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Bruise Damage and Quality Changes in Impact-Bruised, Stored Tomatoes

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Abstract: This study examined three main possible effects (impact, storage temperature, and duration) that cause and extend the level of bruising and other quality attributes contributing to the deterioration of tomatoes. The impact threshold level required to cause bruising was conducted by subjecting tomato samples to a steel ball with a known mass from different drop heights (20, 40, and 60 cm). The samples were then divided and stored at 10 and 22 °C for 10 days for the further analysis of bruise area and any physiological, chemical, and nutritional changes at two day intervals. Six prediction models were constructed for the bruised area and other quality attribute changes of the tomato. Storage time, bruise area, weight loss, redness, total color change, color index, total soluble solids, and pigments content (lycopene and carotenoids) showed a significant ($p < 0.05$) increase with the increase of drop height (impact level) and storage temperature. After 10 days of storage, high drop impact and storage at 22 °C generated a higher reduction in firmness, lightness, yellowness, and hue° (color purity). Additionally, regression model findings showed the significant effect of storage duration, storage temperature, and drop height on the measured variables (bruise area, weight loss, firmness, redness, total soluble solids, and lycopene) at a 5% probability level with a determination coefficient (R^2) ranging from 0.76 to 0.95. Bruising and other quality attributes could be reduced by reducing the temperature during storage. This study can help tomato transporters, handlers, and suppliers to understand the mechanism of bruising occurrence and how to reduce it.

Keywords: bruising; drop height; storage; tomato; prediction model

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1. Introduction

Tomato fruits are a significant component of many human diets and their quality is also very important [1]. Unfortunately, fresh produce like the tomato is very susceptible to mechanical damage during harvesting, transporting, and packaging, and quality can be substantially decreased by poor handling [2]. Mechanical damage can accelerate the deterioration of the whole produce during the supply chain system which can increase losses by 51%, which is considered a critical economic and food safety problem [3].

Opara and Pathare [4] reviewed that bruising is the most common form of mechanical damage that occurrs during the harvesting-consumption system. Bruising is a type of failure in the subcutaneous tissue that occurs without rupture of the fresh produce skin. The discoloration that exists in the injured tissue indicates the presence of the damaged area. Based on the degree of damage, Sun et al. [5] highlighted that the presence of bruises may take more than 12 h of incubation to become visible, which may not be recognized until the products reach consumers at the point of consumption. According to Opara and Pathare [4], bruising can occur due to excessive vibration and impact during dynamic loading. Xia et al. [6] and Hussein et al. [7] stated that dropping the product against another surface material is another cause of fresh produce bruising.

Generally, bruising is originated from cell membrane breakage, which leads to a loss in cell wall integrity and other subsequent reductions in peel resistance due to mechanical damages [8]. The presence of bruising can accelerate the physiological [5] and metabolic activities that lead to internal browning, faster ripening, and a loss of the quality attributes of fresh produce [4]. Bruising can affect the textural properties of Yali pear [9], kiwifruits [10], tomato [11], and "Galaxy" apples [12]. Besides, bruising accelerates an increase in lycopene content for tomato [11], weight loss, respiration rate, total soluble solids, titratable acidity, [13], and external color changes during storage for pomegranate, thus, reducing consumer's acceptance of a particular fresh produce [8].

Identifying the impact conditions which can cause bruising is essential to improve harvesting, handling, sorting, and transporting equipment and procedure [14]. Experiments to identify the impact have employed various devices designed to measure a specific impact and an amount of energy during impact on individual vegetables and fruit [15]. Two basic measuring techniques are the pendulum [16–18] and the drop test method [5–7,11,19].

Bruise damage is considered as a measure of external loading which mostly depends on post-climacteric factors such as temperature [11]. Temperature accelerates tissue flexibility and increases the bruising damage of fresh products [20]. Hence, the objective of this study is to investigate the extent of bruising and other quality attribute changes of tomato as affected by three drop impact levels and storage at two different conditions for a specific time. Prediction (regression) models were also performed to emphasize the effect of independent variables (drop height, storage temperature, and storage duration) on some dependent variables (bruise area, weight loss, firmness, redness, total soluble solids, and lycopene) for 10 days.

2. Materials and Methods

2.1. Plant Material, Bruise Measurement, and Storage

Fresh tomato samples of the "Miral" variety were packed in wooden boxes obtained from a local market (Al-Mawalih, Muscat, Oman). Tomato samples were harvested at the mature stage from a tomato farm located in Al-Suwaiq, North Al-Batinah, and delivered to the Postharvest Technology Research Laboratory at Sultan Qaboos University, Muscat, Oman. A total of 111 tomatoes of uniform color and weight (104.4 ± 1.53 g) without any physical defects like sunburn, cracking, bruising, and blemishes, were selected for the experiment. Tomato bruising was carried out in the laboratory using the drop test method as described by Hussein et al. [7]. In this method, a steel ball impactor (110.05 g) was dropped freely through a PVC hollow pipe from pre-determined drop heights; 20 cm, 40 cm, and 60 cm for low, medium, and high impact levels, respectively (Figure 1). Prior to the impact test, some fruits were analyzed for day-0 analysis ($n = 3$). A total of 108 tomato fruits were subjected to an impact ($n = 36$ fruit per drop height). After the impact test, the created bruise region of the tomato fruit was marked to facilitate bruise measurements.

Immediately after the fruit were damaged, the samples from each impact level were divided equally and stored at 10 °C (85 ± 5% RH) and 22 °C (45 ± 5% RH). Further measurements of bruise area, physical (weight loss, firmness, and color), chemical (total soluble solids), and nutritional (lycopene and carotenoids) analyses were performed at 2 day intervals for the 10 day storage period. In the current study, a total of three replicates were used per treatment.

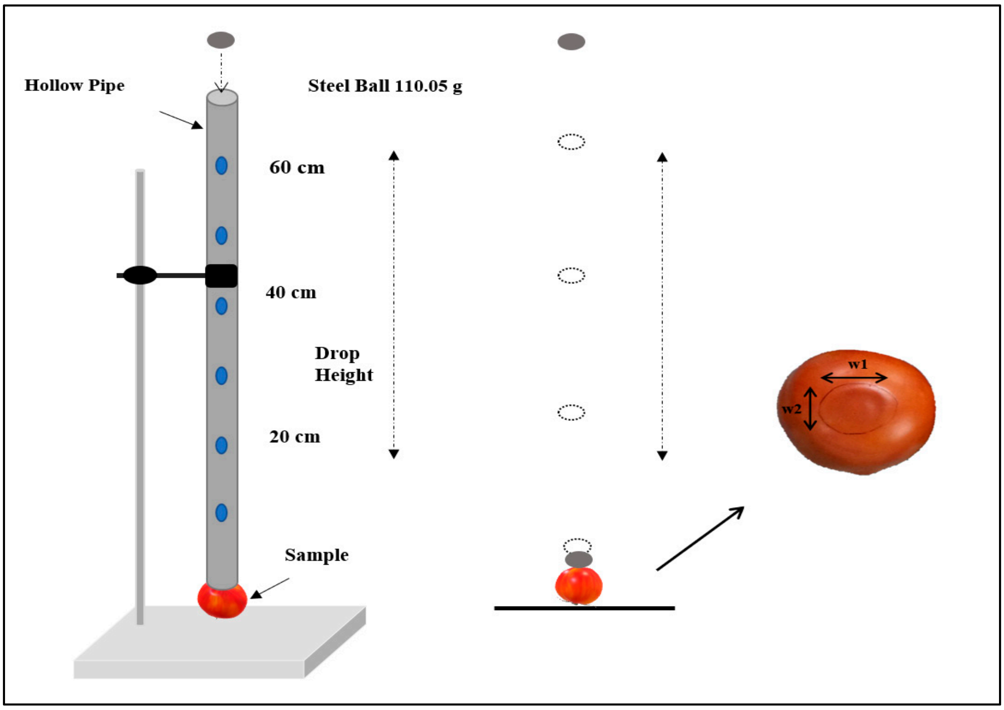

Figure 1. Schematic experimental setup. w_1 and w_2 are major and minor widths (diameter).

Based on Equation (1), the impact energy (*Ei*, mJ) resulting from each drop height was 215.91 mJ, 431.83 mJ, and 647.75 mJ for low, medium, and high impact levels, respectively [7].

$$E_i = m_b g h \tag{1}$$

where E_i is the impact energy, m_b is the mass of dropped ball (110.05 g), g is the gravitational constant (9.81 ms^{-2}), and h is the drop height in cm. The bruise area (BA, mm^2) of the tomato fruit was measured by performing the following equation (Equation (2)):

$$BA = \frac{\pi}{4} w_1\, w_2 \tag{2}$$

where BA is the bruise area and w_1 and w_2 are major and minor widths (diameter) (Figure 1). The diameter was measured by using the digital caliper (Model: Mitutoyo, Mitutoyo Corp., Kawasaki, Japan).

