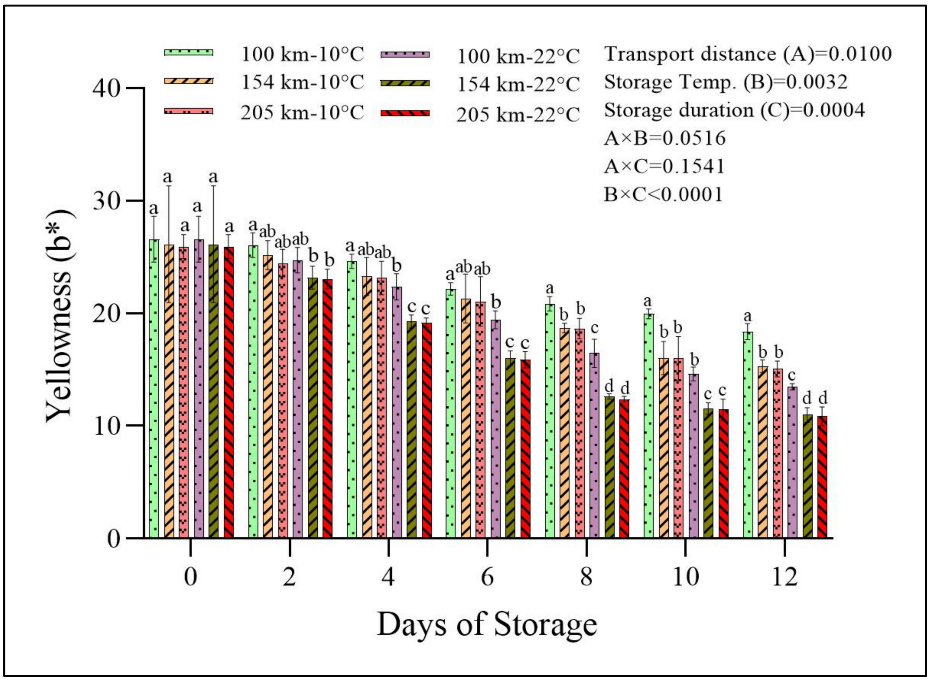

Figure 7. b* value of tomatoes from three different distances stored at (A) 10 ± 0.5 °C (95 ± 1% RH) and (B) 22 ± 1 °C (65 ± 5% RH) for 12 days. Error bars represent standard error (SE) of the mean values ±S.E. of 25 measurements (readings) of 5 tomato replicates. Bars with different letters (per day) are significantly different (p < 0.05) performed by the Tukey HSD test and numerical values of A, B, and C are p-values.

