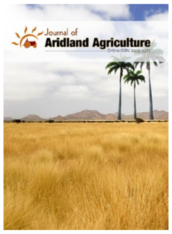
Journal of Aridland Agriculture 2024, 10: 108-119
doi: 10.25081/jaa.2024.v10.8944
https://updatepublishing.com/journal/index.php/jaa

Research Article



ISSN: 2455-9377

Response of tomato fruit to consecutive impact loading

Hossein Ghaffari-Setoubadi[1]*, Hamid-Reza Ghassemzadeh[1], Khosro Mohammadi-Ghermezgoli[1], Seyed Abbas Rafat[2], Omid Halimi-Milani[3]

[1]Department of Bio systems Engineering, Faculty of Agriculture, University of Tabriz, Tabriz, Iran, [2]Department of Animal science, Faculty of Agriculture, University of Tabriz, Tabriz, Iran, [3]Amirkabir University of Technology-AUT, Tehran, Iran

Received: July 19, 2023
Revised: April 29, 2024
Accepted: May 05, 2024
Published: July 26, 2024

***Corresponding author:**
Hossein Ghaffari-Setoubadi
E-mail: Ghaffari@tabrizu.ac.ir

ABSTRACT

Tomato fruits receive successive impacts during harvest and postharvest operations. This paper is a study of the response of tomato fruit to mono and multiple dynamic loadings and the ability to withstand consecutive impacts, which play the most critical role in downgrading and postharvest loss of fresh tomato fruits and designing harvest, and postharvest handling and processing equipment. The fruits were subjected to consecutive impacts by an instrumented pendulum one to three times successive impacts at the same location with the three different impact energy levels: 125, 250, and 500 mJ to establish a comprehensive model and refining by adding various groups of contributing factors to understand better and find out which parameters are more likely to cause and contribute in tomato mechanical damage. Twenty sub-models were evaluated using AIC and R^2 values. The parameters of the preferred logistic model consist of response variables (peak contact force, contact time, and Elast), loading conditions (one, two, and three-times impact at the same location), and fruit quality parameter (total soluble solids). Also, another model was suggested for rapid assessment of bruise development.

KEYWORDS: Bruise probability, Impact damage, Statistical models, Successive loading

INTRODUCTION

Tomato (*Lycopersicon esculentum* L.) is one of the commercially essential fruits and major vegetable components of human nutrition worldwide (Mansourbahmani *et al*., 2017). It is grown in a wide range of climates on the farm, and even under protection in plastic greenhouses and heated glasshouses (Atherton & Rudich, 1986; Adedeji *et al*., 2006). Apart from its characteristics like flavor and aroma, it is also a good source of vitamins (A and C) and minerals (Akanbi & Oludemi, 2004). Tomato is consumed in relatively large quantities: directly as salads, cooked into soups, or processed into juice, ketchup, whole-peeled tomato, and paste (Adedeji *et al*., 2006). In some cases, tomatoes are picked at a mature red stage when they are almost suitable for a fresh market (Ghaffari *et al*., 2015).

The mechanization of harvest and postharvest operations may cause mechanical damage to agricultural products (Wang *et al*., 2018). Advanced technologies may help to reduce postharvest losses (Sanches *et al*., 2019). The fruit and vegetable industry suffers considerable economic losses due to bruising and post-harvest physical injuries occurring before and after harvesting operations (Ghaffari *et al*., 2015). Mechanical damage is considered significant challenge in postharvest chain operations, which may be caused by successive impacts, so it can be of the researcher's interest to reduce the fruit and vegetable injuries (Wang *et al*., 2019). Effective damage prevention is possible when the contributing factors responsible for bruise development are completely known (Van Linden *et al*., 2008).

The solid-body behavior studies concerning stress, force, or deformation are not enough to discuss partial impact characteristics such as wave propagation and case contact; therefore, in most issues, empirical methods have been used, and the impact phenomenon can be easily implemented by special tests such as drop, falling mass or plunger, simple pendulum, compound pendulum and impact ram (Mohsenin, 1986).

The analysis of agriculture product impact loading leads to very complicated mathematical relationships. The recommended analyzed models are scarce, and these models were derived using some reasonable hypotheses, estimations, and numerical calculations.

A bruise prediction model connects the results of dynamic impact loading characteristics such as drop height and impacts energy level with bruise damage, taking into consideration some fruit attributes such as physicochemical and mechanical properties (Van Zeebroeck *et al.*, 2007a; Hussein *et al.*, 2019b), leading recommendations for fruit handling, packaging and transporting (Hussein *et al.*, 2020).

To obtain bruising models and study the procedure of bruise development, researchers exerted different levels of impact energy by the pendulum and free-falling test on the tomato fruit varying from 13 to 920 mJ (Desmet *et al.*, 2003, 2004b; Lee *et al.*, 2004; Van Linden *et al.*, 2006a, b; Van Zeebroeck *et al.*, 2007b; Ahmadi *et al.*, 2014). In fruits, such as litchi, the browning predominantly occurs on the external surface. In contrast, in other fruits, such as pear and tomato, browning occurs internally, so it is difficult to measure by objective methods (Quevedo *et al.*, 2009). This is the only method presented in the literature; giving a mark depends on the observed damaging degree of permanent external deformation (Sargent *et al.*, 1992). Precise bruise damage determination on the tomato fruit is challenging. The number of bruising tomato models described in the literature is very limited to the maturity effect on the bruising susceptibility (Van Zeebroeck *et al.*, 2007b).

Researchers used Impact energy or peak contact force as a criterion to estimate bruise susceptibility of apples (Van Zeebroeck *et al.*, 2007a), tomatoes (Desmet *et al.*, 2002, 2003, 2004a, b; Van Linden *et al.*, 2006a), pear (Blahovec & Paprštein, 2005; Stropek & Gołacki, 2019), peach (Ahmadi *et al.*, 2010), potato (Gao & Rao, 2019) and blueberry (Sun *et al.*, 2024). However, these recent models were all established to predict the damage caused by a single impact.

A sliding-based approach was proposed by Fu *et al.* (2023) to better understand bruising damage in apple-to-apple collisions. Also, Hou *et al.* (2024) studied a multiscale finite element model based on the anatomical structures of blueberries and employed to simulate their bruise susceptibility. The dielectric method was used to investigate blueberries bruise microstructure under quasistatic compression (Sun *et al.*, 2024).

Limited information exists on contributing factors related to tomato bruising as well as studies have confirmed that there is a dearth of information on the effect of successive impacts at the same location on the bruising of tomato fruit. Therefore, the objectives of this paper were; 1. establish bruising models for predicting the bruise susceptibility of tomato fruits based on logistic regression procedure for single and successive impacts separately, and 2. to determine fruit attributes that contribute significantly to the bruising damage.

MATERIALS AND METHODS

To establish the bruising model, tomato fruit sample attributes at the maturity stage were determined and subjected to dynamic impact loading (Figure 1). A full factorial design was performed, consisting of impact times (one, two, and three), three impact energy levels (low (LE), medium (ME), and high (HE)) with ten replications. After treatments, bruised and unbruised fruits were evaluated about 72 hours after the tests, and bruised (being watery and soft). Unbruised fruits were coded with 1 and 0 as a response variable, respectively. It can also be taken into account that the deforming and being watery impact location should be considered as a criterion to evaluate bruised fruit (Van Zeebroeck *et al.*, 2007b).

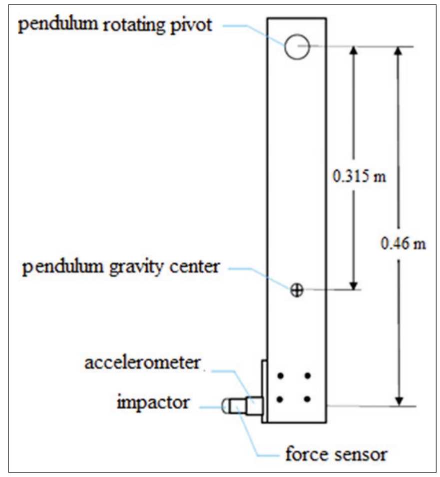


Figure 1: Pendulum dimensions and its instruments

For all experiments, the explanatory variables were divided into four groups, and a stepwise evaluation procedure was conducted to find out the influence of various kinds of parameters on bruise development. Group 1 is the impact variable and includes three levels of impact energy LE (125 mJ), ME (250 mJ), and HE (500 mJ). Group 2 illustrates the combination of external and internal factors; the restitution coefficient, the peak contact force at the impact and the contact time. The obtained results from dynamic impact loading are called response variables. A third group represents the number of impacts in which the tomatoes were impacted one to three times at the same location. The response of fruits at the first, second, and third impact was recorded for the subsequent the analysis step. Finally, the fruit characteristics were grouped as the fourth group, including color, mass, acoustic stiffness, dimensions, and moisture content.