2.2. Determinations of Weight Loss, Firmness, and Color

A total of 18 tomatoes with uniform size were selected (three per treatment) and weighed prior to and after bruising for 10 days at two day intervals. The percentage of weight loss was measured by subtracting the weight of the tomato samples from their initial weights and expressed as a percentage of the initial weight. This was performed using an electric weight balance (Model: GX-4000, Japan) with an accuracy of ±0.01 g. Two firmness measurements (non-bruised region) were recorded from each replicate per treatment (36 readings per day) using a digital fruit firmness tester (Model: FHP-803, L.L.C., USA) and expressed as N. A total of 108 external color readings were recorded per day (6 per replicate for the non-bruised region) using the computer vision system technique as described by Al-Dairi et al. [21]. The measured color was expressed as L* (lightness), a* (redness or greenness), and b* (yellowness or blueness). Total color difference (ΔE^*) (Equation (3)), chroma (Equation (4)), hue° (Equation (5)), and color index (CI) (Equation (6)) were also calculated [22] as follows:

$$\Delta E* = \sqrt{\Delta \mathrm{a}*^2 + \Delta \mathrm{b}^2 + \Delta \mathrm{L}*^2} \tag{3}$$

$$Chroma = \sqrt{a*^2 + b*^2} \tag{4}$$

$$Hue^\circ = \tan^{-1}\left(\frac{\mathrm{b}*}{\mathrm{a}*}\right) \tag{5}$$

$$CI = a^*/b^* \tag{6}$$

2.3. Determinations of Total Soluble Solids (TSS), Total Lycopene, and Carotenoids

An extraction of tomato juice was obtained by homogenizing three tomato fruits of each drop impact stored at both storage conditions for one minute using a food blender (Model: LM2201, Moulinex, Jianmen, China). The extracted juice was filtered using a muslin cloth. A total of 36 readings per day (2 × 18 replicates) of total soluble solids were determined from all treatments by adding one to two clear drops of the juice on the prism surface of the digital refractometer (Model: PR-32 α, ATAGO Co., Ltd., Tokyo, Japan), presented as °Brix [23]. Previously prepared juice was used to measure lycopene and carotenoid pigments and both were determined by using the spectrophotometric method as explained by Munhuewyi [24]. Two readings of total lycopene and carotenoid pigments were taken from each tomato juice per treatment. Total lycopene and carotenoid contents were calculated based on the following Equations (7) and (8):

$$Total\ Carotenoids\left(\mu g.g^{-1}\right) = \frac{OD_{502} \times 4}{mass\ of\ the\ sample\ (g)} \times 1000 \tag{7}$$

$$Total\ lycopne\ \left(\mu g.g^{-1}\right) = \frac{OD_{502} \times 3.12}{mass\ of\ the\ sample\ (g)} \times 1000 \tag{8}$$

2.4. Regression Model

Sometimes, two or more independent variables have a significant effect on a dependent variable. In this case, multiple regression is performed to predict the dependent variable [25]. In this study, six multiple linear regression models were performed to study the effect of independent variable (drop height, storage temperature, and storage duration) on the dependent variables (bruise area, weight loss, firmness, redness, total soluble solids, and lycopene) at a 5% significance level. Furthermore, to determine the accuracy of each model, a determination coefficient (R^2) was recorded.

2.5. Statistical Analysis

The analysis of all obtained data was performed using SPSS 20.0 (International Business Machine Crop., Armonk, NY, USA). The data were subjected to three-way analysis of variance (ANOVA) (factor A: drop height; factor B: storage condition; factor C: storage duration) where the mean values were considered at a 5% significance level ($p < 0.05$). All resulted data were expressed in mean ± standard deviation. The Pearson correlation coefficient was carried out to assess the relationship among the dependent variables (bruise area and other quality parameters) subjected to an impact from three different heights and stored at two temperature conditions.

3. Results

3.1. Effect on Bruise Area

The bruise area (*BA*) values during storage for 10 days are presented in Figure 2. *BA* was affected by drop height ($p = 0.0001$), storage temperature ($p < 0.0001$), and storage duration ($p < 0.0001$) (Table S1). Storage at 10 °C and impact from the lowest level (20 cm) were much more effective in slowing down the occurrence of *BA* (201.87 mm^2) compared to impact levels from 40 cm (234.93 mm^2) and 60 cm (297.98 mm^2) drop heights at the same storage conditions on the last day of storage. A higher *BA* was recorded on the tomatoes impacted from the high drop height (impact energy = 647.75 mJ) stored at room temperature, with 344.95 mm^2. Generally, as drop height, storage condition, and storage duration increased, *BA* increased. Tabatabaekoloor [14] found similar results for peach bruising. They found that increasing the drop height from 5 to 15 cm increased *BA* by 15% due to the increase in the potential energy which accelerates the contact intensity. Experimentally, Hussein et al. [13] showed a positive correlation between the drop height and *BA* occurrence in pomegranate. Regarding storage conditions, Cui et al. [2] found that bruising incidence in tomatoes is less severe as temperatures are reduced. Table 1 presents the final *BA* model (1) which includes all the independent variables. For this model, the plot of predicted *BA* versus measured *BA* is shown in Figure 3. A strong fit with $R^2 = 0.95$ was observed between the measured and predicted *BA* values.

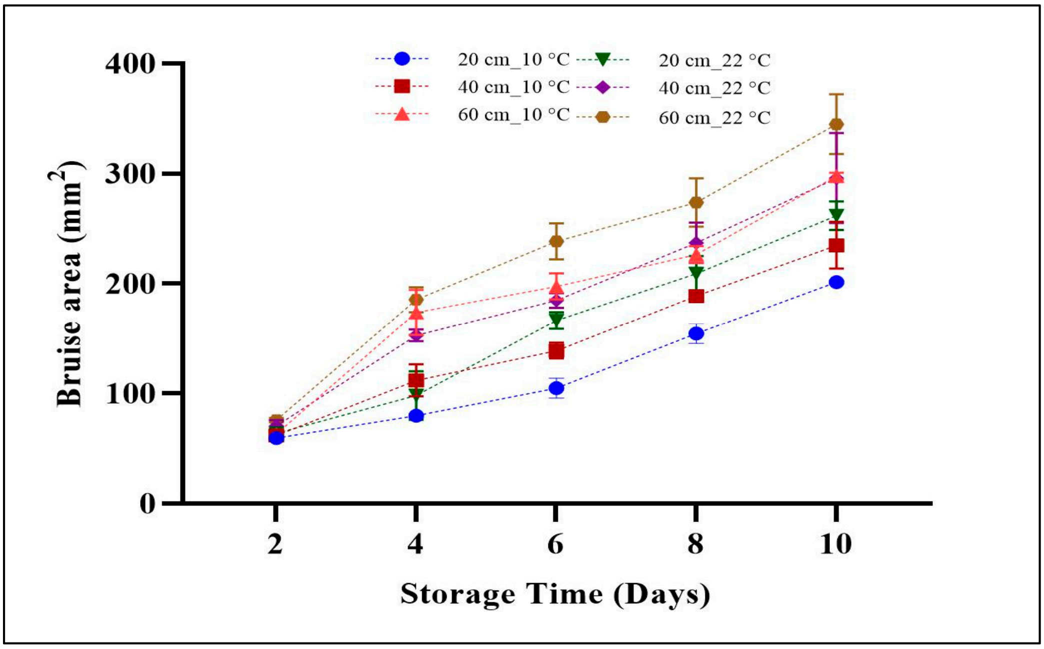

Figure 2. Bruise area of tomato impacted at different drop heights (20 cm, 40 cm, and 60 cm) for 10 days stored in 10 °C and 22 °C storage conditions. Error bars represent the standard deviation (SD) of the mean values ± S.D. of three readings of three replicates.

Table 1. Linear regression equations of bruise area (*BA*), weight loss (WL), firmness (F), total soluble solids (TSS), and lycopene in relation to storage duration (SD), temperature (T), and drop height (DH) as independent variables.

Model	Equation	Adjusted R^2	Residuals	
			Min	Max
1	$BA = -92.472 + 26.42\ SD + 31.35\ T + 28.251\ DH$	0.95	−54.99	44.52
2	$WL = -5.867 + 0.612\ SD + 3.263\ T + 0.533\ DH$	0.87	−2.27	2.53
3	$F = 31.968 - 0.698\ SD - 3.031\ T - 0.849\ DH$	0.86	−2.04	2.68
4	$a^* = 18.017 + 1.143\ SD + 2.158\ T + 1.100\ DH$	0.91	−2.13	3.20
5	$TSS = 3.837 + 0.056\ SD + 0.115\ T + 0.085\ DH$	0.88	−0.15	0.19
6	$Lycopene = 0.231 + 0.043\ SD + 0.254\ T + 0.071\ DH$	0.76	−0.29	0.25

WL = weight loss; SD = storage day; T = temperature; DH = drop height; F = firmness; a* = redness; TSS = total soluble solids. Minimum probability threshold $p < 0.05$.

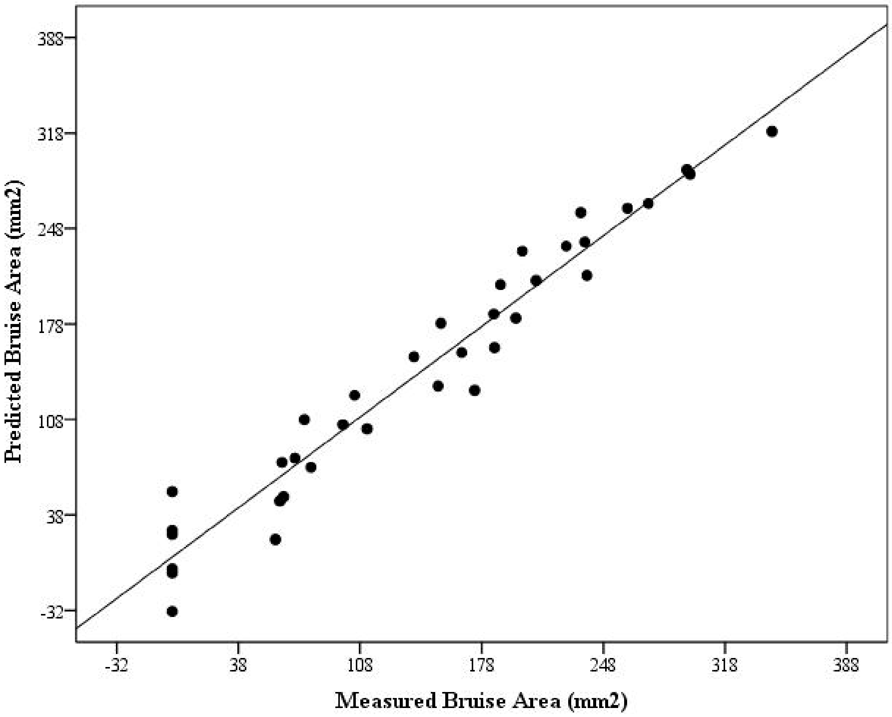

Figure 3. Results for the prediction of bruise area (*BA*) values based on linear regression models. Predicted *BA* versus measured *BA* (model 1).

