Europ.J.Hort.Sci., **78** (5). S. 219–224, 2013, ISSN 1611-4426. © Verlag Eugen Ulmer KG, Stuttgart

Sensitivity of Tomatoes to Internal Bruising Induced by Mechanical Stress

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Summary

Tomato bruising is a major type of postharvest damage that substantially reduces fruit quality and marketability. Bruises show local tissue softening in parallel with textural changes. Among perishable commodities, tomatoes are considerably sensitive to mechanical damage. Impact power and fruit-related properties that affect tomato bruise susceptibility were investigated in this study. A bruise prediction model was constructed for the damage susceptibility of tomato (measured by absorbed energy) using multiple linear regression analyses. Tomatoes were subjected to dynamic loading by means of a pendulum at three levels of impact. Significant effects of acoustic stiffness, temperature, the radius of curvature and some interactions on bruising were obtained at 5 % probability level. It was concluded that increases in temperature during impacts as well as high acoustic stiffness and low radius of curvature of fruit will reduce the absorbed energy and, thus alleviate bruise damage of tomatoes.

Key words. absorbed energy – bruising susceptibility – fruit properties – impact – tomato

Introduction

Mechanical damage causes pronounced postharvest losses of fruits and vegetables especially in undeveloped countries. Substantial scientific efforts are necessary to improve the current situation. If fruit is mechanically damaged, it is more susceptible microbial infection causing decay of the produce. Bruising is the most common type of damage to tomatoes, but cuts, punctures, scars and scuffs are also inflicted by impact, compression or vibration damage through poor handling. Impacts are transitory movements due to sudden acceleration or deceleration causing great dissipation of energy and, consequently, damage to the fruit. During packing stage, fruit and vegetables are more exposed to impact and vibration than to compression forces (Garcia et al. 1988). Both impact and compression bruising can cause significant damage, discolor tissues and detraction from the visual and eating quality of the commodity. It is, thus, desirable to assess the level of bruising occuring on fresh tomatoes during handling, transport and processing. The mechanisms of bruising are, still, not fully understood and the parameters mainly responsible for bruise damage are not yet entirely characterized (Van Linden et al. 2006a). The bruising is considered to be a two step process, in which mechanical damage occurs first and then the affected tissue shows soft spots on the surface during the first 2–3 days after impact (Van Linden et al. 2006b). Tomatoes are commercially main vegetable worldwide, and their interior structure properties differ from one another. In addition, the biological material of tomatoes is heterogeneous, and an intact tomato has pericarp, cross-wall, locular gel and seed tissue etc. The texture of tomato tissue is largely determined by the mechanical properties of the pericarp tissue. Changes in its texture will alter the fruit mechanical properties and will affect the quality and the bruise susceptibility of the commodity. When a tomato is mechanically damaged, the enzymes that act on the cell wall can face a more accessible substrate. In fact, the wall is loosened and bonds are broken. This could result in a rapid enzymatic breakdown of the cell wall polysaccharides, which is observed as soft on the fruit, called bruises (Hetong et al. 2002; Xiubing et al. 2009).

External bruises are caused by the failure of the outer pericarp due to cell rupture or fracture between cells when the tissue receives an impact above the bio-yield point (Holt and Schoorl 1982). However, internal bruising can be caused by impacts lower than the bio-yield point if the impact energy is transmitted to the underlying tissue with sufficient force so as to impair ripening, as indicated by subsequent abnormal color development and increased gel viscosity. Physical impact of tomato fruit can cause internal

bruising, a physiological disorder that results from an impairment of normal ripening (Halsey 1955). Moretti et al. (1998) observed that impact bruising increased ethylene and carbon dioxide evolution, and altered chemical composition and physical properties of impacted pericarp and locule tissues, lowering fruit quality. The stage of fruit ripeness at harvest is one of the major factors affecting the susceptibility of commodity to mechanical damage; riper tomatoes are more susceptible to mechanical damage (Olorunda and Tung 1985).