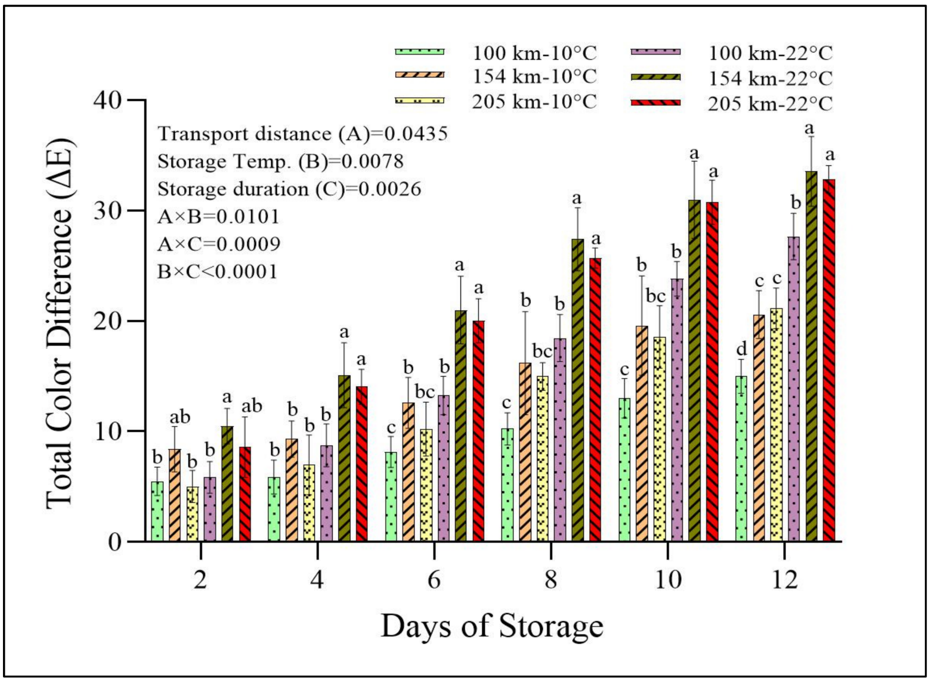

Figure 8. Total color differences (ΔE) value of tomatoes from three different distances stored at (A) 10 ± 0.5 °C (95 ± 1% RH) and (B) 22 ± 1 °C (65 ± 5% RH) for 12 days. Error bars represent standard error (SE) of the mean values ±S.E. of 25 measurements (readings) of 5 tomato replicates. Bars with different letters (per day) are significantly different ($p < 0.05$) performed by the Tukey HSD test and numerical values of A, B, and C are p-values.

This study showed a significant interaction between hue value and investigated factors like transportation distance ($p = 0.0037$), storage temperature ($p = 0.0002$), and storage duration ($p = 0.0004$) (Table S1). Hue value maximum reduction percentage was 64.48% by Day 12 in tomato transported from the longest distance and stored at 22 °C (Table 1). The percentage of hue value reduction of tomato transported from medium distance 63.65%, while it was 57.13% on tomato transported from the short distance. The least reduction (33%) was observed on tomatoes transported from the shortest distance and stored at 10 °C (Table 1). As expected, the reduction in hue value of tomato stored at 22 °C was greater than those stored at 10 °C due to the natural relationship found between the rate of biochemical reaction and temperature [49]. Long transport distance also showed a high increase in hue and chroma during storage at ambient storage temperature [44]. There was a significant effect of storage at 4, 20, and 30 °C for 16 days on the intensity (chroma) and purity (hue) of tomato color. In contrast to the current study, storage at a high temperature can retain the purity of color (hue) compared to low temperature [50]. However, there was no statistical difference ($p > 0.05$) between chroma and the investigated factors for 12 days of storage (Table 1 and Table S1). However, La Scalia et al. [15] recorded a significant reduction in chroma value of the vibrated fresh produce (strawberry) stored at cold storage temperature.

Color index (CI) was statistically influenced by transport distance ($p = 0.0149$), storage temperature ($p = 0.0148$), and storage duration ($p \leq 0.0001$). Besides, a similar scenario was observed with tomato color index (COL) (Table S1). The dramatic increase in tomato CI and COL was mostly shown in tomato stored at 22 °C after it was transported from a 205 km distance (Table 1). However, 100 km transportation distance showed the lowest development of color indices for 12 days storage. According to Tadesse et al. [50], the increase in color indices can indicate the development of a dark red color in the investigated tomato. They recorded a high red color increment in tomatoes stored at 20 and 30 °C than tomatoes stored at low temperature (4 °C) which attributed to lycopene development associated with the internal membrane system of tomato.

Table 1. Chroma, Hue, CI, and COL changes in tomatoes transported from three distances (100 km, 154, and 205 km) stored at ambient (22 °C) and optimum (10 °C) for 12 days storage period. The data were expressed in mean ± standard deviation of 25 measurements (readings) of 5 tomato replicates. Mean values with different letters in a column (per parameter) differ significantly ($p < 0.05$) performed by the Tukey HSD test. Numerical values of A, B, and C are p-values. All p-values in bold are statistically significant (Tukey HSD test., $p < 0.05$).