Tomatoes mass was obtained using a precision electronic balance (accuracy of 0.01 g) (Mohsenin, 1986; Aydın & Özcan, 2002; Allende *et al.*, 2004; Li, 2013). True volume was determined using a platform scale, and specific gravity (gr/cm^3) was also calculated by dividing fruit weight by its volume (Mohsenin, 1986).

The moisture content (M_{wb}) of a fruit specifies the water content in the wet sample, which is one of the influential factors that may affect the total properties of the product. In this study, wet based method was used to calculate the moisture content (Sacilik *et al.*, 2006) (Equation 1):

$$M_{wb} = \frac{m_1 - m_2}{m_1} * 100 \quad (1)$$

Where m_1, is the weight of wet sample and m_2, is the weight of the dried sample.

The radius of curvature was calculated using the equation described by Mohsenin (1986) and the curvature meter made by the researcher. Because tomatoes are not perfect spheres, the harmonic average (R) was calculated based on the circumferential (R_1) and meridian radius of curvature (R_2). The harmonic average was preferred over the arithmetic average because it privileges the smaller radius of curvature (Van Zeebroeck *et al.*, 2007a, b), which contributes more to the peak contact pressure (Hertz theory):

$$R = \frac{2R_1R_2}{R_1 + R_2} \quad (2)$$

To determine the different color descriptors, a digital image analysis system was designed, including two main parts: (1) an image acquisition system to take images from tomato fruit and (2) an image analysis algorithm written in MATLAB. The image acquisition system consisted of a digital camera (Sony Cyber-shot DSC-W100, 8.1 MP), a computer, and a lightning chamber (Lana *et al.*, 2006), including a combination of white and yellow fluorescent lights (MX396Y8Z -8W). Two high-quality images from samples were taken by a digital camera with remote capturing capability mounted at a vertical distance of 25 cm above the samples. The images were transferred to the computer and loaded into the image processing toolbox of MATLAB software for further analysis (Setareh *et al.*, 2023). The L^*, a^*, and b^* components were determined using the algorithm, which utilizes the color space environment data of R, G, and B (León *et al.*, 2006). The color indices of C^* and h^* were determined by Equations 3 and 4. Therefore, they can be analyzed to determine the best color index considered to be significant in the bruising models.

$$C^* = \left[a^{*2} + b^{*2}\right]^{\frac{1}{2}} \quad (3)$$

$$h^* = \arctan\left[\frac{b^*}{a^*}\right] \quad (4)$$

The TSS is a refractometric index that indicates the proportion (%) of dissolved solids in a solution (Beckles, 2012). The total soluble solids (TSS) were determined by a refractometer (Model PAL-1 ATAGO, Japan). The drop of tomato juice was placed on the prism of the refractometer and expressed as a °Brix (Khan *et al.*, 2017; Salim *et al.*, 2018).

Determination of Impact and Response Parameters

The pendulum device was used to obtain response variables resulting from impact loadings. This is following previous studies, where the pendulum instrument has been described by several researchers as a well-suited device to exert controlled impact energy on biomaterials (Zhang & Brusewitz, 1991; Bielza *et al.*, 2003; Van Zeebroeck *et al.*, 2003, 2006a, 2007a; Desmet *et al.*, 2004b; Blahovec & Paprštein, 2005; Van Linden *et al.*, 2006a, 2008; Ahmadi, 2012; Hussein *et al.*, 2018, 2019a, 2020; Stropek & Gołacki, 2019).

Impact and response parameters extracted from the pendulum experiments were absorbed energy (Ea), peak contact force (PF), contact time (t), Elast (EL), and restitution coefficient (R_c) may contribute to the bruising models. To obtain these factors, an experimental setup was established consisting of an instrumented pendulum and accessory devices. This setup exerted the controlled dynamic load with certain impact energy levels (Figure 1). A force sensor (PCB, USA, 110.71 mV/N) and an accelerometer sensor (PCB, USA, 100.5 mV/g) are attached to the bottom end of the pendulum. Moreover, semi-aluminum spherical as an impactor screwed on the force sensor head (Figure 2). The total mass of the pendulum arm with sensors was about 315 g.

The angular motion of the pendulum pivot was measured by an encoder (SICK STEGMANN Gmbh-DFS60B-S4PK 10000, Germany, resolution: 0.036 degrees). An attached circuit improved the final encoder output accuracy to about 0.009 degrees (40000 pulses/rev). A digital counter monitored the amount of angular pendulum rotation as pulses, and it is possible to exert the precise impact energy level to the fruit by using a zero-set circuit. Hence, it eliminates the deviation of fruit size and shape, which was ignored in the previous research. All of the signals (angular motion, pendulum arm rotation direction, force, and accelerometer sensors) were recorded by a signal analyzer (Econ-AVANT series MI-7016, China) as a function of time (Figure 3).

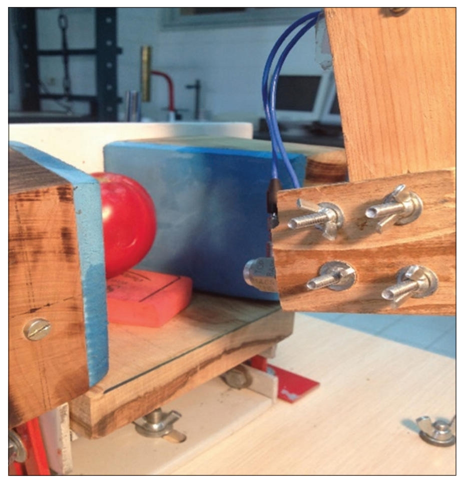


Figure 2: Force and accelerometer sensors

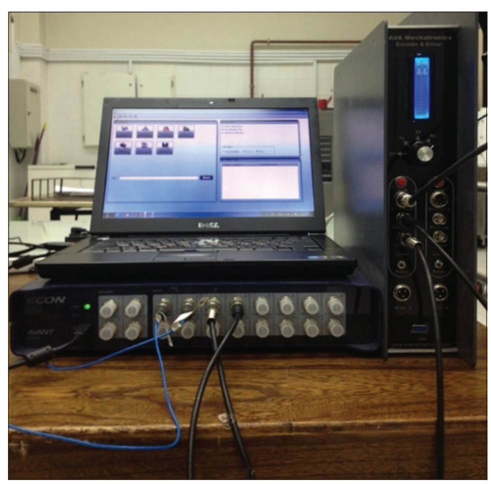


Figure 3: Data acquisition system

The impact is defined as the period between exceeding a pre-set threshold for the contact force (1 N) and the moment at which the force has dropped to 1 N again.

The absorbed energy, Ea, was determined by the following formula (Equation 5):

$$Ea = Ei - Er \tag{5}$$

Ei = the impact energy in mJ, Er = the returned energy in mJ.

To obtain Ea, the values of Ei and Er must be initially calculated. Referring to studied research, there is a relationship between a given impact energy level and the peak contact force. To obtain the value of peak contact force, some experiments were conducted by Desmet *et al.* (2004a) using electronic fruit (PMS-60) in the various tomato mechanized systems. The peak contact force value of 54.5 N was measured in the worst and most challenging conditions of mechanized operations. In this research, the maximum impact energy level corresponding to the 54.5 N peak contact force using the impact loading test was 500 mJ and considered the highest impact energy level (HE). Therefore, three impact energy levels, 125 (LE), 250 (ME), and 500 (HE) mJ, were applied by various rotating angles of the pendulum (θ_i) obtained from the following procedure (Equations 6 & 7):

$$E_i = M_p gl(1-\cos\theta_i) \tag{6}$$

$$\theta_i = \cos^{-1}(1-\frac{E_i}{M_p gl}) \tag{7}$$

Where i=1, 2, and 3, refer to three different impact energy levels, E_i = the applied impact energy in mJ, M_p = the pendulum mass (g), g = is the gravity acceleration in m s^{-2}, l= is the radius of the rotating pendulum arm in m, θ_i = the rotating angle of the pendulum arm related to E_i.

The pulse numbers of the encoder (n_i) were calculated using Equation 8 to apply specific impact energies. After contacting the impactor to the tomato surface, turned the zero-set push bottom on. Consequently, the pendulum pivot rotated to the calculated pulse number (n_i), and then the tomatoes were impacted by a spherical aluminum indenter.

$$n_i = \theta_i \times \frac{N}{360} \tag{8}$$

Where n_i, = the pulse number related to θ_i, N, = the number of pulses sent per one pivot rotation by encoder equals 40000.