Models predicting bruising of peaches, apples, tomatoes and potatoes according to the impact properties and fruit properties are well documented in literature (Bajema and Hyde 1998; Menesatti et al. 1999; Van Linden et al. 2006a; Opara 2007; Van Zeebroeck et al. 2007a, b; Ahmadi et al. 2010). Contrast to apples, no browning of damaged tissue occur in tomatoes, making objective measurement of tomato bruise damage (softening of the fruit tissue) to be very difficult. Until now, no such method has been introduced. Van Linden et al. (2006a, b) tried to present a method to evaluate bruise damage in tomato and establish a method to determine the bruise susceptibility of different tomato cultivars by a statistical model. Because of the lack of precise bruise determination of tomatoes, research about tomato bruise susceptibility is rare (Van Zeebroeck et al. 2007b).

The objective of this study was to develop bruise prediction models for tomato using peak contact force together with the fruit properties such as fruit temperature, acoustic stiffness and radius of curvature as independent variables. In this research, absorbed energy was used to quantify bruise damage. For one experimental object, it can be stated that higher absorbed energy indicates higher bruise damage.

Materials and Methods

Experimental setup

All experiments were conducted using tomato 'Platero' cultivar which was harvested in 2010 from a greenhouse in the west of Iran. Uniform, red color and healthy tomatoes were used in the experiments which were stored in optimal conditions (3 °C, 85 % RH) during measurement, with maximum three day storage before measurement. At least 10 h before the actual measurement, the tomatoes were maintained at the desired temperature. Tomatoes at 8 °C were measured within 7 min to minimize fruit warming in the measuring room at 20 °C. A total of 180 tomatoes were used for conducting the experiments. These tomatoes were divided into six groups and, consequently, 30 tomatoes were tested for each treatment (temperature × impact level combination). Each tomato was impacted once. Fruits were mounted on a pendulum (Ahmadi et al. 2010) and impacted by a spherical steel indenter (R = 25 mm).

Normally, bruise is visible on the surface of most fruits such as apple, pear and potato, while generally invisible in tomatoes. The absorbed energy was used as a dependent variable in the bruise prediction model. Absorbed energy is calculated by subtracting rebound energy of the impact energy (Ahmadi 2012). Three nominal impact levels were applied as outlined in Table 1. These levels of impact were selected based on the results obtained by Van Linden et al. (2006a). The impact energy levels in the experiment were chosen above the critical impact level of tomatoes. All three impact levels were recorded during mechanical harvest, handling and transporting. The lower limit of the applied impact level was based on the measured impact force and acceleration during handling and transporting, but the higher impact level was obtained in mechanical harvester. For each impact, the exact peak contact force was measured and logged to a data file. The independent variables that were used in the regression models were:

- Peak contact force (PF) (N).
- Two tomato temperatures (T): 8 and 20 °C.
- Tomato radius of curvature (R) at the location of impact (mm).
- Tomato acoustic stiffness (S) (s^{-2} $kg^{2/3}$).

The radius of curvature was measured at the location of contact by a radius of curvature meter (Ahmadi et al. 2010). The maximum and minimum values of curvature radius obtained in measurement were, respectively, 40.7 and 24.3 mm. The tomato acoustic stiffness was calculated on preconditioned fruit based on the acoustic impulse-response technique (Ahmadi et al. 2010). The extreme values (Max. and Min.) of acoustic stiffness measured based on this method in experiments were 4.2 and 8.7 s^{-2} $kg^{2/3}$.

Table 1. Impact parameters extracted from a pendulum experiment and fruit properties for tomato at red ripe stage.