3.2. *Effect on Physical Auality Attributes*

3.2.1. Effect on Weight Loss

Weight loss (WL)% varied in the tomato depending on drop height ($p = 0.0218$), storage temperature ($p = 0.0298$), and storage duration ($p < 0.0001$) (Table S1). High (60 cm) and medium (40 cm) impact bruised tomato had a higher WL% than the tomato with low (20 cm) drop impact at both storage conditions during storage (Figure 4). At the end of the 10 days of room temperature storage, WL reached 10.91%, 9.35%, and 8.70% for the high, medium, and low drop-impacted bruised tomatoes, respectively. However, storage at 10 °C showed less reduction in WL with 3.88%, 3.15%, and 1.77% for the high, medium, and low drop-impacted bruised tomatoes, respectively. The recorded higher WL% in the bruised produce could be attributed to tissue damage and possible alterations of the cell wall tissue permeability that resulted in a higher rate of transpiration during storage [26]. In terms of storage temperature conditions, Al-Dairi and Pathare [27] observed a high reduction in WL% in tomato fruit stored at room temperature due to respiration and water dehydration processes compared to storage at a cold temperature during 12 days of storage. The results of the linear regression analysis between WL% and the independent variables (storage duration, storage temperature, and drop height) are presented in Table 1. Figure 5 presents the predicted WL% plotted against the measured WL% in relation to the independent variables (model 2). A good fit with a determination coefficient (R^2) of 0.87 was obtained between the predicted and measured WL%.

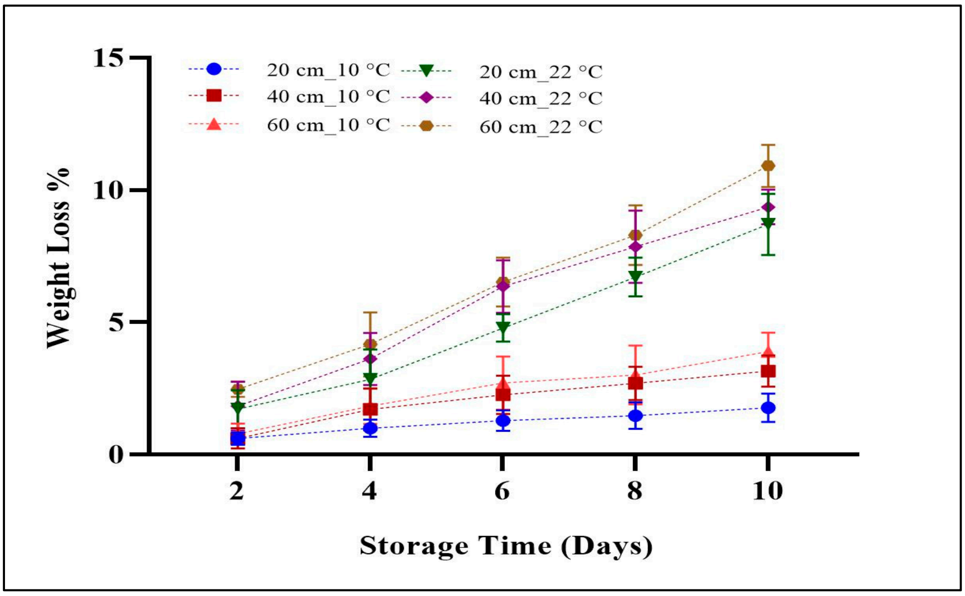

Figure 4. Weight loss (%) of tomato impacted at different drop heights (20 cm, 40 cm, and 60 cm) and stored for 10 days in 10 °C and 22 °C storage conditions. Error bars represent the standard deviation (SD) of the mean values ± S.D. of three replicates.

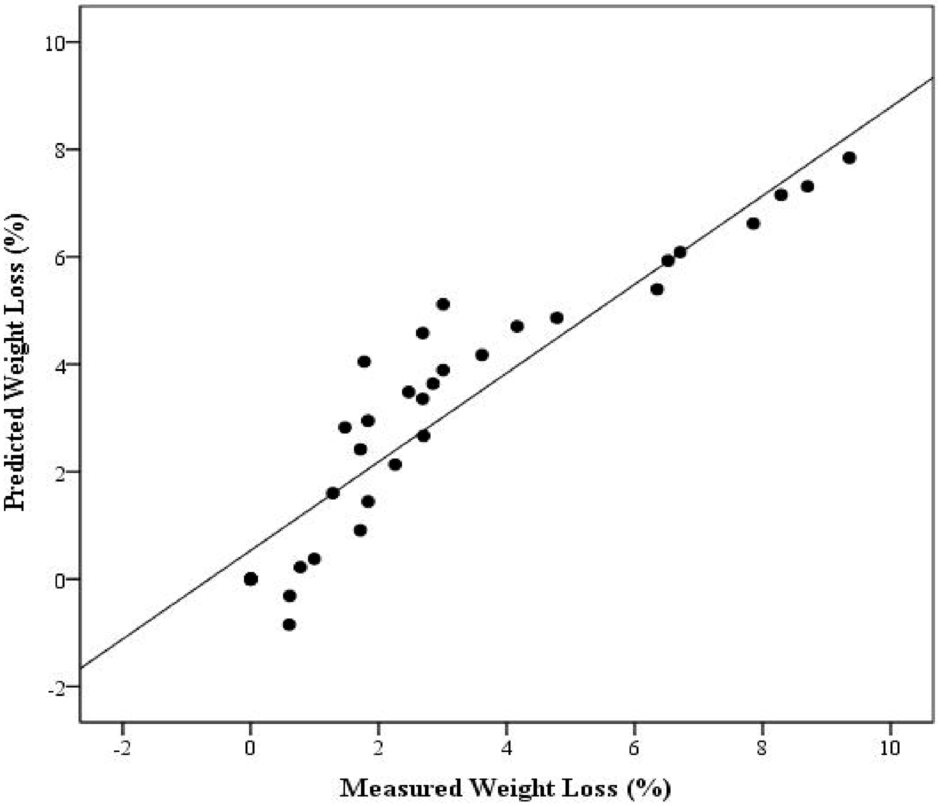

Figure 5. Results for the prediction of weight loss (WL) values based on linear regression models.

3.2.2. Effect on the Firmness

After drop tests and storage, the firmness values of the tomatoes decreased significantly ($p < 0.05$) (Table S1). Prior to the impact test, the initial value of firmness was 26.04 N. Firmness reduction was the highest after 10 days of storage at room temperature with high (15.32 N), medium (17.04 N), and low (19.08 N) drop-impacted bruised tomatoes, respectively (Figure 6). On the 10th day of storage at 10 °C, firmness declined and reached 20.25, 21.20, and 22.41 N for the high, medium, and low drop-impacted bruised tomatoes, respectively. As observed, the firmness of the tomato declined gradually at both storage conditions for all impact levels, however, the reduction was higher in the tomatoes bruised from the highest level stored at room temperature. Similar results were recorded by Cui et al. [2], where the firmness loss in the bruised tomato increased with the increase in the drop impact height. Additionally, Buccheri and Cantwell [11] recorded higher firmness reduction with high (99 cm) drop impact levels compared to 33 cm and 66 cm drop impact levels, respectively. Besides, Azadbakht et al. [17] and Hussein et al. [26] found that increasing the drop impact level (height) decreased the firmness status of stored apple and pomegranate, respectively. Storage at room temperature (22 °C) increased enzyme activity and resulted in higher cell wall and polysaccharide degradation, thus, reduced the firmness of tomato [27] which is mostly accelerated by increasing the impact level as revealed in the current study. Table 1 presents the results of the linear regression analysis between firmness (F) and the independent variables (storage duration, storage temperature, and drop height). For the firmness prediction model (3), the plot of measured firmness versus the predicted firmness is depicted in Figure 7. A good fit was observed between the measured and predicted firmness (R^2 = 0.86).

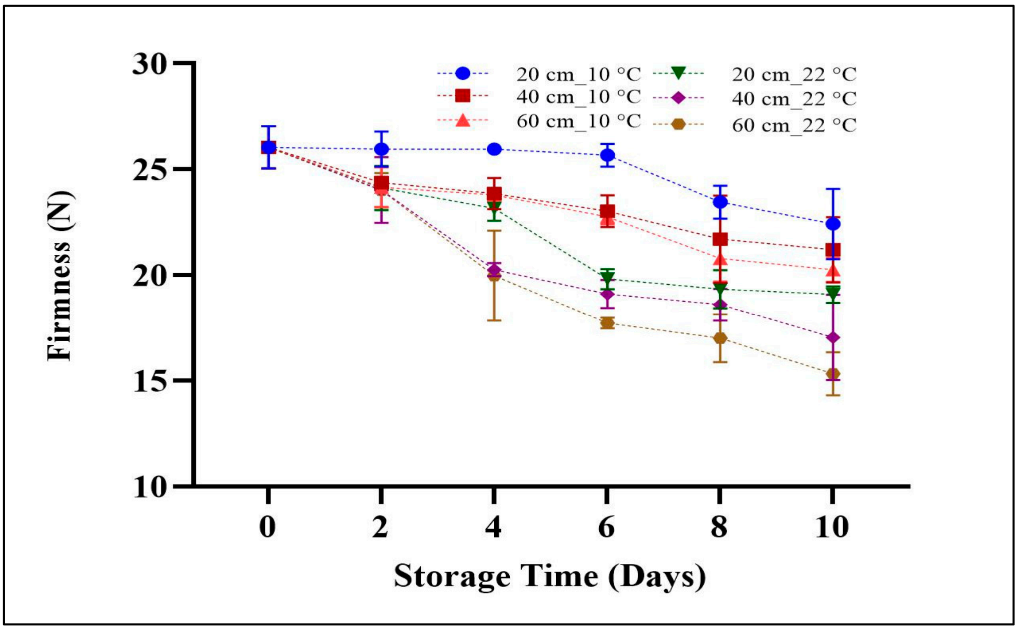

Figure 6. The firmness of tomato impacted at different drop heights (20 cm, 40 cm, and 60 cm) and stored for 10 days in 10 °C and 22 °C storage conditions. Error bars represent the standard deviation (SD) of the mean values ± S.D. of six readings of three replicates.