Color Quality Parameters	Distances (Km)	ST (°C)	Days of Storage						
			0	2	4	6	8	10	12
Chroma	100	10	33.38 ± 1.70^{a}	33.23 ± 0.53^{a}	32.83 ± 0.67^{a}	31.72 ± 0.73^{a}	31.81 ± 1.00^{a}	32.02 ± 0.60^{ab}	31.65 ± 0.52^{b}
		22		32.68 ± 0.80^{a}	32.82 ± 1.00^{a}	31.06 ± 1.07^{a}	32.43 ± 1.89^{a}	33.79 ± 1.25^{a}	34.93 ± 0.92^{a}
	154	10	33.59 ± 4.17^{a}	32.80 ± 1.38^{a}	32.38 ± 1.32^{a}	32.92 ± 1.68^{a}	32.60 ± 0.54^{a}	31.68 ± 0.55^{b}	32.39 ± 1.22^{b}
		22		32.28 ± 1.28^{a}	31.52 ± 0.84^{a}	30.70 ± 0.94^{a}	32.78 ± 0.66^{a}	33.76 ± 1.51^{a}	34.88 ± 0.87^{a}
	205	10	33.37 ± 0.82^{a}	32.63 ± 1.51^{a}	32.32 ± 0.65^{a}	32.50 ± 1.46^{a}	32.70 ± 0.55^{a}	31.72 ± 1.33^{b}	32.49 ± 1.17^{b}
		22		32.49 ± 1.26^{a}	31.51 ± 0.61^{a}	30.69 ± 0.55^{a}	32.84 ± 0.66^{a}	33.86 ± 0.50^{a}	35.15 ± 0.58^{a}
Hue	100	10	0.92 ± 0.05^{a}	0.90 ± 0.04^{a}	0.85 ± 0.04^{a}	0.77 ± 0.02^{a}	0.71 ± 0.05^{a}	0.67 ± 1.04^{a}	0.61 ± 0.02^{a}
		22		0.86 ± 0.37^{ab}	0.76 ± 0.04^{b}	0.67 ± 0.02^{a}	0.53 ± 0.02^{c}	0.44 ± 0.44^{c}	0.39 ± 0.01^{c}
	154	10	0.88 ± 0.08^{a}	0.87 ± 0.01^{a}	0.80 ± 0.03^{a}	0.70 ± 0.05^{a}	0.61 ± 0.00^{b}	0.53 ± 0.04^{b}	0.49 ± 0.01^{b}
		22		0.80 ± 0.03^{b}	0.65 ± 0.01^{c}	0.54 ± 0.01^{c}	0.39 ± 0.00^{d}	0.34 ± 0.02^{d}	0.32 ± 0.01^{d}
	205	10	0.89 ± 0.02^{a}	0.84 ± 0.03^{a}	0.79 ± 0.04^{a}	0.70 ± 0.05^{a}	0.60 ± 0.03^{b}	0.52 ± 0.04^{b}	0.48 ± 0.02^{b}
		22		0.78 ± 0.03^{b}	0.65 ± 0.02^{c}	0.54 ± 0.03^{a}	0.38 ± 0.01^{d}	0.34 ± 0.02^{d}	0.03 ± 0.02^{d}
CI	100	10	0.75 ± 0.08^{a}	0.79 ± 0.06^{c}	0.88 ± 0.07^{c}	1.02 ± 0.04^{c}	1.15 ± 0.11^{d}	1.25 ± 0.11^{d}	1.41 ± 0.07^{b}
		22		0.86 ± 0.08^{bc}	1.04 ± 0.10^{b}	1.25 ± 0.05^{b}	1.70 ± 0.16^{b}	2.09 ± 0.12^{b}	2.41 ± 0.11^{b}
	154	10	0.82 ± 0.14^{a}	0.84 ± 0.02^{c}	0.97 ± 0.07^{bc}	1.19 ± 0.14^{b}	1.44 ± 0.03^{c}	1.73 ± 0.20^{c}	1.88 ± 0.05^{c}
		22		0.97 ± 0.07^{ab}	1.29 ± 0.03^{a}	1.65 ± 0.07^{b}	2.42 ± 0.06^{a}	2.77 ± 0.20^{a}	3.04 ± 0.19^{a}
	205	10	0.84 ± 0.04	0.88 ± 0.06^{abc}	0.98 ± 0.09^{bc}	1.18 ± 0.13^{b}	1.45 ± 0.10^{c}	1.74 ± 0.21^{bc}	1.94 ± 0.11^{c}
		22		0.99 ± 0.06^{a}	1.31 ± 0.06^{a}	1.67 ± 0.12^{b}	2.47 ± 0.10^{a}	2.82 ± 0.23^{a}	3.21 ± 0.28^{a}
COL	100	10	26.47 ± 2.09^{a}	28.38 ± 2.07^{c}	30.84 ± 1.60^{c}	31.48 ± 1.28^{c}	34.46 ± 1.28^{d}	36.56 ± 0.33^{d}	41.79 ± 1.46^{b}
		22		30.48 ± 1.19^{bc}	36.28 ± 1.70^{b}	43.36 ± 0.99^{b}	52.69 ± 1.37^{b}	55.12 ± 1.37^{b}	63.84 ± 1.40^{b}
	154	10	28.59 ± 3.41^{a}	30.05 ± 1.70^{c}	47.49 ± 2.39^{bc}	41.24 ± 3.32^{b}	50.25 ± 3.32^{c}	56.77 ± 3.17^{c}	60.23 ± 0.80^{c}
		22		36.30 ± 1.63^{ab}	35.17 ± 1.73^{a}	60.96 ± 2.37^{b}	79.01 ± 3.89^{a}	92.17 ± 7.80^{a}	104.35 ± 7.02^{a}
	205	10	28.44 ± 1.69^{a}	31.36 ± 1.43^{abc}	35.93 ± 3.30^{bc}	41.28 ± 2.06^{b}	49.81 ± 2.06^{c}	56.87 ± 3.31^{ab}	60.25 ± 2.07^{c}
		22		37.02 ± 3.22^{a}	48.09 ± 3.15^{a}	61.06 ± 2.68^{b}	75.17 ± 4.50^{a}	93.58 ± 5.84^{a}	106.44 ± 75.38^{a}