Impact and fruit properties	Impact Level		
	Level 1	Level 2	Level 3
Impact energy (J)	0.024	0.073	0.170
Average of rebound energy (J)	0.0084	0.0176	0.0180
Average of absorbed energy (J)	0.0192	0.0554	0.1520
Average of peak contact force (N)	13.67	26.18	49.37
Average of radius of curvature (mm)	30.7	35.2	31.6
Average of acoustic stiffness (s^{-2} $kg^{2/3}$)	6.9	5.7	6.3

Statistical analyses

The dependent variable was the absorbed energy (AE) of tomato. In the bruise prediction model independent variables were peak contact force (PF), radius of curvature at the location of impact (R), tomato acoustic stiffness (S) and temperature (T). A backward multiple regression procedure was conducted to select the relevant independent variables influencing the dependent variable using 5 % significance level. Furthermore, in order to verify the accuracy of multiple regression models, a chi-square test was carried out using the predicted and experimental data. SAS software (version 8.2, The SAS Institute Inc., NC, USA) was used for data analysis.

Results and Discussion

Bruise will occur in the locale where stresses induced in the fruit are equal to or exceeds the failure stress of the fruit tissue. The mechanical impact, fruit properties and their interactions have a considerable effect on the bruise susceptibility of tomato. When fruit was impacted at the highest impact level, the probability to develop a bruise was greatly increased; therefore, it can be stated that bruise damage increases when the impact level increases. The high impact level results in a high peak contact stress (based on Hertz theory). AHMADI et al. (2010), VAN LINDEN et al. (2006a, b) and VAN ZEEBROECK et al. (2007a, b), respectively, reported that bruising damage in peach, tomato and apple increased by increase of impact level. At low to normal impacts, most common in practice, fruit properties play a predominant role; at high impacts, however, influence of fruit properties on the bruise damage seems to be reduced. Severity of damage depends on physiological and biochemical properties of fruit, such as plant cell chemical oxidation reactions (STREHMEL et al. 2010).

Results of a multiple linear regression analysis between absorbed energy and the independent variables peak contact force, radius of curvature, acoustic stiffness and temperature are presented in Table 2. All of the terms in the model had a significant effect at 5 % probability level. Fig. 1 presents the predicted absorbed energy depicted versus the measured absorbed energy in relation to this model. A good fit was obtained between the measured and predicted absorbed energy.

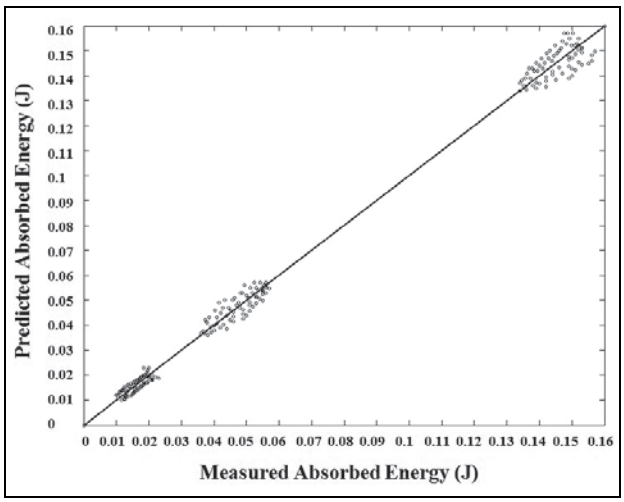


Fig. 1. Measured absorbed energy (J) vs. absorbed energy predicted by model 1.

Effect of tomato radius of curvature on absorbed energy

In this study, we observed more absorbed energy with high radius of curvature. Indeed, tomatoes with large radius of curvature had more bruising than those with a smaller radius of curvature (at the location of impact) (Fig. 2). No significant interaction was obtained between radius of curvature and peak contact force. The difference in absorbed energy between two extremes of tomato curvature radius (24.3 and 40.7 mm) was 21 % at the low impact (13.7 N) but only 9 % at the high impact (49.4 N).