The pendulum returned angle, φ, was calculated using recorded data by the signal analyzer and written code in MATLAB software, and also the returned energy, Er, was measured by the following Equation 9:

$$E_r = M_p gl(1-\cos\phi) \tag{9}$$

The contact time is the time elapsed between two points in which the contact force rises from 1 N (pre-set threshold trigged at 1 N) and goes down to about 1 N again. From the maximum force at contact (peak contact force, PF) and the contact time (t), a new parameter related to elasticity Elast (N/s) can be derived (Van Linden *et al.*, 2006a) (Equation 10):

$$Elast = \frac{PF}{t} \tag{10}$$

The restitution coefficient (R_c) is the capacity of a material for the storage of strain energy in the elastic range. From another point of view, the coefficient of restitution is a measure of energy recovery (Equation 11). The restitution coefficient is also a measure of the damping characteristics of the fruit (Mohsenin, 1986; Van Zeebroeck *et al.*, 2007b):

$$R_c = \frac{\sin\left(\frac{\theta}{2}\right)}{\sin\left(\frac{\phi}{2}\right)} \tag{11}$$

Releasing and returning pendulum arm angles (θ and φ, respectively) were measured by the encoder and recorded by the mentioned signal analyzer.

Acoustic Firmness Measurement

To measure the acoustic firmness, a microphone (PCB, USA; Model: HT426E01 ISP 016685) was placed at a distance of three millimeters behind the tomato on the opposite sides of the impactor was used to record the sound produced as the tomato fruit being impacted. To obtain resonance frequency, the received signals were in the time domain transferred to the frequency domain using Fast Fourier Transformation (FFT) by MATLAB software (Ahmadi *et al.*, 2010). The first resonance frequency was then selected from the obtained frequency spectrum.

The acoustic firmness (S) can be determined by following Equation (12) (Schotte *et al.*, 1999);

$$S = f^2.M^{\frac{2}{3}} \tag{12}$$

Where M= is the tomato mass in gram, f= is the first resonance frequency in Hz.

Statistical Analysis

Logistic regression measures the relationship between the dependent variable and one or more independent variables by estimating probabilities using the underlying logit function. The dependent variable in logistic regression is usually dichotomous; that is, the dependent variable can take the value 1 with a probability of success π, or the value 0 with the probability of failure 1-π. This type of variable is called a Bernoulli (or binary) variable. The relationship between the predictor and response variables is not a linear function in logistic regression; instead, the logistic regression function is used, which is the logit transformation of $\pi(x)$ (Agresti, 2018):

$$(x) = \frac{e^{(\alpha+\beta_1 x_1+\beta_2 x_2+....+\beta_i x_i)}}{1+e^{(\alpha+\beta_1 x_1+\beta_2 x_2+....+\beta_i x_i)}} \quad (13)$$

Where, π is the probability defined by the proportion of bruised tomatoes, α = the constant of the equation, βi = the coefficient of the predictor variables, and x_i (e.g., impact energy, number of impacts, contact time, mass, moisture content, the radius of curvature, acoustic firmness, geometric mean diameter, density, color parameters, and TSS) indicates the observation for the *i*th explanatory variables.An alternative form of the logistic regression equation is (Equation 14):

$$\text{logit}\left[\pi(x)\right] = \log\left[\frac{\pi(x)}{1-\pi(x)}\right] = \alpha + \beta_1 x_1 + \beta_2 x_2 + ... + \beta_i x_i \quad (14)$$

The data were processed with the statistical software package SAS (SAS version 9.4, The SAS Institute Inc., Cary, NC, U.S.A.). To study and avoid multi-collinearity between the bruising models, Spearman correlation analysis was calculated for explanatory variables. To select an appropriate subset of independent variables, a stepwise logistic regression procedure was performed on the dataset. Variables were entered into the model and removed from the model using the Chi-Square distributed Wald test statistics ($p<0.05$) (Van Linden *et al.*, 2006a). The Hosmer and Lemeshow method was used to validate the obtained model. The established models were compared using Akaike's Information Criterion, AIC, or the R^2 value of the linear regression in the logits, which measure the model's goodness of fit. The smaller value of AIC and the larger value of R^2 indicate a preferable model. However, the physical or scientific significance of the parameters should also be considered by the researchers in judging and selecting the models.

RESULTS AND DISCUSSION

A summary of the results of the determined physicochemical and mechanical parameters is shown in Tables 1 and 2.

Table 2 shows the results of conducted tests related to some impact parameters obtained from the pendulum experiments. Impact properties were significantly different per impact level except for contact time. The restitution coefficient, as well as *PF*, increased with the intensity of the applied impact. Since

Table 1: Some physicochemical properties of studied tomatoes

Properties	Mean value	Standard Deviation (%)
M, gr	100.7838	31.77
M_{wb}, (%)	65.9073	29.50
R_c, mm	36.5213	19.09
S, $10^6 m^2 Hz^{2/3}$	8.84	14.59
TSS	3.58	28.77
TA	4.00	12.25
V, cm^3	98.9663	32.42
S_g, gr/cm^3	1.0223	5.58

Table 2 represents only the overview of the results of conducted experiments and there are not any explanations about the correlation between measured and obtained parameters, so the correlation analysis was performed to obtain the correlations to achieve a better understanding and quick identification of dependencies. Correlations were calculated between test variables to avoid multi-collinearity in the models. Table 3 represents the spearman correlation between fruit physical parameters. All correlations were significant at the probability level of 0.01. These correlation values were between a minimum of 0.398 and a maximum of 0.986 for *T* (thickness) and *R* (curvature radius); *M* (mass), and V (volume), respectively. The correlation coefficients between fruit dimensions, including *L* and *W*; L and *T*; W and *T*; were 0.723, 0.685, and 0.922, respectively. Very high correlations were found between the fruit's physical properties, especially between the *M* and the V, with the studied physical properties. Therefore, the physical parameters, including *L*, W, *T*, *Dg*, *R*, and V, were omitted from the analysis due to the high correlation with the mass.

The highest correlation was found between the impact energy and the absorbed energy (data are not shown). On average, 91% of the impact energy was absorbed by the tomato at the impact, representing that the fruit has a highly damped texture. Because of the simplicity of excreting impact energy level, it was chosen to contribute to the bruise predicting models.

Several alternative color descriptors were proposed as indicators for fruit ripeness. Table 4 shows the Spearman correlation coefficients between alternative color descriptors. The a^* indicates the color range from green (-) to red (+); it is associated with the color of the fruit flesh. In contrast, b^* varies between blue (-) and yellow (+) and relates mainly to skin color. Color indexes such as c^* (*chroma*) $[(a^{*2}+b^{*2})^{1/2})]$ can be used as an alternative to both chromatic components, a^* and b^*. Since the alternative color indices are well correlated with c^*, therefore, it was selected as a color descriptor to be included in the bruising model parameters.

Comprehensive Model

A comprehensive model was established for different dynamic impact loadings, including three impact energy levels and the number of impacts accompanying fruit properties. In this procedure, adding various groups of contributing factors refined the model. All models were built, and their AIC value and R^2 and contributing factors were shown in Figure 4 and Table 5, respectively.

Model Selection Procedure

Models of 1 (AIC value = 141.75, R^2= 0.18) and 2 (AIC value = 140.43, R^2= 0.19) using the impact energy level and impact number respectively as contributing factors were very weak basis to predict the probability of the bruising damage. Addition of response variables including restitution coefficient and Elast improved the model significantly (Model 3, AIC value = 125.5, R^2= 0.31).