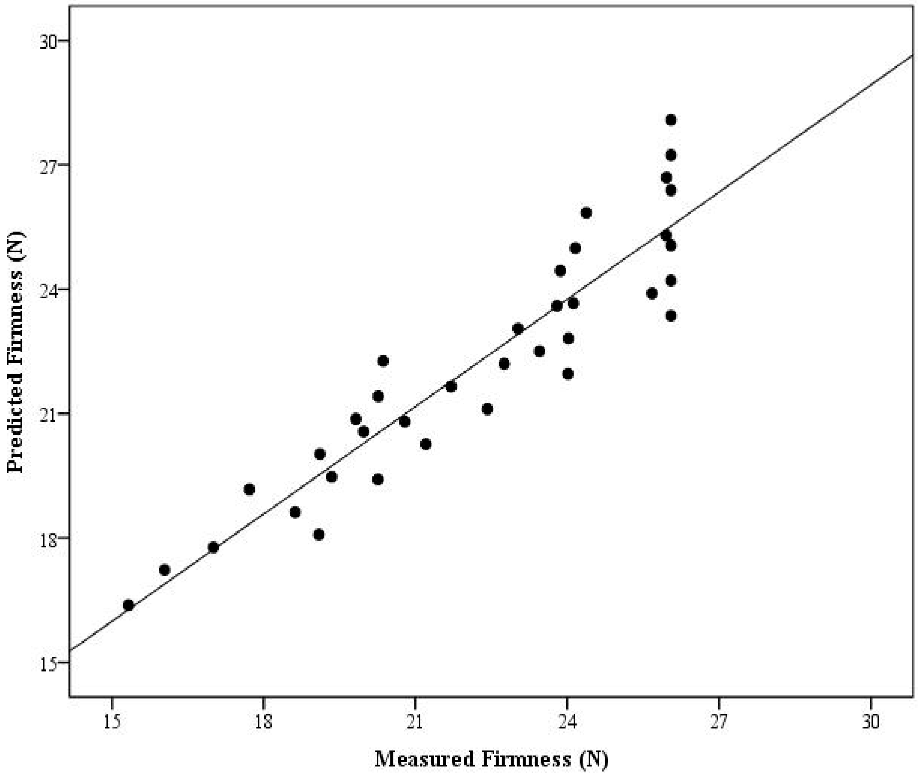

Figure 7. Results for the prediction of firmness values based on the linear regression models.

3.2.3. Effect on Color

All color attributes lightness (L*), redness (a*), and yellowness (b*), total color change (Δ*E**), hue°, and color index (CI) were significantly ($p < 0.05$) influenced by all studied factors storage duration, storage temperature, and drop height. However, chroma was not affected by storage temperature and storage duration (Table S1). With storage time, a decreasing trend in the color attributes of L* and b*, and hue° and an increasing trend in a*, Δ*E**, and CI values were observed in all impacted tomatoes at both storage conditions. L* reduction was higher for the high impact bruised tomatoes (14.68) compared to the medium (19.19) and low (21.49) drop-impacted bruised tomatoes at the end of storage at 22 °C. Storage at 10 °C showed less reduction in L* values for the high, medium, and low drop-impacted bruised tomatoes (Figure 8A). In contrast, storage at room temperature showed a maximum development of redness a* value on the last day of storage for the high-impact bruised tomatoes. The highest value of a* was observed on the 10th day of storage for the high-impact bruised tomatoes (39.43) stored at 22 °C (Figure 8B). The b* value (Figure 8C) decreased gradually with storage duration and was statistically lower in tomatoes bruised from the highest impact level (60 cm) and stored at room temperature (22 °C). On the last day of storage, the b* values were 18.82, 19.43, and 19.66 for the high, medium, and low drop-impacted bruised tomatoes stored at 22 °C. Similar observations were made by Lee et al. [28], who observed a lightness (L*) reduction in bruised tomatoes at room temperature. Besides, Hussein et al. [13] recorded the significant effect of drop height and storage duration on the red color value of pomegranate, where fruit appeared redder after 12 weeks of storage. In this study, storage at room temperature accelerated the increase of lightness L* reduction due to tomato darkening as a result of carotenoids synthesis and an increased redness a* value due to lycopene synthesis and chlorophyll degradation [27]. Additionally, Al-Dairi et al. [21] found a significant reduction in the yellowness b* value of the tomato stored at 22 °C after 12 days of storage.

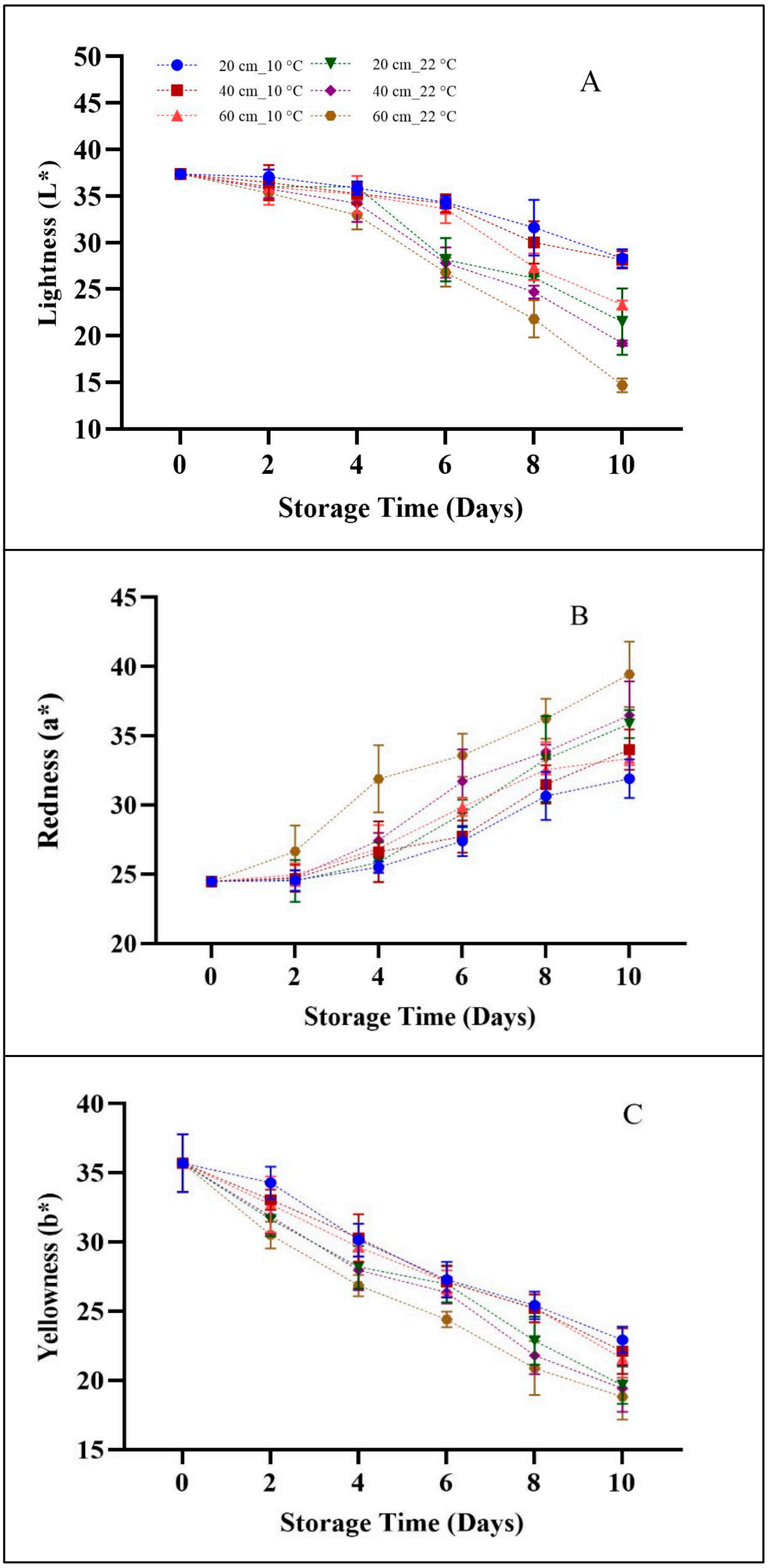

Figure 8. Lightness (**A**), redness (**B**), and yellowness (**C**) of the tomato impacted at different drop heights (20 cm, 40 cm, and 60 cm) and stored for 10 days at 10 °C and 22 °C storage conditions. Error bars represent the standard deviation (SD) of the mean values ± S.D. of 18 readings of three replicates.

Table 1 presents the final a* model (4) which includes all independent variables (storage duration, storage temperature, and drop height). For this model, the plot of predicted a* values versus measured a* values is shown in Figure 9. A strong fit with the determination of coefficient (R^2) = 0.91 was observed between the measured and predicted a * values.