Studies on the effect of curvature radius on tomato bruise susceptibility are rare. VAN ZEEBROECK et al. (2007a) stated that tomatoes at 15 °C absorb more energy when the radius of curvature increases (more flat), but tomatoes at 20 °C absorb less energy when the radius of curvature increases; therefore, the effect of the radius of curvature on the absorbed energy of the tomatoes depends on the temperature. An explanation of the effect of

Table 2. Regression equation of absorbed energy (in J) of the tomato (AE) in relation to peak contact force (PF), temperature (T), acoustic stiffness (S) and radius of curvature (R) as independent variables.

Model 1	R^2
$AE = -8.62 \times 10^{-2} + 4.58 \times 10^{-3}\ PF + 3.347 \times 10^{-4}\ T - 3.635 \times 10^{-3}\ S$	
$- 5.273 \times 10^{-3}\ R + 4.574 \times 10^{-4}\ PF * R + 1.714 \times 10^{-4}\ PF * S$	0.91

Note: minimum probability threshold $P \leq 0.05$

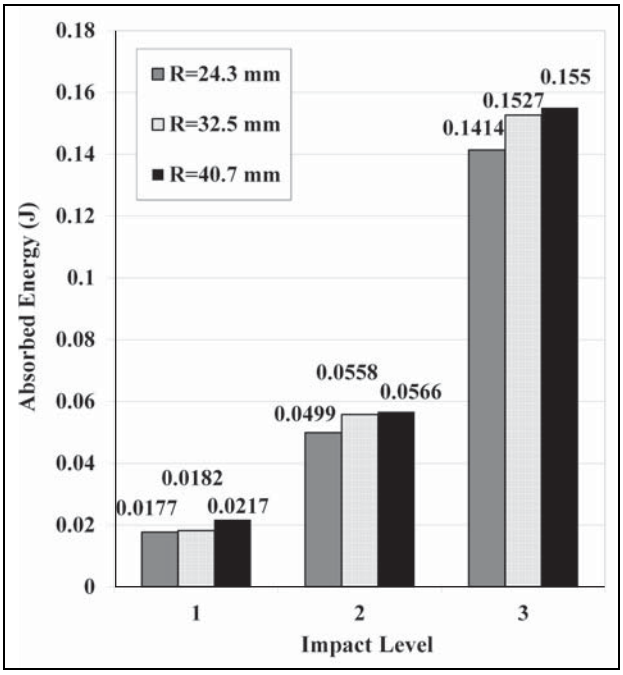


Fig. 2. Effect of curvature radius on the absorbed energy (J) of tomato at 8 °C for each peak contact force level.

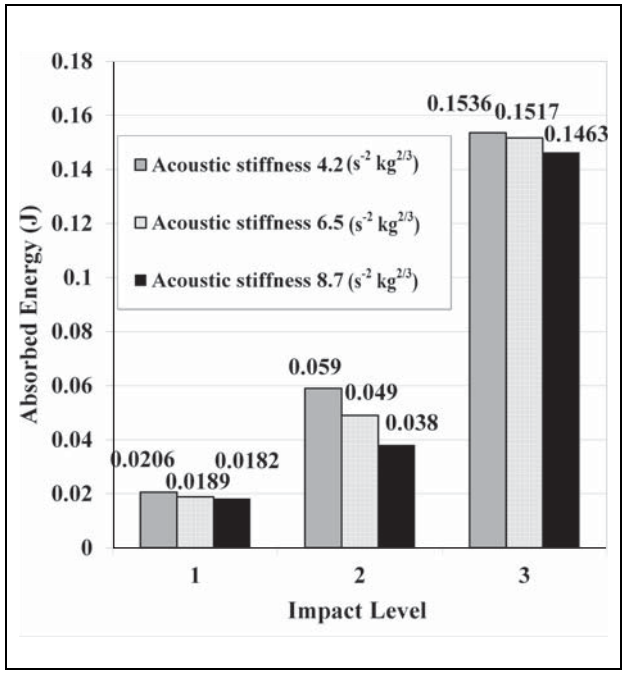


Fig. 3. Effect of acoustic stiffness on the absorbed energy (J) of tomato at 8 °C for each peak contact force level.