Table 2: Some mechanical properties of studied tomatoes

Impact energy Level (mJ)	Impact number	Contact time (s)		Elast (N/s)		*Rc*	SD (%)	*PF*	SD (%)
		MV	SD (%)	MV	SD (%)				
	First	0.0153	13.07	1730.52[a]	24.72	0.2234[a]	21.84	26.89[a]	14.43
125	Second	0.0150	14.67	2837.72[b]	28.58	0.2740[b]	22.43	31.81[b]	15.26
	Third	0.0161	13.66	2122.10[b]	25.32	0.2860[b]	13.81	32.31[b]	13.83
	First	0.0165	9.70	2200.43[a]	21.44	0.2679[a]	15.04	35.70[a]	12.52
250	Second	0.0155	9.03	2767.28[b]	23.10	0.3157[b]	10.83	42.23[b]	14.68
	Third	0.0160	9.38	2655.18[b]	30.23	0.3217[b]	9.88	41.50[b]	18.67
	First	0.0154	11.69	3653.60[a]	25.91	0.2671[a]	13.07	55.06[a]	14.93
500	Second	0.0147	9.52	4522.57[b]	25.81	0.3020[b]	10.30	65.34[b]	15.67
	Third	0.0144	12.50	4936.12[b]	26.09	0.3043[b]	5.55	69.15[b]	13.64

Table 3: Spearman correlation coefficients between studied fruit physical parameters

	L	*W*	*T*	*M*	D_G	*R*	*V*
L		0.723	0.685	0.756	0.845	0.447	0.775
W			0.922	0.918	0.965	0.403	0.921
T				0.962	0.928	0.348	0.969
M					0.939	0.398	0.986
DG						0.423	0.946
R							0.408
V							

All correlation is significant at the 0.01 level

Table 4: Spearman correlation coefficients between alternative color descriptors

	*a**	*b**	*a*/b**	*c**	*hue*	*CI*
*a**		0.22	0.21	0.516	-0.211	-0.021
*b**			-0.824	0.92	0.824	-0.89
a/b**				-0.606	-1	0.936
*c**					0.606	-0.748
hue						-0.935
CI						

All correlation is significant at the 0.01 level

To establish more elaborated models (Models 4 to 12), the various batches of contributing factors from groups 1 to 4, according to Table 5, were used, and the AIC value decreased by about 12.5 %. As shown in Figure 4 noticeable drop can be seen between the AIC values of models 12 and 13 (109.11 to 57.82 units). It may be referred as the effects of selected contributing factors, especially TSS, according to Table 5. The same trend is seen in models 13 to 19. According to AIC and R^2 values (Figure 4 & Table 5), Model 20 presents the best fit. That result was confirmed by the Hosmer and Lemeshow goodness-of-fit test so this model. For studying the contributing factors that affect bruising prediction, model 20 (AIC=42.62 and R2=0.69) is preferred. For practical applications, models14 (AIC=54.25 and R^2=0.62), model 15 (AIC=50.22 and R^2=0.65), and model 17 (AIC=47.75 and R^2=0.63) are the better options because they include no response variables which must be determined by laboratory experiments.

Van Linden *et al.* (2006b) established a relationship between tomato loading conditions and the resulting damage. The obtained general model contains a mixture of the four groups of variables (including Impact, response, environmental and, or fruit parameters), indicating that they all have their specific

Table 5: The contributing factors of bruising models

Model Number	Contributing Factors	R^2
1	*Ei*	0.18
2	*Ni*	0.19
3	*Ei, EL, Rc*	0.31
4	*Rc, EL*	0.29
5	*Rc, EL, Ni*	0.34
6	*Ei, Ni*	0.35
7	*Ei, PF, t, Rc, El*	0.37
8	*PF, t, Rc, El*	0.35
9	*Ei, Ni, EL, Rc*	0.38
10	*Ei, Ni, PF, t, Rc, EL*	0.42
11	*Ei, Ni, PF, t, Rc, EL , c**	0.44
12	*Ni, PF, t, Rc, EL*	0.42
13	*Ei, TSS, c*, M, S*	0.62
14	*TSS, c*, M, S*	0.62
15	*Ei, Ni, TSS, c*, M, S*	0.65
16	*Ei, Ni, PF, t, Rc, EL, TSS, M, S*	0.67
17	*Ni, TSS, c*, M, S*	0.63
18	*Rc, EL, Ni, TSS, c*, M, S*	0.66
19	*Ei, EL, Rc, Ni, TSS, c*, M, S*	0.68
20	*Ei, Ni, PF, t, EL, Rc, TSS, c*, M, S*	0.69
21	*Rc, EL, TSS, c*, M, S*	0.66
22	*Ni, PF, t, Rc, EL, TSS, c*, M, S*	0.68
23	*PF, t, Rc, El, TSS, c*, M, S*	0.67
24	*Ei, PF, t, EL, Rc, TSS, c*, M, S*	0.68
25	*Ei, Rc, EL, TSS, c*, M, S*	0.67

influence on tomato bruising damage. By comparing AIC and R^2 values related to Van Linden *et al.* (2006b) (AIC value = 725 and R^2=0.41) and this study (AIC=42.62 and R^2=0.69), it can be found which model is more capable of predicting tomato bruise damage. The AIC value of the model for this study is considerably low (about 14 times) and the R^2 relatively high (about 40 percent).

Table 6 outlines the relating logistic regression analysis. The parameter estimates with their 95% Wald confidence intervals are listed. In this model, the total variables were significantly varied from zero (α=0.05). As indicated by the small P-value, the explanatory variables are highly significant and have a main effect on bruising development. The following classification of the importance of the contributing variables in bruising incidence is based on the Wald Chi-Square statistics (Table 6): TSS, Elast, number of impacts, *t*, and *PF*.

From Table 6, the odds of being bruised are 59.55 times higher for two times impacts than one impact at the same location. Similarly, the odds of three times impacts being bruised are

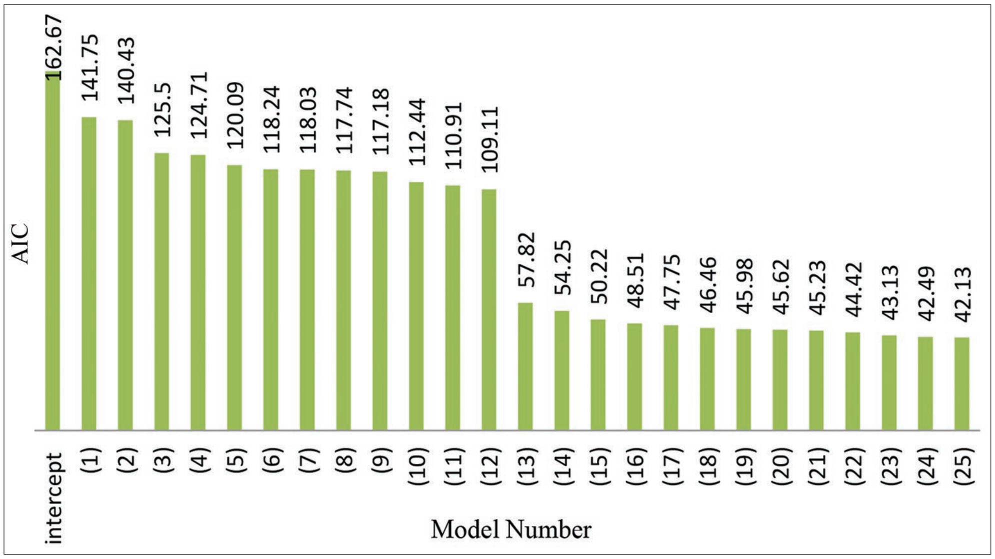


Figure 4: Overview of the model selection for bruise prediction as a function of contributing factors of Groups 1, 2, 3 and 4

Table 6: Summary of the logistic regression analysis of factors contributing bruise development in tomato fruit (R^2=0.69) in the preferred model (Model 20)

Explanatory variable (X)	Parameter estimate	Effect Wald χ^2	Parameter 95% Wald confidence limits		Odds ratio estimates	P-value
			Lower	Upper		
Intercept	-67.54	11.3178	-	-	-	0.0008
Number of Impact$^{2 \text{ vs } 1}$	4.0870	6.0877	2.319	>999.999	59.55	0.0136
Number of Impact$^{3 \text{ vs } 1}$	4.4236	6.1332	2.516	>999.999	83.39	0.0133
Number of Impact$^{3 \text{ vs } 2}$			-2.13	2.08	1.4	0.7895
PF	-0.9657	4.9014	0.162	0.895	0.381	0.0268
t	2.6608	7.1656	2.039	100.411	14.310	0.0074
EL	14.6896	5.5567	11.892	>999.999	>999.999	0.0184
TSS	6.4626	12.9851	19.072	>999.999	640.700	0.0003

All variables significantly entered in the model (α=0.05). AIC value: 162.67 intercept only, 45.62 intercept and covariates

83.39 times that of one impact at the same location. However, there is no significant difference in bruise susceptibility of two times impact and three times impacts. By increasing one millisecond of contact time, the bruising probability increases by 7times. One unit increase in *PF* value will decrease the odds by 62%.