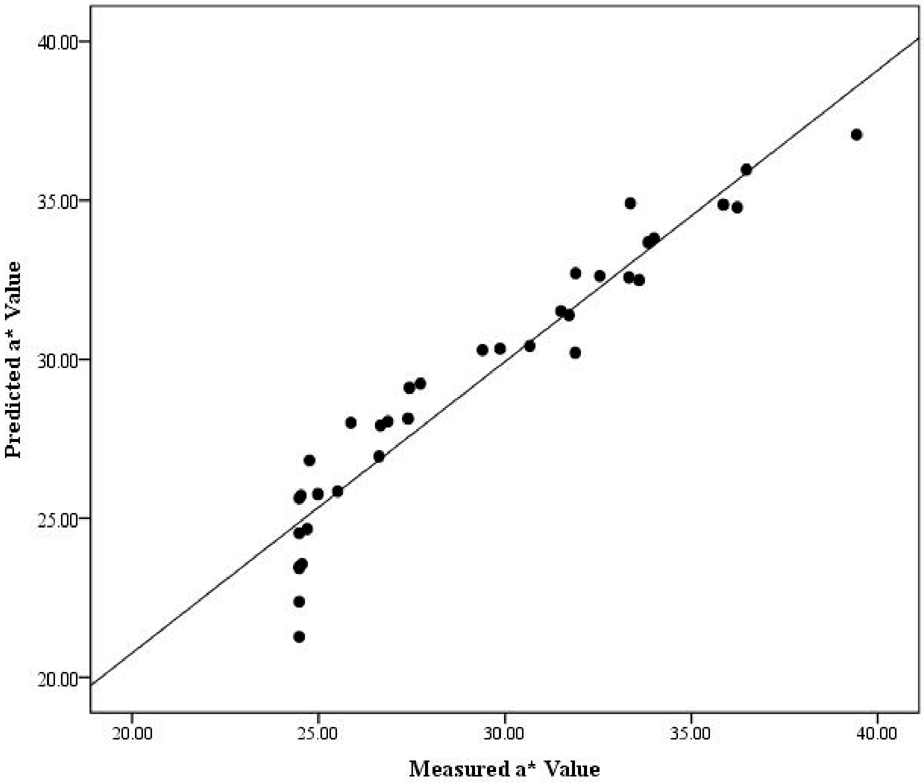

Figure 9. Results for the prediction of redness (a*) values based on linear regression models.

The obtained results in total color change (Δ*E**) after 10 days of storage were significantly higher for highly (32.04) impacted bruised tomatoes followed by the medium (27.35) and low (25.37) impact-bruised tomatoes stored at room temperature (22 °C) (Table 2). Storage at 10 °C and a low impact reduced the increase of Δ*E** for all bruised tomatoes after 10 days of storage. Generally, higher bruising induced higher color discoloration due to the increase in the ripening process of pear Bodner and Scampicchio [29]. Besides, Hussein et al. [8] revealed the significant influence of drop height, storage duration, and storage temperature on the Δ*E** of pomegranate fruit. Chroma showed a fluctuated value during storage at both storage conditions (Table 2). However, on the last day of storage, the highest (43.70) and lowest (39.30) values of chroma were observed for the high and low impacted tomato fruit stored at 10 and 22 °C, respectively. Table 2 shows that the color purity (hue°) of the tomato sample declined sharply until the end of the storage duration, particularly for high-impact bruised tomatoes stored at room temperature (22 °C). Overall, the rate of reduction in hue° for high (647.75 mJ), medium (431.83 mJ), and low (215.91 mJ) drop-impacted bruised tomatoes was lower at 10 °C storage conditions after 10 days of storage. Dobrzanski and Rybezynski [30] found that the color attributes of bruised apples were significantly affected by bruise damage. The gradual decline in hue° at room temperature is attributed to the natural relation between storage conditions and biochemical reactions which increase with an increase of temperature [1].

Table 2. The values of total color difference (Δ*E*), chroma, hue°, and color index (CI) changes of tomato during 10 days at two different temperatures and three drop heights. Error bars represent the standard deviation (SD) of the mean values ± S.D. of 18 readings of three replicates.

Quality Parameter	**Storage Temp.**	**Drop Height**	**Storage Days**					
			0	**2**	**4**	**6**	**8**	**10**
Δ*E**	10 °C	20 cm	0	1.81 ± 0.93	5.87 ± 1.30	9.48 ± 0.85	13.49 ± 2.16	17.35 ± 1.42
		40 cm		3.56 ± 2.34	6.61 ± 0.93	9.71 ± 1.12	14.73 ± 1.07	19.04 ± 1.44
		60 cm		3.81 ± 2.03	7.25 ± 0.45	11.02 ± 2.04	17.19 ± 2.06	21.88 ± 2.03
	22 °C	20 cm		4.49 ± 1.08	8.32 ± 0.84	13.72 ± 1.68	19.33 ± 0.95	25.37 ± 2.10
		40 cm		4.23 ± 1.48	9.03 ± 1.00	15.20 ± 3.06	21.12 ± 1.58	27.35 ± 1.93
		60 cm		6.32 ± 1.23	12.44 ± 3.06	18.00 ± 1.98	24.61 ± 2.33	32.04 ± 1.52
Chroma	10 °C	20 cm	43.30 ± 1.76	39.66 ± 1.34	39.50 ± 0.69	38.68 ± 1.34	39.85 ± 1.56	39.30 ± 1.58
		40 cm		41.27 ± 1.07	40.33 ± 2.73	38.81 ± 1.32	40.35 ± 1.26	40.57 ± 2.07
		60 cm		41.19 ± 1.22	40.02 ± 0.81	40.34 ± 0.91	40.63 ± 1.90	39.77 ± 0.57
	22 °C	20 cm		40.05 ± 1.52	38.29± 1.04	39.91 ± 0.37	40.48 ± 2.23	40.91 ± 1.29
		40 cm		40.34 ± 1.25	39.19 ± 1.17	41.25 ± 2.22	40.27 ± 1.01	41.36 ± 2.33
		60 cm		40.55 ± 0.60	41.73 ± 1.41	41.53 ± 1.54	41.87 ± 0.31	43.70 ± 2.79
Hue°	10 °C	20 cm	55.52 ± 0.03	54.37 ± 0.01	49.74 ± 0.03	44.88 ± 0.03	39.68 ± 0.03	35.71 ± 0.02
		40 cm		53.23 ± 0.01	48.72 ± 0.01	44.38 ± 0.02	38.67 ± 0.03	33.01 ± 0.02
		60 cm		52.59 ± 0.04	47.83 ± 0.04	42.22 ± 0.01	36.80 ± 0.02	32.90 ± 0.03
	22 °C	20 cm		52.23 ± 0.03	47.45 ± 0.05	42.51 ± 0.04	34.54 ± 0.07	28.71 ± 0.03
		40 cm		52.12 ± 0.01	45.50 ± 0.03	39.75 ± 0.02	32.76 ± 0.03	28.05 ± 0.04
		60 cm		48.86 ± 0.05	40.16 ± 0.05	36.02 ± 0.01	29.98 ± 0.06	25.49 ± 0.02
CI	10 °C	20 cm	0.69 ± 0.04	0.72 ± 0.01	0.85 ± 0.05	1.01 ± 0.05	1.21 ± 0.08	1.39 ± 0.05
		40 cm		0.75 ± 0.02	0.88 ± 0.02	1.02 ± 0.05	1.25 ± 0.08	1.54 ± 0.06
		60 cm		0.77 ± 0.07	0.91 ± 0.08	1.10 ± 0.03	1.34 ± 0.06	1.55 ± 0.11
	22 °C	20 cm		0.78 ± 0.05	0.92 ± 0.09	1.09 ± 0.09	1.47 ± 0.21	1.83 ± 0.11
		40 cm		0.79 ± 0.02	0.98 ± 0.05	1.20 ± 0.06	1.56 ± 0.09	1.89 ± 0.19
		60 cm		0.88 ± 0.09	1.19 ± 0.12	1.38 ± 0.04	1.75 ± 0.24	2.10 ± 0.08
	Level of significance		Drop impact (A)	Storage temperature (B)	Storage duration (C)	A × B	A × C	B × C
	Δ*E**		=0.0301	=0.0010	=0.0030	=0.0130	=0.0080	<0.0001
	Chroma		=0.0128	=0.0973	=0.0651	=0.0936	=0.4831	=0.0138
	Hue°		=0.0042	=0.0104	<0.0001	=0.0221	=0.1315	=0.0015
	CI		=0.0104	<0.0001	<0.0001	=0.0223	=0.1305	=0.0006

3.3. Effect on Chemical and Nutritional Attributes

3.3.1. Total Soluble Solids (TSS)

TSS were affected by storage duration ($p = 0.0010$), storage temperature ($p = 0.0230$), and drop height ($p = 0.0020$) (Table S1). As shown in Figure 10, the highest TSS content was observed on days 8 and 10 of storage with a value of 4.96 °Brix for the high drop-impacted bruised tomatoes at room temperature storage conditions. The lowest value of TSS (4.53 °Brix) was observed in the tomatoes from the low drop impact group stored at 10 °C. Storage at room temperature (22 °C) increased the TSS content of bruised tomatoes, which is attributed to the conversion of complex sugars (starch) to simpler sugars (e.g., fructose) by the active enzymes [21]. The results are in agreement with the findings of Maia et al. [31], who revealed that the TSS content of banana increased as mechanical bruise damage increased under room temperature storage conditions. The final total soluble solids model (5) which includes all main independent variables (drop height, storage temperature, and storage duration) of this study is presented in Table 1. In Figure 11, the plot of the predicted TSS values versus measured TSS values is presented with a good fit ($R^2 = 0.88$).