ST, storage temperature; CI, color index; COL, tomato color index.

3.2.3. Firmness

Tomato fruit firmness significantly influenced by transport distance (p = 0.0129), storage temperature (p = 0.0012), and storage duration (p = 0.0036) (Figure 9). Overall, firmness decreased drastically during the period of storage at both storage temperatures in all distances of transported tomato. In this study, as distance duration increases, the firmness of the tomato reduces. Firmness reduced by 50.82%, 51.44, and 58.39% for short, medium, and long-stored at 22 °C, respectively (Figure 9). However, the reduction in firmness at 10°C was 28.36%, 33.69%, and 37.12% for the same distances, respectively. The results indicated that the maximum acceleration occurrence can affect the firm state of the longest distance transported tomatoes. The distribution of fresh produce during transportation can cause critical problems affecting ripening and firmness [12]. In terms of storage conditions, ambient temperature can cause a continuous reduction in tomato firmness due to moisture loss through transpiration and enzymatic changes [37] which can degrade tomato cell wall [45,51]. Texture/firmness reduction is attributed to different factors like losses in cell turgor pressure as well as the cell wall and polysaccharides degradation. Besides, the firmness state is closely correlated with the ripening stage of the fresh produce that causes a rapid increase in enzyme activity [16]. Furthermore, Zhou et al. [44] determined that firmness reduction and softening can occur due to the active state of pectic enzymes and cellulose on polysaccharides in the cell wall of the product. Jung and Park [16] experienced a firmness reduction on vibrated tomato with 33.2% compared to 21.9% of the control group for 30 days storage. Zhou et al. [44] also found that pear fruit exposed to less vibration stress retained higher firmness. Pear fruit exposed to high transit time and stored at ambient temperature had a higher softening rate. The findings of this study agreed with the findings reported by Munhuewyi [7], Park et al. [41], and Kabir et al. [25] who recorded similar reduction trends of et tomato firmness at cold and ambient temperature. Al-Dairi et al. [1] also recorded a 67.80% reduction in tomato firmness at ambient temperature for 12 days.