Effect of Consecutive Impacts on Bruise Susceptibility

According to Table 6, it is clear that the impact number has a substantial effect on the bruise susceptibility of tomatoes; still there is no significant difference between the two times and three times impacts at the same location (P value=0.78). This phenomenon is interesting from studying how bruising occurs at successive impacts at the same location (Diener *et al.*, 1979). Bruise damage is correlated with either impact energy or absorbed energy. The restitution coefficient ($R_c = E_e/E_i$ while E_e and E_i elastic and impact energy, respectively) can be seen as an estimation of the degree of absorbed energy(Van Zeebroeck *et al.*, 2007c). In other words, the capacity of a material to store strain energy in the elastic range is called resilience (i.e., coefficient of restitution). As shown in Table 2, the increasing procedure can be seen only for the one and two times impact related to the restitution coefficient value, and the three times impact is not following the mentioned procedure (there is no significant difference between two and three times impact) at all applied impact energy levels. By considering the values of restitution coefficient at two and three times impact, it can be concluded that the impact energy can be recovered as elastic energy (E_e), so a very little impact energy is absorbed to perform plastic deformation or raise the probability of bruising susceptibility. A slight increase of resilience coefficient value results from firming impact place while applying two and three times impacts. The higher percentage of impact energy in three times impact was stored in the elastic form and recoverable in the rebound stage. Therefore, exerting third and other impacts do not significantly affect the bruising susceptibility (Figure 5).

This study's results coincide with the research of Sargent *et al.* (1992). They found that the number of impacts had a significant effect on both the incidence and severity of tomato internal bruising. For mature-green (MG) tomatoes, two drops on the same location from the height of 20 cm caused 20% to 30% internal bruising. In addition, for breaker stage tomatoes, Two drops on a single location from the height of 10 cm caused 50% to 68% internal bruising.

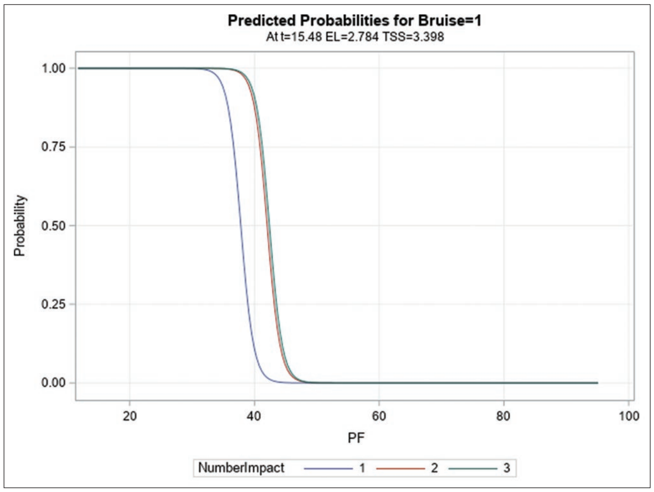


Figure 5: Predicted bruise damage for one, two and three times impacts

The following Equations represent the bruise susceptibility prediction models related to one (N_1), two (N_2), and three (N_3) times impact (Equations 15, 16 & 17 respectively);

$$logit(\pi_{ij})_{N_1} = -67.54 - 0.9657PF + 2.66t + 14.68EL + 6.46TSS \quad (15)$$

$$logit(\pi_{ij})_{N_2} = -67.54 + 4.08N_2 - 0.9657PF + 2.66t + 14.68EL + 6.46TSS \quad (16)$$

$$logit(\pi_{ij})_{N_3} = -64.54 + 4.42N_3 - 0.9657PF + 2.66t + 14.68EL + 6.46TSS \quad (17)$$

Since in logistic regression procedure, the one-time impact is considered a reference, it can be said that the effect of two times and three times impact vs. one-time impact are 4.08 and 4.42, respectively, at the same conditions of equality values of other model parameters. This matter is illustrated in Figure 5. As shown, the S-shape bruise probability curve of the two and three times impact almost coincides with each other, which indicates that there is no significant difference between two and three times impact on the tomato bruise probability at the same location.

Effect of Response Variables on Bruise Susceptibility

According to Table 6, between studied response variables, the effect of Elast, t, and Peak contact force was significant and expressed in the following. By referring to the negative sign of *PF* in the bruising susceptibility of models, it can be concluded that by increasing peak contact force, the bruise susceptibility is decreased. Several fruit properties indirectly affect bruising through peak contact force. Kilcast (2004) reported that the higher peak contact force contributes less to the bruising phenomena. Previous studies have revealed that mature fruits are more susceptible to bruise damage than immature fruit (Van Zeebroeck *et al.*, 2007b; Cañete *et al.*, 2015). Chen and De Baerdemaeker (1995) and Lien *et al.* (2009) proposed that the ripeness and firmness of fruit can be evaluated non-destructively using different response variables, including peak contact force, the ratio of peak force to contact time, coefficient of restitution, contact time, and frequency spectrum under dynamic impact loading.

It is assumed that the bruising occurs in the fruit whenever the stresses due to impact loading exceed the maximal allowable stress, strain, and shear strength of the fruit tissue or energy (Mohsenin *et al.*, 1978; Van Linden, 2007)

In the bioengineering materials like fruit and vegetables, maximum stress can be either bio yield stress or rupture stress. The higher peak stresses are necessary to overcome the high failure stress (Van Zeebroeck *et al.*, 2007b). The maximum surface stress (S_{max}) developed in fruit due to impact can be approximated by the use of Hertz contact theory (S_{max}=3/2 ($F_{max}/\pi ab$)) as given by Mohsenin (1986), where F_{max} is equal to peak contact force and *a* and, *b* are the major and minor semi-axes of the elliptic contact area. The maximum internal shear stress (τ_{max} = 0.27 S_{max}), which is assumed to cause tissue failure, may be approximated by the relationship given by Shigley *et al.* (2004) and Li *et al.* (2017). Tomatoes often have only the rupture stress indicating macro-failure of the tissue (Van Linden, 2007). Therefore, the peak contact force is responsible for creating rupture stress that leads to mechanical damage.

Some studies have been performed to obtain impact responses of fruits and vegetables and their relationship with bruise probability. Brusewitz and Bartsch (1989) established experiments related to the dropping of fruits (five varieties of apples) onto a plate, instrumented with a piezoelectric force transducer. They concluded that by increasing storage time, the firmness decreases, and the relationship of' bruise volume/ absorbed energy' changes gradually. Other researches show different or opposite results (Holt & Schoorl, 1984; Hung & Prussia, 1988); while the firmness is reduced, there was an increase in the ratio of 'bruise volume/absorbed energy'. Sinn (1990) performed free-fall impact testing of cherries and plums. In this and other reported results, a good correlation was observed between impact forces and fruit damage impacting high energy levels (Ruiz-Altisent, 1991).

Van Zeebroeck *et al.* (2006a, b) developed discrete element models to predict the impact damage of apples in boxes or bulk bins during transport and handling, considering peak contact force as independent variables (bruise depth= 5.67 ln (*PF*) − 18.99, R^2 = 0.89). Statistical bruise models were established for apple by Van Zeebroeck *et al.* (2007b) and Javadi *et al.* (2010), pear by Ahmadi *et al.* (2010), kiwifruit by Ahmadi (2012) with peak contact force as the main independent variable.

Since impulse measurements (*P*) play an essential role in the impact experiments, most fruit impact testers, such as the pendulums, have been instrumented to measure impulse during the impact. The impulse-momentum law cannot correctly explain the phenomenon of the fruit impact, and there should be a difference between the measured impulses. Momentum change (Δmv) in the case of fruit impact (Inequality. 19), and this difference might have a significant meaning. These researchers announced that this difference is called absorbed momentum, responsible for fruit damage (Mohsenin, 1986).

$$P = \int_0^t F dt \geq \Delta mv \quad (18)$$

Where F = the measured contact force, t = the impact duration or contact time.

From the recent inequality, it can be seen that the contact duration of impact, t, contributes to the impulse-momentum, so its effect should be taken into account. Longer contact times will cause more fruit damage.

Van Linden *et al.* (2006b) established a general bruise susceptibility model using a logistic regression procedure so that the contact time represents the main effect on tomato bruising. The total contact time was also used as a firmness and maturity indicator represented by Zhang and Brusewitz (1991) and Lien *et al.* (2009), respectively. Zhang and Brusewitz (1991) established an impact force model related to peach firmness by conducting the free fall test. The measured parameters were impact force, variable time, impact duration, and time-to-peak contact force. It was reported that the fruits with more void space, like soft tomatoes, have a longer tail force-time curve which indicates much total contact time so that this parameter can be used as a firmness indicator.

Lien *et al.* (2009) conducted the non-destructive impact test to study three groups of unripe, half-ripe, and ripe tomatoes. The calculated parameters from falling impact, especially total contact time, together with linear discriminant analysis, provide a promising non-destructive approach to assessing the maturity of tomatoes.