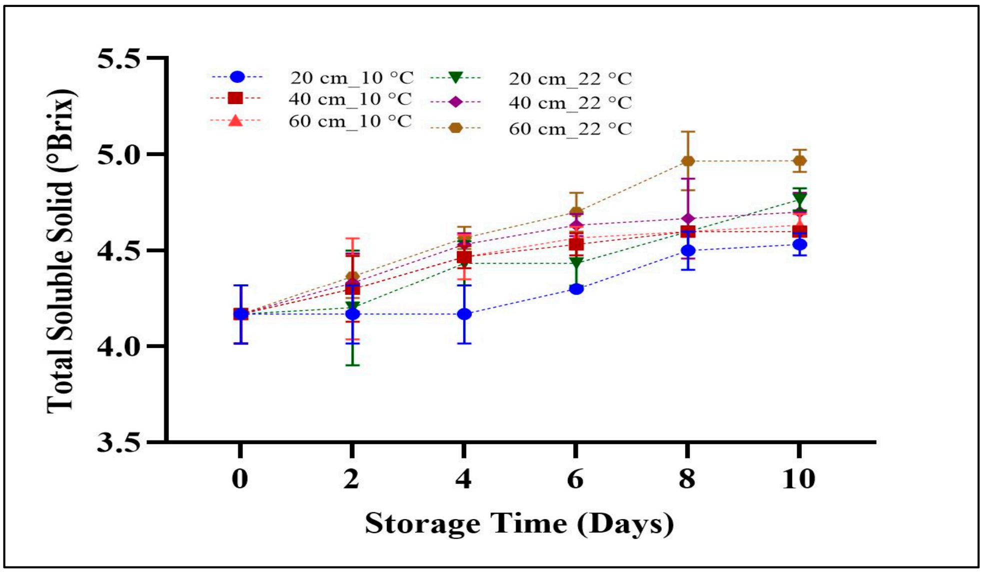

Figure 10. TSS of tomatoes impacted at different drop heights (20 cm, 40 cm, and 60 cm) and stored for 10 days in 10 °C and 22 °C storage conditions. Error bars represent the standard deviation (SD) of the mean values ± S.D. of six readings of three replicates.

3.3.2. Total Lycopene and Carotenoids

A significant influence of storage duration ($p = 0.0330$), storage temperature ($p = 0.0070$), and drop height ($p = 0.0050$) was observed on tomato lycopene content as shown in Table S1. In this study, lycopene content reached its peak on the 8th day of storage at room temperature for the high drop-impacted bruised tomatoes, with a value of 1.55 mg 100 g^{-1} which was later reduced on the last day of storage by 7.74%. The increase in lycopene content (0.93 mg 100 g^{-1} FW) observed on low and medium drop-impacted bruised tomatoes stored at 10 °C was five times lower than the high impact bruised tomatoes at 22 °C (Figure 12A). Similarly, total carotenoids content was significantly ($p < 0.05$) affected by all tested factors (Table S1). Increasing storage temperature, duration, and drop height (impact) increased the carotenoids content of tomatoes. The lowest carotenoid content was reported in the early stage of the experiment and gradually increased in all bruised tomatoes at both conditions. The total carotenoid content increased by 135.71% and 88.16% on day 8 of storage for the high (60 cm) and medium (40 cm) impact bruised tomatoes at room temperature (Figure 12B). The lowest percentage (42.85%) of increase in total carotenoids was recorded in the low (20 cm) and medium (40 cm) impact bruised tomatoes stored at 10 °C. Buccheri and Cantwell [11] recorded an increase in tomato pigments (e.g., lycopene) at 20 °C storage conditions particularly in bruised tomatoes compared to non-damaged tomatoes. Additionally, Park et al. [32] and Munhuewyi [24] reported a high increase of tomato pigment content at room temperature during storage. As recorded by Fagundes et al. [33], pigment increments at room temperature or in the range of 12–32 °C could be attributed to the biosynthesis of lycopene during storage. Table 1 presents the final lycopene model which includes all independent variables (model 6). The coefficient of determination $R^2 = 0.95$ between the measured and predicted values of lycopene is an acceptable index to investigate the prediction performance of the model. Figure 13 shows the relationships between the measured and predicted values obtained for lycopene from the multiple regression model.

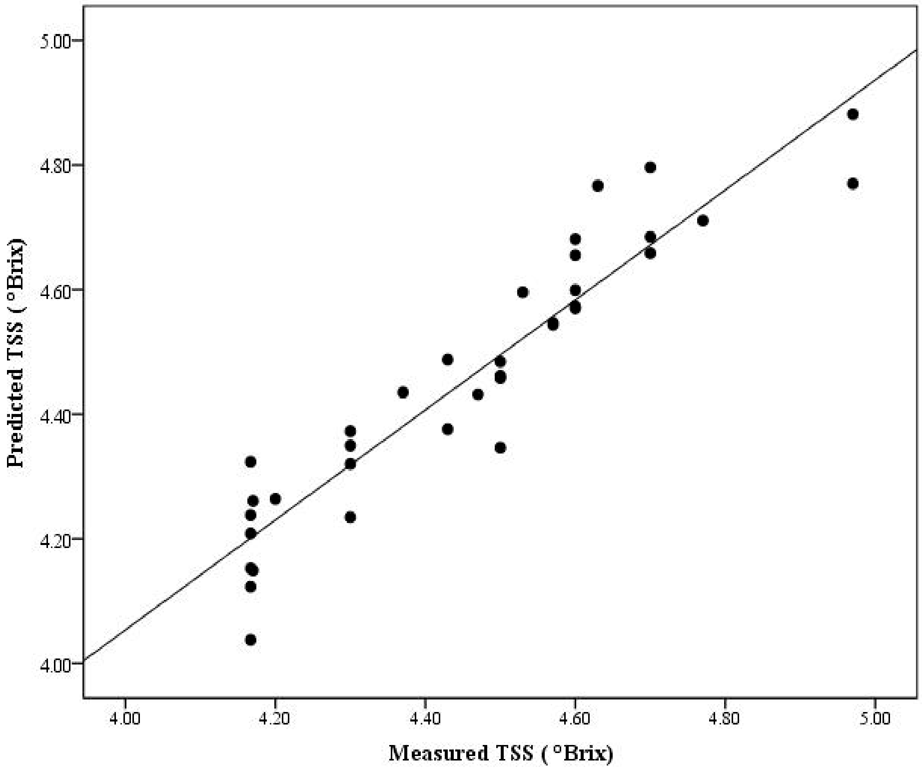

Figure 11. Results for the prediction of TSS values based on linear regression models.

3.4. *Pearson's Correlation Coefficient*

Pearson's correlation analysis was performed to establish the relationship between the measured variables, e.g., bruise area, weight loss, firmness, total soluble solids, lycopene, carotenoids, lightness, redness, yellowness, total color change, hue°, and color index (Table 3). The *BA* of all impacted tomatoes stored at both conditions showed a strong positive correlation (**, $p < 0.01$, *, $p < 0.05$) with WL ($r \geq 0.972$), TSS ($r \geq 0.916$), lycopene ($r \geq 0.839$), a* ($r \geq 0.933$), ΔE* ($r \geq 0.956$), and CI ($r \geq 0.941$), as well as a strong negative correlation with firmness ($r \geq -0.903$), L* ($r \geq -0.869$), b* ($r \geq -0.966$), and hue° ($r \geq -0.962$). This implies that increasing bruise area could cause higher changes in the quality attributes of the produce. Besides, WL correlated significantly with all studied parameters. A similar significance was exhibited between firmness and other physical (color parameters), chemical (TSS), and nutritional (lycopene) quality attributes across all tested factors.