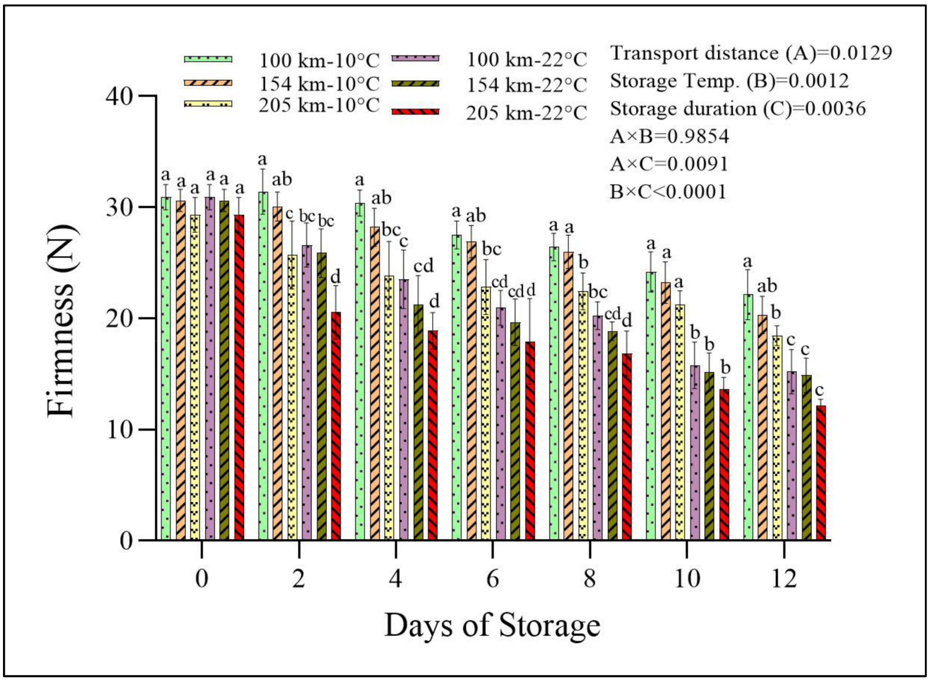

Figure 9. The firmness of tomatoes from three different distances stored at (A) 10 ± 0.5 °C (95 ± 1% RH) and (B) 22 ± 1 °C (65 ± 5% RH) for 12 days. Error bars represent standard error (SE) of the mean values ±S.E. of 10 measurements (readings) of 5 tomato replicates. Bars with different letters (per day) are significantly different ($p < 0.05$) performed by the Tukey HSD test and numerical values of A, B, and C are p-values.

4. Conclusions

The results of this study indicated that vibration generated from different transportation distances significantly affected tomato physical quality parameters. Storage temperature and duration were also found to have a significant impact on the physical quality attributes like weight, color, and firmness. Among all studied distances, long transportation distances highly increased weight and firmness reduction and produced greater color changes during storage. Moreover, storage at ambient temperature conditions (22 °C) accelerated all of these quality changes for 12 days storage period. Nevertheless, storage at a lower temperature (10 °C) showed slower reductions and enhancement of the studied parameters as affected by transport distance, storage time, and storage condition. The results of this study can help the industrial sector to avoid all the critical issues during the transport and storage of fresh produce. In this way, adequate packaging, transportation, and handling facilities, and storage temperature management, need to be available to reduce all expected damages due to transportation and storage.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/horticulturae7070163/s1, Table S1: the three-way analysis of variance (ANOVA) of chroma, hue, CI, and COL color parameters.

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