The effect of PF and t on the probability of developing a bruise, as predicted by model 20, is shown in Figure 6.

Figures 6 a, b and c illustrate the probability of bruising for one, two, and three times impact at the same place, respectively. It is evident that the two and three times impacts are more harmful to tomatoes. Figure 6a shows the noticeable increase (0.7 to 1) by 30% in bruise probability with increasing contact time and peak contact force, ranging from about 13.4 to 19.8 ms and ranging from approximately 41 to 72 N, respectively. In the case of two times impact (Figure 6b), it can be concluded that the combinations of PF ranging from about 55-76 N and t from 13.5 to 19.8 ms resulted in a high bruising probability level (>0.9). For three times impact, the higher probability of bruising (Logit $\pi \geq 0.9$) was observed at the PF value >74, and all values of contact time ranged from 11.8 to 18.5 ms (Figure 6c).

The response variable Elast is the ratio of PF/t. As for the preferred model, Elast has the most considerable effect on tomato bruising. Holt and Schoorl (1984) and Hung and Prussia (1988) reported that there is a close relation between impact contact time with fruit firmness decreasing, as well as the ratio of peak contact force/contact time (PF/t). Zhang and Brusewitz (1991) conducted the free fall test to establish the impact force model. They found that it is possible to obtain a correlation between peak force and time- to- peak force (PF/t_p), which was nearly similar to the parameter Elast developed by Van Linden *et al.* (2006b).

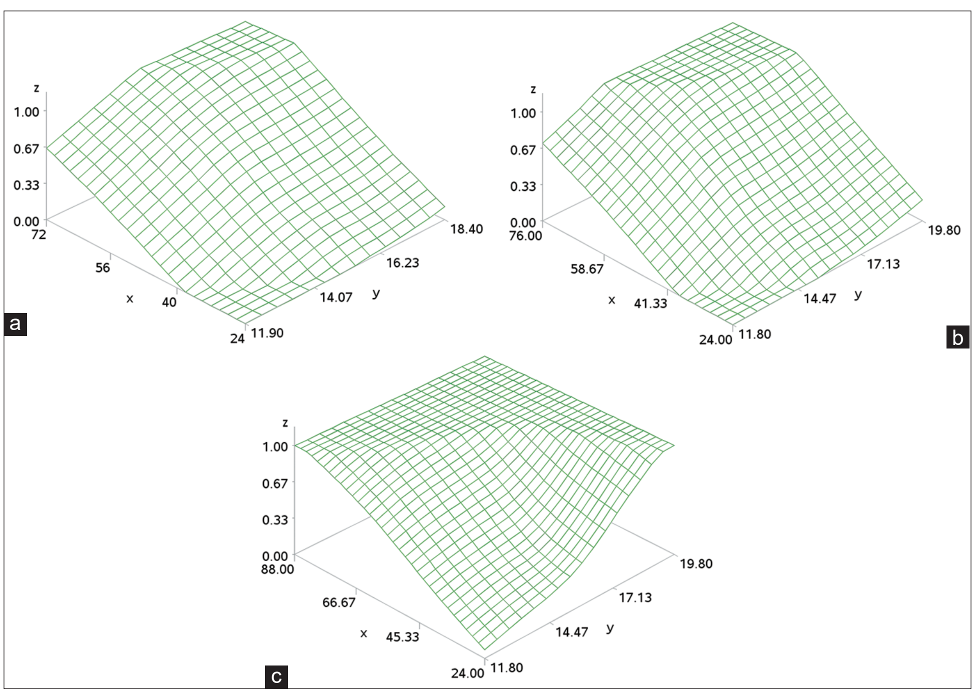


Figure 6: Effect of peak contact force and contact time on probability to develop bruise as predicted by preferred model (Model 20) related to a) one, b) two and c) three times impact

Effect of TSS on Bruise Susceptibility

One of the most important explanatory variables for the incidence of bruise damage, based on the Wald Chi-Square statistics, was the total soluble solids. TSS of tomato fruit is a fundamental factor of quality related to the composition and texture (Weibel *et al.*, 2004; Peck *et al.*, 2006). The TSS is a refractometric index that indicates the proportion (%) of dissolved solids in a solution. It is the sum of sugars (sucrose and hexoses; 65%), acids (citrate and malate; 13%), and other minor components (phenols, amino acids, soluble pectins, ascorbic acid, and minerals) in the tomato fruit pulp (Beckles, 2012). The amount of TSS can be increased by breaking down starch into sugars (Beaudry *et al.*, 1989; Crouch, 2001) or the hydrolysis of cell wall polysaccharides. The increase of soluble pectin affects the cell-wall integrity (Ben & Gaweda, 1985), causing the tomato fruit is less able to sustain against external impact forces and can be easily disrupted (Afsharnia *et al.*, 2017).

CONCLUSION

This research gave the first insight into the response of the tomato fruit to mono and multiple dynamic loadings. Due to commercial handling and packaging operations, probably, tomato fruit undergoes several impacts. Thus one, two-, and three-times impacts were exerted by an inventory instrumented pendulum at the same place on the fruit to investigate the effects of impact energy levels and fruit parameters on the susceptibility to bruising damage. The logistic comprehensive model shows the effects of impact energy levels, the number of impacts, and some fruit physical and chemical attributes. The performed models can be selected from the researcher's point of view to be the appropriate model and can predict the bruise damage of tomatoes considering loading conditions in practice. The number of impacts affects the bruise susceptibility of tomato fruits, but the difference between the two times and three times impacts at the same location was not significant.

REFERENCES

Adedeji, O., Taiwo, K. A., Akanbi, C. T., & Ajani, R. (2006). Physicochemical properties of four tomato cultivars grown in Nigeria. *Journal of Food Processing and Preservation, 30*, 79-86. https://doi.org/10.1111/j.1745-4549.2005.00049.x

Afsharnia, F., Mehdizadeh, S. A., Ghaseminejad, M., & Heidari, M. (2017). The effect of dynamic loading on abrasion of mulberry fruit using digital image analysis. *Information Processing in Agriculture, 4*(4), 291-299. https://doi.org/10.1016/j.inpa.2017.07.003

Agresti, A. (2018). *An Introduction to Categorical Data Analysis*. (3rd ed.). New Jersey, US: Wiley.

Ahmadi, E. (2012). Bruise susceptibilities of kiwifruit as affected by impact and fruit properties. *Research in Agricultural Engineering, 58*(3), 107-113. https://doi.org/10.17221/57/2011-RAE

Ahmadi, E., Barikloo, H., & Soliemani, B. (2014). The effect of fruit properties on the apricot bruises susceptibility. *Journal of Food Measurement and Characterization, 8*, 46-53. https://doi.org/10.1007/s11694-013-9164-1

Ahmadi, E., Ghassemzadeh, H. R., Sadeghi, M., Moghaddam, M., & Neshat, S. Z. (2010). The effect of impact and fruit properties on the bruising of peach. *Journal of Food Engineering, 97*(1), 110-117. https://doi.org/10.1016/j.jfoodeng.2009.09.024

Akanbi, C. T., & Oludemi, F. O. (2004). Effect of processing and packaging on the lycopene content of tomato products. *International Journal of Food Properties, 7*(1), 139-152. https://doi.org/10.1081/JFP-120024173

Allende, A., Desmet, M., Vanstreels, E., Verlinden, B. E., & Nicolaï, B. M. (2004). Micromechanical and geometrical properties of tomato skin related to differences in puncture injury susceptibility. *Postharvest Biology and Technology, 34*(2), 131-141. https://doi.org/10.1016/j.postharvbio.2004.05.007

Atherton, J. G., & Rudich, J. (1986). *The Tomato Crop*. (1st ed.). Dordrecht, Netherlands: Springer. https://doi.org/10.1007/978-94-009-3137-4

Aydın, C., & Özcan, M. (2002). Some physico-mechanic properties of terebinth (*Pistacia terebinthus* L.) fruits. *Journal of Food Engineering, 53*(1), 97-101. https://doi.org/10.1016/S0260-8774(01)00145-5

Beaudry, R. M., Severson, R. F., Black, C. C., & Kays, S. J. (1989) Banana ripening: implications of changes in glycolytic intermediate concentrations, glycolytic and gluconeogenic carbon flux, and fructose 2, 6-bisphosphate concentration. *Plant Physiology, 91*(4), 1436-1444. https://doi.org/10.1104/pp.91.4.1436

Beckles, D. M. (2012). Factors affecting the postharvest soluble solids and sugar content of tomato (*Solanum lycopersicum* L.) fruit. *Postharvest Biology and Technology, 63*(1), 129-140. https://doi.org/10.1016/j.postharvbio.2011.05.016

Ben, J., & Gaweda, M. (1985). Changes of pectic compounds in Jonathan apples under various storage conditions. *Acta Physiologiae Plantarum, 7*(2), 45-54.