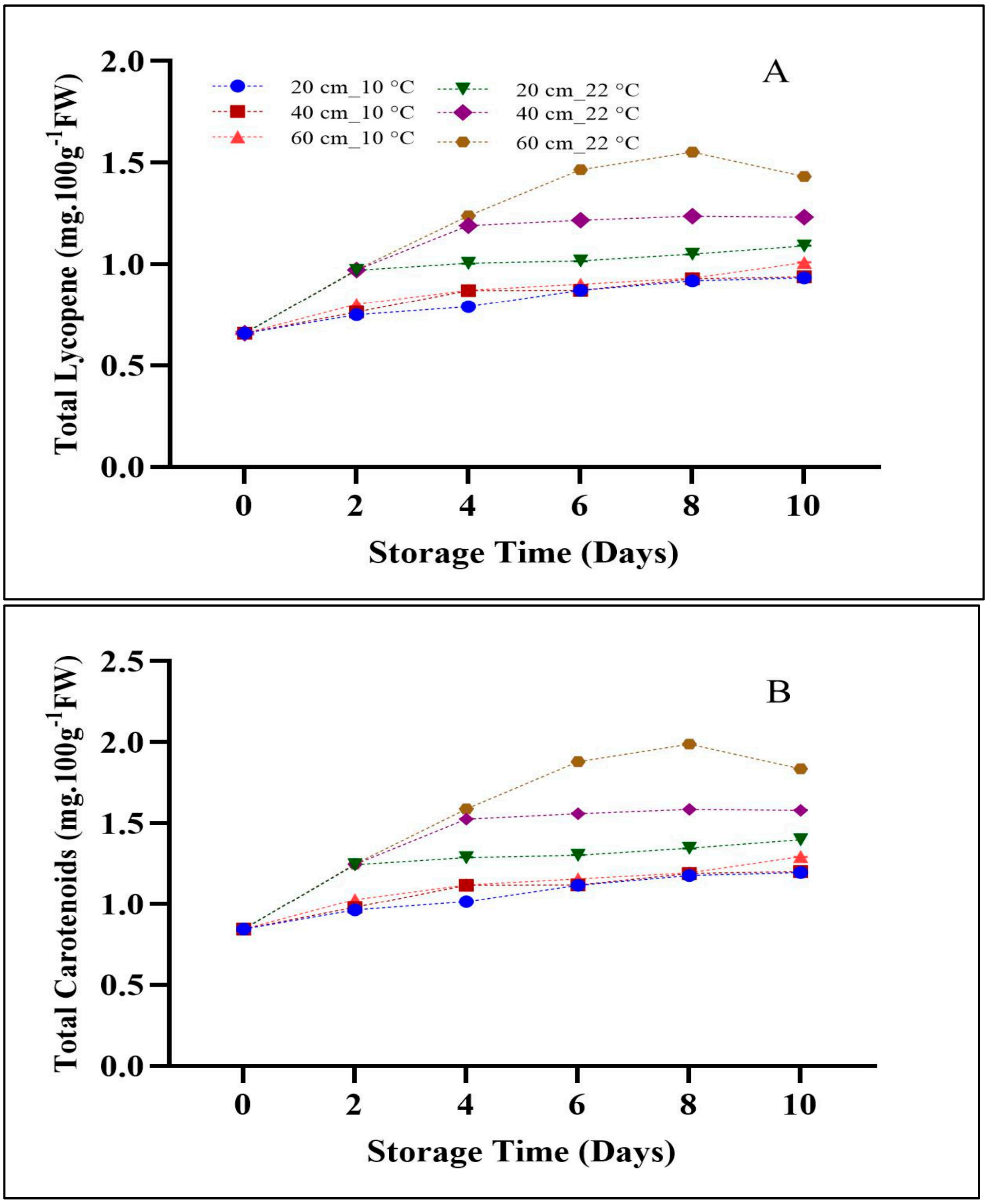

Figure 12. (**A**) Lycopene and (**B**) carotenoid contents of tomato impacted at different drop heights (20 cm, 40 cm, and 60 cm) and stored for 10 days at 10 °C and 22 °C storage conditions. Error bars represent the standard deviation (SD) of the mean values ± S.D. of six readings of three replicates.

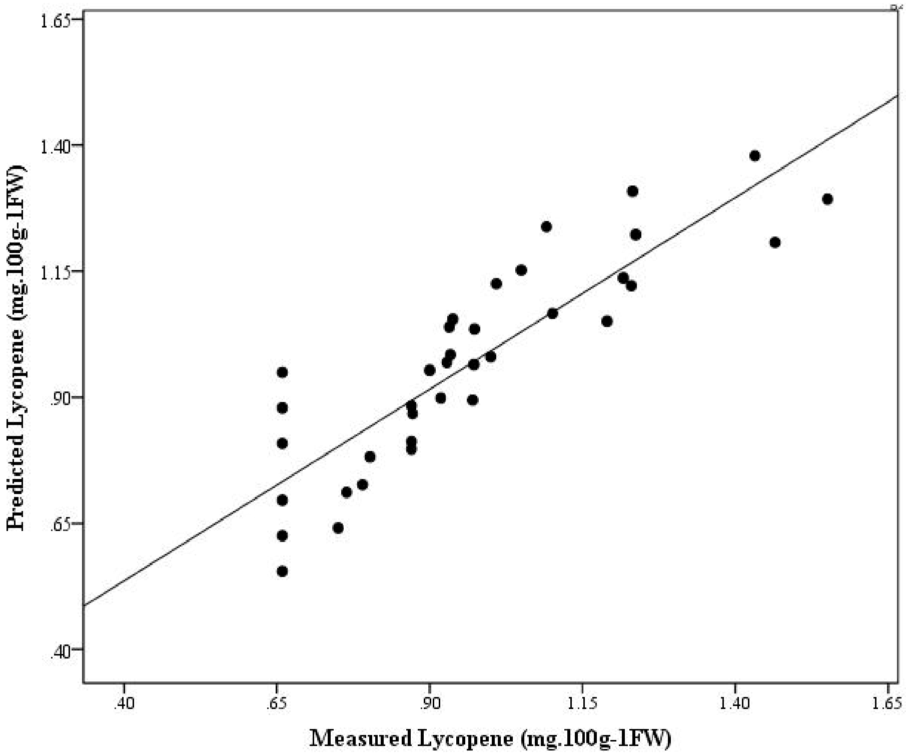

Figure 13. Results for the prediction of lycopene values based on linear regression models.

TSS showed a significant and strong negative correlation with L*, b*, and hue angle and exhibited a positive correlation with lycopene, a *, Δ*E**, and CI. Based on the observed data, lycopene content was negatively correlated with L* ($r \geq -0.722$), b* ($r \geq -0.798$), and hue° ($r \geq -0.763$). Additionally, lycopene was significantly and positively correlated with color redness ($r \geq 0.842$) across all tested factors. Besides, hue° was greatly influenced by b* values in all studied factors, particularly for high drop-impacted tomatoes stored at room temperature ($r = 0.997$, $p < 0.001$). Pandurangaiah et al. [34] recorded a strong positive correlation between hue and b* values of tomatoes ($r = 0.939$) and a high positive correlation existed between lycopene and a* ($r = 0.877$). Similarly, a good negative correlation was shown between total lycopene content and b* values in tomato ($p < 0.01$).

Table 3. Pearson correlation coefficients (r) ($n = 6$) between quality attributes on tomato subjected to an impact from three different heights and stored at 10 °C and 22 °C. Significant correlations of two-tailed tests are indicated: * $p < 0.05$; ** $p < 0.01$.

Tomato Quality Parameter	Drop Height	Storage Temp.	*BA*	WL	Firmness	TSS	Lycop-ene	L*	a*	b*	ΔE*	Hue°	CI
BA	20 cm	10 °C	1	0.972 **	−0.903 *	0.916 *	0.966 **	−0.958 **	0.949 **	−0.966 **	0.980 **	−0.971 **	0.970 **
		22 °C	1	0.996 **	−0.906 *	0.960 **	0.839 *	−0.980 **	0.959 **	−0.988 **	0.995 **	−0.986 **	0.959 **
	40 cm	10 °C	1	0.987 **	−0.992 **	0.961 **	0.959 **	−0.952 **	0.951 **	−0.993 **	0.990 **	−0.981 **	0.960 **
		22 °C	1	0.986 **	−0.990 **	0.970 **	0.898 *	−0.946 **	0.959 **	−0.995 **	0.983 **	−0.985 **	0.959 **
	60 cm	10 °C	1	0.991 **	−0.941 **	0.980 **	0.980 **	−0.869 *	0.933 **	−0.982 **	0.956 **	−0.962 **	0.941 **
		22 °C	1	0.984 **	−0.996 **	0.976 **	0.939 **	−0.938 **	0.995 **	−0.991 **	0.984 **	−0.996 **	0.972 **
WL	20 cm	10 °C	0.972 **	1	−0.785	0.838 *	0.988 **	−0.887 *	0.886 *	−0.976 **	0.960 **	−0.945 **	0.924 **
		22 °C	0.996 **	1	−0.879 *	0.971 **	0.805	−0.986 **	0.977 **	−0.989 **	1.000 **	−0.996 **	0.980 **
	40 cm	10 °C	0.987 **	1	−0.972 **	0.985 **	0.971 **	−0.914 *	0.921 **	−0.988 **	0.968 **	−0.964 **	0.929 **
		22 °C	0.986 **	1	−0.970 **	0.956 **	0.857 *	−0.975 **	0.987 **	−0.986 **	0.993 **	−0.994 **	0.971 **
	60 cm	10 °C	0.991 **	1	−0.960 **	0.980 **	0.971 **	−0.893 *	0.964 **	−0.993 **	0.974 **	−0.984 **	0.965 **
		22 °C	0.984 **	1	−0.970 **	0.975 **	0.896 *	−0.980 **	0.987 **	−0.987 **	0.999 **	−0.989 **	0.992 **
Firmness	20 cm	10 °C	−0.903 *	−0.785	1	−0.964 **	−0.802	0.968 **	−0.964 **	0.844 *	−0.905 *	0.913 *	−0.943 **
		22 °C	−0.906 *	−0.879 *	1	−0.895 *	−0.884 *	0.833 *	−0.790	0.917 *	−0.880 *	0.863 *	−0.791
	40 cm	10 °C	−0.992 **	−0.972 **	1	−0.956 **	−0.952 **	0.949 **	−0.939 **	0.983 **	−0.984 **	0.969 **	−0.944 **
		22 °C	−0.990 **	−0.970 **	1	−0.978 **	−0.914 *	0.920 **	−0.943 **	0.973 **	−0.960 **	0.963 **	−0.929 **
	60 cm	10 °C	−0.941 **	−0.960 **	1	−0.932 **	−0.948 **	0.945 **	−0.967 **	0.983 **	−0.986 **	0.979 **	−0.972 **
		22 °C	−0.996 **	−0.970 **	1	−0.972 **	−0.957 **	0.919 **	−0.988 **	0.982**	−0.969 **	0.989 **	−0.954 **
TSS	20 cm	10 °C	0.916 *	0.838 *	−0.964 **	1	0.881 *	−0.961 **	0.992 **	−0.902 *	0.943 **	−0.957 **	0.968 **
		22 °C	0.960 **	0.971 **	−0.895 *	1	0.763	−0.944 **	0.949 **	−0.981 **	0.975 **	−0.980 **	0.968 **
	40 cm	10 °C	0.961 **	0.985 **	−0.956 **	1	0.991 **	−0.854 *	0.854 *	−0.953 **	0.923 **	−0.911 *	0.859 *
		22 °C	0.970 **	0.956 **	−0.978 **	1	0.964 **	−0.871 *	0.909 *	−0.953 **	0.925 **	−0.936 **	0.873 *
	60 cm	10 °C	0.980 **	0.980 **	−0.932 **	1	0.969 **	−0.807	0.928 **	−0.965 **	0.926 **	−0.946 **	0.906 *
		22 °C	0.976 **	0.975 **	−0.972 **	1	0.946 **	−0.938 **	0.978 **	−0.991 **	0.978 **	−0.990 **	0.970 **
Lycopene	20 cm	10 °C	0.966 **	0.988 **	−0.802	0.881 *	1	−0.888 *	0.912 *	−0.975 **	0.963 **	−0.956 **	0.933 **
		22 °C	0.839 *	0.805	−0.884 *	0.763	1	−0.722	0.883 *	−0.858 *	0.798	−0.763	0.701
	40 cm	10 °C	0.959 **	0.971 **	−0.952 **	0.991 **	1	−0.846 *	0.842 *	−0.936 **	0.914 *	−0.895 *	0.846 *
		22 °C	0.898 *	0.857 *	−0.914 *	0.964 **	1	−0.729	0.871 *	−0.874 *	0.812 *	−0.824 *	0.740
	60 cm	10 °C	0.980 **	0.971 **	−0.948 **	0.969 **	1	−0.844 *	0.894 *	−0.966 **	0.936 **	−0.933 **	0.908 *
		22 °C	0.939 **	0.896 *	−0.957 **	0.946 **	1	−0.807	0.914 *	−0.945 **	0.889 *	−0.937 **	0.859 *
L *	20 cm	10 °C	−0.958 **	−0.887 *	0.968 **	−0.961 **	−0.888 *	1	−0.983 **	0.938 **	−0.973 **	.975 **	−0.991 **
		22 °C	−0.980 **	−0.986 **	0.833 *	−0.944 **	−0.722	1	−0.984 **	0.952 **	−0.986 **	0.983 **	−0.973 **
	40 cm	10 °C	−0.952 **	−0.914 *	0.949 **	−0.854 *	−0.846 *	1	−0.996 **	0.952 **	−0.982 **	0.984 **	−0.988 **
		22 °C	−0.946 **	−0.975 **	0.920 **	−0.871 *	−0.729	1	−0.990 **	0.954 **	−0.989 **	0.981 **	−0.990 **
	60 cm	10 °C	−0.869 *	−0.893 *	0.945 **	−0.807	−0.844 *	1	−0.940 **	0.933 **	−0.970 **	0.948 **	−0.976 **
		22 °C	−0.938 **	−0.980 **	0.919 **	−0.938 **	−0.807	1	−0.956 **	0.940 **	−0.982 **	0.950 **	−0.987 **