Bielza, C., Barreiro, P., Rodríguez-Galiano, M. I., & Martín, J. (2003). Logistic regression for simulating damage occurrence on a fruit grading line. *Computers and Electronics in Agriculture, 39*(2), 95-113. https://doi.org/10.1016/S0168-1699(03)00021-8

Blahovec, J., & Paprštein, F. (2005). Susceptibility of pear varieties to bruising. *Postharvest Biology and Technology, 38*(3), 231-238. https://doi.org/10.1016/j.postharvbio.2005.07.005

Brusewitz, G. H., & Bartsch, J. A. (1989). Impact parameters related to post harvest bruising of apples. *Transactions of the ASAE, 32*(3), 953-957. https://doi.org/10.13031/2013.31097

Cañete, M. L., Hueso, J. J., Pinillos, V., & Cuevas, J. (2015). Ripening degree at harvest affects bruising susceptibility and fruit sensorial traits of loquat (*Eriobotrya japonica* Lindl.). *Scientia Horticulturae, 187*, 102-107. https://doi.org/10.1016/j.scienta.2015.03.008

Chen, H., & De Baerdemaeker, J. (1995). Optimization of Impact Parameters for Reliable Excitation of Apples During Firmness Monitoring. *Journal of Agricultural Engineering Research, 61*(4), 275-282. https://doi.org/10.1006/jaer.1995.1055

Crouch, I. (2001). 1-Methylcyclopropene (Smartfresh TM) as an alternative to modified atmosphere and controlled atmosphere storage of apples and pears. *Acta Horticulturae, 600*, 433-436. https://doi.org/10.17660/ActaHortic.2003.600.64

Desmet, M., Lammertyn, J., Scheerlinck, N., Verlinden, B. E., & Nicolaï, B. M. (2003). Determination of puncture injury susceptibility of tomatoes. *Postharvest Biology and Technology, 27*(3), 293-303. https://doi.org/10.1016/S0925-5214(02)00115-1

Desmet, M., Lammertyn, J., Var linden, V., Verlinden, B. E., Darius, P., & Nicolaï, B. M. (2004b). The relative influence of stem and fruit properties on stem puncture injury in tomatoes. *Postharvest Biology and Technology, 33*(2), 101-109. https://doi.org/10.1016/j.postharvbio.2004.02.001

Desmet, M., Lammertyn, J., Verlinden, B. E., & Nicolaï, B. M. (2002). Mechanical properties of tomatoes as related to puncture injury susceptibility. *Journal of Texture Studies, 33*(5), 415-429. https://doi.org/10.1111/j.1745-4603.2002.tb01357.x

Desmet, M., Van linden, V., Hertog, M. L. A. T. M., Verlinden, B. E., De Baerdemaeker, J., & Nicolaï, B. M. (2004a). Instrumented sphere prediction of tomato stem-puncture injury. *Postharvest Biology and Technology, 34*(1), 81-92. https://doi.org/10.1016/j.postharvbio.2004.04.006

Diener, R. G., Elliott, K. C., Nesselroad, P. E., Ingle, M., Adams, R. E., & Blizzard, S. H. (1979). Bruise energy of peaches and apples. *Transactions of the ASAE, 22*(2), 287-290. https://doi.org/10.13031/2013.35007

Fu, H., Liu, G., Yang, J., Du, W., Wang, W., & Yang, Z. (2023). Bruising damage in apple-to-apple collision via a sliding method. *Biosystems Engineering, 235*, 150-165. https://doi.org/10.1016/j.biosystemseng.2023.09.017

Gao, Y., & Rao, X. (2019). Blackspot bruise in potatoes: susceptibility and biospeckle activity response analysis. *Journal of Food Measurement and Characterization, 13*, 444-453. https://doi.org/10.1007/s11694-

018-9958-2

Ghaffari, H., RezaGhassemzadeh, H., Sadeghi, M., & Alijani, S. (2015). Some physical, mechanical and chemical properties of tomato fruit related to mechanical damage and bruising models. *Biological Forum, 14*.

Holt, J. E., & Schoorl, D. (1984). Mechanical properties and texture of stored apples. *Journal of Texture Studies, 15*(4), 377-394. https://doi.org/10.1111/j.1745-4603.1984.tb00393.x

Hou, J., Park, B., Li, C., & Wang, X. (2024). A multiscale computation study on bruise susceptibility of blueberries from mechanical impact. *Postharvest Biology and Technology, 208*, 112660. https://doi.org/10.1016/j.postharvbio.2023.112660

Hung, Y., & Prussia, S. (1988). *Determining bruise susceptibility of peaches*. ASAE paper 88-6026, St Joseph, MI, USA: ASAE.

Hussein, Z., Fawole, O. A., & Opara, U. L. (2018). Preharvest factors influencing bruise damage of fresh fruits – a review. *Scientia Horticulturae, 229*, 45-58. https://doi.org/10.1016/j.scienta.2017.10.028

Hussein, Z., Fawole, O. A., & Opara, U. L. (2019a). Bruise damage susceptibility of pomegranates (*Punica granatum*, L.) and impact on fruit physiological response during short term storage. *Scientia Horticulturae, 246*, 664-674. https://doi.org/10.1016/j.scienta.2018.11.026

Hussein, Z., Fawole, O. A., & Opara, U. L. (2019b). Determination of physical, biochemical and microstructural changes in impact-bruise damaged pomegranate fruit. *Journal of Food Measurement and Characterization, 13*, 2177-2189. https://doi.org/10.1007/s11694-019-00138-z

Hussein, Z., Fawole, O. A., & Opara, U. L. (2020). Harvest and Postharvest Factors Affecting Bruise Damage of Fresh Fruits. *Horticultural Plant Journal, 6*(1), 1-13. https://doi.org/10.1016/j.hpj.2019.07.006

Javadi, A., Ahmadi, E., Abbaspour-Fard, M. H., Sadeghi, M., Ghassemzadeh, H. R., Zarifneshat, S. & Shervani-Tabar, M. T. (2010). Effect of impact level and fruit properties on golden delicious apple bruising. *American Journal of Agricultural and Biological Science, 5*(2), 114-121. https://doi.org/10.3844/ajabssp.2010.114.121

Khan, M. A., Butt, S. J., Khan, K. A., Nadeem, F., Yousaf, B., & Javed, H. U. (2017). Morphological and physico-biochemical characterization of various tomato cultivars in a simplified soilless media. *Annals of Agricultural Sciences, 62*(2), 139-143. https://doi.org/10.1016/j.aoas.2017.10.001

Kilcast, D. (2004). *Texture in Food: Solid Foods*. Sawston, UK: Woodhead Publishing Limited.

Lana, M. M., Tijskens, L. M. M., & van Kooten, O. (2006). Modelling RGB colour aspects and translucency of fresh-cut tomatoes. *Postharvest Biology and Technology, 40*(1), 15-25. https://doi.org/10.1016/j.postharvbio.2005.12.016

Lee, E., Berry, A. D., & Sargent, S. A. (2004). Impact thresholds to maximize postharvest quality of Roma-type tomato. *Proceedings of the Florida State Horticultural Society, 117*, 373-377.

León, K., Mery, D., Pedreschi, F., & León, J. (2006). Color measurement in L∗a∗b∗ units from RGB digital images. *Food Research International, 39*(10), 1084-1091. https://doi.org/10.1016/j.foodres.2006.03.006

Li, Z. (2013). The effect of compressibility, loading position and probe shape on the rupture probability of tomato fruits. *Journal of Food Engineering, 119*(3), 471-476. https://doi.org/10.1016/j.jfoodeng.2013.06.024

Li, Z., Miao, F., & Andrews, J. (2017). Mechanical Models of Compression and Impact on Fresh Fruits. *Comprehensive Reviews in Food Science and Food Safety, 16*(6), 1296-1312. https://doi.org/10.1111/1541-4337.12296

Lien, C.-C., Ay, C., & Ting, C.-H. (2009). Non-destructive impact test for assessment of tomato maturity. *Journal of Food Engineering, 91*(3), 402-407. https://doi.org/10.1016/j.jfoodeng.2008.09.036

Mansourbahmani, S., Ghareyazie, B., Kalatejari, S., Mohammadi, R. S., & Zarinnia, V. (2017). Effect of post-harvest UV-C irradiation and calcium chloride on enzymatic activity and decay of tomato (*Lycopersicon esculentum* L.) fruit during storage. *Journal of Integrative Agriculture, 16*(9), 2093-2100. https://doi.org/10.1016/S2095-3119(16)61569-1

Mohsenin, N. N. (1986). *Physical Properties of Plant and Animal Materials: Structure, Physical Characteristics, and Mechanical Properties*. New York, US: Gordon and Breach.

Mohsenin, N. N., Jindal, V. K., & Manor, A. K. (1978). Mechanics of impact of a falling fruit on a cushioned surface. *Transactions of the ASAE, 21*(2), 594-600. https://doi.org/10.13031/2013.35350

Peck, G. M., Andrews, P. K., Reganold, J. P., & Fellman, J. K. (2006). Apple orchard productivity and fruit quality under organic, conventional, and integrated management. *HortScience, 41*(1), 99-107. https://doi.org/10.21273/HORTSCI.41.1.99

Quevedo, R., Díaz, O., Ronceros, B., Pedreschi, F., & Aguilera, J. M. (2009). Description of the kinetic enzymatic browning in banana (Musa cavendish) slices using non-uniform color information from digital images. *Food Research International, 42*(9), 1309-1314. https://doi.org/10.1016/j.foodres.2009.04.004

Ruiz-Altisent, M. (1991). Damage mechanisms in the handling of fruits. In J. Matthews (Eds.), Progress in agricultural physics and engineering (pp. 231-255) Willingford, UK: Commonwealth Agricultural Bureaux (CAB) International.

Sacilik, K., Keskin, R., & Elicin, A. K. (2006). Mathematical modelling of solar tunnel drying of thin layer organic tomato. *Journal of Food Engineering, 73*(3), 231-238. https://doi.org/10.1016/j.jfoodeng.2005.01.025

Salim, M. M. R., Rashid, M. H., Hossain, M. M., & Zakaria, M. (2018). Morphological characterization of tomato (*Solanum lycopersicum* L.) genotypes. *Journal of the Saudi Society of Agricultural Sciences, 19*(3), 233-240. https://doi.org/10.1016/j.jssas.2018.11.001

Sanches, A. G., da Silva, M. B., Silva Moreira, E. G., dos Santos, E. X., Menezes, K. R. P., & Cordeiro, C. A. M. (2019). Ethylene absorber (KMnO4) in postharvest quality of pinha (*Anona squamosa* L.). *Emirates Journal of Food and Agriculture, 31*(8), 605-612. https://doi.org/10.9755/ejfa.2019.v31.i8.1992

Sargent, S. A., Brecht, J. K., & Zoellner, J. J. (1992). Sensitivity of tomatoes at mature-green and breaker ripeness stages to internal bruising. *Journal of the American Society for Horticultural Science, 117*(1), 119-123. https://doi.org/10.21273/JASHS.117.1.119

Schotte, S., De Belie, N., & De Baerdemaeker, J. (1999). Acoustic impulse-response technique for evaluation and modelling of firmness of tomato fruit. *Postharvest Biology and Technology, 17*(2), 105-115. https://doi.org/10.1016/S0925-5214(99)00041-1

Setareh, R., Mohammadi-Ghermezgoli, K., Ghaffari-Setoubadi, H., & Alizadeh-Salteh, S. (2023). The effectiveness of hot-air, infrared and hybrid drying techniques for lemongrass: appearance acceptability, essential oil yield, and volatile compound preservation. *Scientific Reports, 13*, 18820. https://doi.org/10.1038/s41598-023-44934-6

Shigley, J. E., Mischke, C. R., & Budynas, R. G. (2004). *Mechanical Engineering Design*. New York, US: McGraw-Hill.

Sinn, H. (1990). Mechanics of impact of cherries and plums falling on different kinds of catching surface. In *International conference on agricultural mechanization, Zaragoza, Spain, 27-30 March 1990. Workshop on impact damage of fruits and vegetables. FIMA, 2*, 67-77.

Stropek, Z., & Gołacki, K. (2019). Impact characteristics of pears. *Postharvest Biology and Technology, 147*, 100-106. https://doi.org/10.1016/j.postharvbio.2018.09.015

Sun, H., Wan, F., Huang, Y., Xu, Z., & Huang, X. (2024). Evaluation of a new method to assess blueberry bruising based on intracellular and extracellular water ratios. *Scientia Horticulturae, 328*, 112896. https://doi.org/10.1016/j.scienta.2024.112896

Van Linden, V. (2007). *Identification of fruit parameters responsible for impact-bruising of tomatoes*. Doctoral Dissertation. Katholieke Universiteit Leuven.

Van Linden, V., De Ketelaere, B., Desmet, M., & De Baerdemaeker, J. (2006a). Determination of bruise susceptibility of tomato fruit by means of an instrumented pendulum. *Postharvest Biology and Technology, 40*(1), 7-14. https://doi.org/10.1016/j.postharvbio.2005.12.008

Van Linden, V., Scheerlinck, N., Desmet, M., & De Baerdemaeker, J. (2006b). Factors that affect tomato bruise development as a result of mechanical impact. *Postharvest Biology and Technology, 42*(3), 260-270. https://doi.org/10.1016/j.postharvbio.2006.07.001

Van Linden, V., Sila, D. N., Duvetter, T., De Baerdemaeker, J., & Hendrickx, M. (2008). Effect of mechanical impact-bruising on polygalacturonase and pectinmethylesterase activity and pectic cell wall components in tomato fruit. *Postharvest Biology and Technology, 47*(1), 98-106. https://doi.org/10.1016/j.postharvbio.2007.06.006

Van Zeebroeck, M., Tijskens, E., Dintwa, E., Kafashan, J., Loodts, J., De Baerdemaeker, J., & Ramon, H. (2006a). The discrete element method (DEM) to simulate fruit impact damage during transport and handling: Case study of vibration damage during apple bulk transport. *Postharvest Biology and Technology, 41*(1), 92-100. https://doi.org/10.1016/j.postharvbio.2006.02.006

Van Zeebroeck, M., Tijskens, E., Dintwa, E., Kafashan, J., Loodts, J., De

Baerdemaeker, J., & Ramon, H. (2006b). The discrete element method (DEM) to simulate fruit impact damage during transport and handling: Model building and validation of DEM to predict bruise damage of apples. *Postharvest Biology and Technology, 41*(1), 85-91. https://doi.org/10.1016/j.postharvbio.2006.02.007

Van Zeebroeck, M., Tijskens, E., Van Liedekerke, P., Deli, V., De Baerdemaeker, J., & Ramon, H. (2003). Determination of the dynamical behaviour of biological materials during impact using a pendulum device. *Journal of Sound and Vibration, 266*(3), 465-480. https://doi.org/10.1016/S0022-460X(03)00579-0

Van Zeebroeck, M., Van linden, V., Darius, P., De Ketelaere, B., Ramon, H., & Tijskens, E. (2007a). The effect of fruit factors on the bruise susceptibility of apples. *Postharvest Biology and Technology, 46*(1), 10-19. https://doi.org/10.1016/j.postharvbio.2007.03.017

Van Zeebroeck, M., Van linden, V., Darius, P., De Ketelaere, B., Ramon, H., & Tijskens, E. (2007b). The effect of fruit properties on the bruise susceptibility of tomatoes. *Postharvest Biology and Technology, 45*(2), 168-175. https://doi.org/10.1016/j.postharvbio.2006.12.022

Van Zeebroeck, M., Van linden, V., Ramon, H., De Baerdemaeker, J., Nicolaï, B. M., & Tijskens, E. (2007c). Impact damage of apples during transport and handling. *Postharvest Biology and Technology, 45*(2), 157-167. https://doi.org/10.1016/j.postharvbio.2007.01.015

Wang, W., Lu, H., Zhang, S., & Yang, Z. (2019). Damage caused by multiple impacts of litchi fruits during vibration harvesting. *Computers and Electronics in Agriculture, 162*, 732-738. https://doi.org/10.1016/j.compag.2019.04.037

Wang, W., Yang, Z., Lu, H., & Fu, H. (2018). Mechanical damage caused by fruit-to-fruit impact of litchis. *IFAC-PapersOnLine, 51*(17), 532-535. https://doi.org/10.1016/j.ifacol.2018.08.154

Weibel, F., Widmer, F., & Husistein, A. (2004). Comparison of production systems: integrated and organic apple production. Part III: Inner quality: composition and sensory. *Obst-und Weinbau, 140*, 10-13.

Zhang, X., & Brusewitz, G. H. (1991). Impact force model related to peach firmness. *Transactions of the ASAE, 34*(5), 2094-2098. https://doi.org/10.13031/2013.31843