Table 3. *Cont.*

Tomato Quality Parameter	Drop Height	Storage Temp.	*BA*	WL	Firmness	TSS	Lycop-ene	L*	a*	b*	ΔE*	Hue°	CI
a*	20 cm	10 °C	0.949 **	0.886 *	−0.964 **	0.992 **	0.912 *	−0.983 **	1	−0.944 **	0.976 **	−0.984 **	0.991 **
		22 °C	0.959 **	0.977 **	−0.790	0.949 **	0.663	−0.984 **	1	−0.943 **	0.978 **	−0.987 **	0.988 **
	40 cm	10 °C	0.951 **	0.921 **	−0.939 **	0.854 *	0.842 *	−0.996 **	1	−0.957 **	0.982 **	−0.989 **	0.995 **
		22 °C	0.959 **	0.987 **	−0.943 **	0.909 *	0.771	−0.990 **	1	−0.964 **	0.990 **	−0.991 **	0.983 **
	60 cm	10 °C	0.933 **	0.964 **	−0.967 **	0.928 **	0.894 *	−0.940 **	1	−0.977 **	0.982 **	−0.994 **	0.987 **
		22 °C	0.995 **	0.987 **	−0.988 **	0.978 **	0.914 *	−0.956 **	1	−0.986 **	0.990 **	−0.996 **	0.986 **
b*	20 cm	10 °C	−0.966 **	−0.976 **	0.844 *	−0.902 *	−0.975 **	0.938 **	−0.944 **	1	−0.992 **	0.987 **	−0.972 **
		22 °C	−0.988 **	−0.989 **	0.917 *	−0.981 **	−0.858 *	0.952 **	−0.943 **	1	−0.989 **	0.984 **	−0.961 **
	40 cm	10 °C	−0.993 **	−0.988 **	0.983 **	−0.953 **	−0.936 **	0.952 **	−0.957 **	1	−0.992 **	0.989 **	−0.969 **
		22 °C	−0.995 **	−0.986 **	0.973 **	−0.953 **	−0.874 *	0.954 **	−0.964 **	1	−0.988 **	0.991 **	−0.971 **
	60 cm	10 °C	−0.982 **	−0.993 **	0.983 **	−0.965 **	−0.966 **	0.933 **	−0.977 **	1	−0.992 **	0.994 **	−0.983 **
		22 °C	−0.991 **	−0.987 **	0.982 **	−0.991 **	−0.945 **	0.940 **	−0.986 **	1	−0.986 **	0.997 **	−0.974 **
ΔE	20 cm	10 °C	0.980 **	0.960 **	−0.905 *	0.943 **	0.963 **	−0.973 **	0.976 **	−0.992 **	1	−0.998 **	0.993 **
		22 °C	0.995 **	1.000 **	−0.880 *	0.975 **	0.798	−0.986 **	0.978 **	−0.989 **	1	−0.997 **	0.982 **
	40 cm	10 °C	0.990 **	0.968 **	−0.984 **	0.923 **	0.914 *	−0.982 **	0.982 **	−0.992 **	1	−0.997 **	0.987 **
		22 °C	0.983 **	0.993 **	−0.960 **	0.925 **	0.812 *	−0.989 **	0.990 **	−0.988 **	1	−0.997 **	0.992 **
	60 cm	10 °C	0.956 **	0.974 **	−0.986 **	0.926 **	0.936 **	−0.970 **	0.982 **	−0.992 **	1	−0.995 **	0.996 **
		22 °C	0.984 **	0.999 **	−0.969 **	0.978 **	0.889 *	−0.982 **	0.990 **	−0.986 **	1	−0.991 **	0.997 **
Hue°	20 cm	10 °C	−0.971 **	−0.945 **	0.913 *	−0.957 **	−0.956 **	0.975 **	−0.984 **	0.987 **	−0.998 **	1	−0.996 **
		22 °C	−0.986 **	−0.996 **	0.863 *	−0.980 **	−0.763	0.983 **	−0.987 **	0.984 **	−0.997 **	1	−0.990 **
	40 cm	10 °C	−0.981 **	−0.964 **	0.969 **	−0.911 *	−0.895 *	0.984 **	−0.989 **	0.989 **	−0.997 **	1	−0.993 **
		22 °C	−0.985 **	−0.994 **	0.963 **	−0.936 **	−0.824 *	0.981 **	−0.991 **	0.991 **	−0.997 **	1	−0.987 **
	60 cm	10 °C	−0.962 **	−0.984 **	0.979 **	−0.946 **	−0.933 **	0.948 **	−0.994 **	0.994 **	−0.995 **	1	−0.993 **
		22 °C	−0.996 **	−0.989 **	0.989 **	−0.990 **	−0.937 **	0.950 **	−0.996 **	0.997 **	−0.991 **	1	−0.982 **
CI	20 cm	10 °C	0.970 **	0.924 **	−0.943 **	0.968 **	0.933 **	−0.991 **	0.991 **	−0.972 **	0.993 **	−0.996 **	1
		22 °C	0.959 **	0.980 **	−0.791	0.968 **	0.701	−0.973 **	0.988 **	−0.961 **	0.982 **	−0.990 **	1
	40 cm	10 °C	0.960 **	0.929 **	−0.944 **	0.859 *	0.846 *	−0.988 **	0.995 **	−0.969 **	0.987 **	−0.993 **	1
		22 °C	0.959 **	0.971 **	−0.929 **	0.873 *	0.740	−0.990 **	0.983 **	−0.971 **	0.992 **	−0.987 **	1
	60 cm	10 °C	0.941 **	0.965 **	−0.972 **	0.906 *	0.908 *	−0.976 **	0.987 **	−0.983 **	0.996 **	−0.993 **	1
		22 °C	0.972 **	0.992 **	−0.954 **	0.970 **	0.859 *	−0.987 **	0.986 **	−0.974 **	0.997 **	−0.982 **	1

BA, bruise area; WL, weight loss; TSS, total soluble solids; L*, lightness; a*, redness; b*, yellowness; ΔE*, total color difference; CI, color index.

4. Conclusions

The study investigated the contribution of different impact levels (20, 40, and 20 cm drop heights) on bruise area and the physical, chemical, and nutritional attributes of tomatoes stored at two different storage conditions over a 10 day storage period. According to the obtained results, the *BA* was dependent on storage temperature, storage duration, and drop height (impact level). Similarly, weight loss, redness, total lycopene and carotenoid content, total color difference, and color index showed a gradual increase as all independent variables increased. However, the other measured variables such as firmness, lightness, yellowness, and hue° were significantly reduced as the studied factors increased for 10 days storage. The intensity of the color (chroma) was not affected by all investigated factors. Based on the prediction models, the main factors (independent variable) had a strong effect on the dependent variables such as bruise area, weight loss, firmness, redness, total soluble solids, and lycopene. Overall, exposure to bruising from high impact levels and storage at higher temperatures can increase the damage of quality changes in fresh produce. For the better quality assessment of bruising, further research is required for a possible comparison between non-bruised (control) and bruised fruits during postharvest storage.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/horticulturae7050113/s1. Table S1. The three-way analysis of variance (ANOVA) of bruise area, weight loss %, firmness, L*, a*, b*, total soluble solids, total lycopene, and carotenoids.

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