the radius of curvature on absorbed energy could be that tomatoes at 15 °C have a lower failure stress, with the consequence that the higher contact area of tomatoes with higher radius of curvature becomes more important than the lower peak stress compared to tomatoes of the lower radius of curvature (based on Hertz theory for elastic bodies) (Van Zeebroeck et al. 2007a). It can be seen that a large radius of curvature results in a higher contact area and thus leads to more bruise damage. This was confirmed by our results about impact levels where a large radius of curvature led to more bruise damage. Van Zeebroeck et al. (2007a) expressed tomatoes of 20 °C have higher firmness (failure stress) and therefore the small radius of curvature gives rise to higher peak stresses necessary to overcome the high failure stress and that probably the opposite effect of radius of curvature for tomatoes of 15 and 20 °C is due to their difference in acoustic stiffness (for tomatoes the positive correlation with firmness is important). The rate of tomato softening is related to fruit size and storage atmosphere.

Effect of tomato acoustic stiffness on absorbed energy

Tomatoes with low acoustic stiffness led to more absorbed energy than fruit with higher acoustic stiffness. Stiffer tomatoes showed less bruise damage. More damage with advanced ripeness was observed. The significant interaction ($P < 0.05$) between acoustic stiffness and peak contact force indicated that the difference in absolute value of the absorbed energy between ripe and unripe tomato increased with peak contact force. However, the relative difference decreased with increase of peak contact force (Fig. 3). The absorbed energy for the acoustic stiffness of 4.2 s^{-2} $kg^{2/3}$ was up to 13 % higher than 8.7 s^{-2} $kg^{2/3}$ at low impacts (13.7 N) and up to 5 % higher at high impacts (49.4 N).

Tomato acoustic stiffness is an index for tomato ripeness when measured within one cultivar. A higher acoustic stiffness indicates a lower ripeness. The stage of fruit ripeness at harvest is one of the major factors affecting the susceptibility of commodity to mechanical injury; riper tomatoes were more susceptible to mechanical damage (Olorunda and Tung 1985). Internal bruising was more pronounced on tomatoes handled at breaker-stage than at mature-green stage (Sargent et al. 1992).

The acoustic stiffness is positively related to the elastic modulus (Duprat et al. 1997). A higher firmness or failure stress for stiffer fruits means that they are more resistant to bruising. The effect of ripeness on bruise susceptibility is the same as that for peaches (Ahmadi et al. 2010) while there is opposite effect for 'Jonagold' apples (Van Zeebroeck et al. 2007b). Van Zeebroeck et al. (2007a) stated that the most likely explanation for the effect of the increasing energy absorption with the increase of ripeness is the decrease in tomato firmness. It was expressed that higher acoustic stiffness leads to higher peak stress during impact (Van Zeebroeck et al. 2007b). This is also the case of tomatoes; however, a higher peak stress for stiffer unripe tomatoes doesn't lead to more bruise damage (absorbed energy) because the failure stress is higher for the unripe

tomatoes as well. Thus, the fact that the stiffer tomatoes suffer from less bruise damage could be due to the dominant effect of the higher firmness or failure stress rather than the higher peak contact stress. It is mainly a measure of the mechanical stiffness of the fruit tissue that is related to the cell wall mechanical strength and turgor (Hertog et al. 2004), which diminish during ripening by enzymatic changes of the cell wall and moisture loss and by the decrease of the cell wall strength, the bruise susceptibility of fruit will increase.

Effect of tomato temperature on absorbed energy

Temperature had an inverse effect on the absorbed energy (Table 2 and Fig. 5) and a lower temperature caused more bruising. The significant interaction ($P < 0.05$) between tomato temperature and peak contact force indicated that the absorbed energy at different peak contact forces differs by the increase in tomato temperature. However, the relative difference decreased with the increase in peak contact force (Fig. 4). The largest difference in absorbed energy between two temperatures was observed at lower impact forces (Fig. 4). This difference ranged from about 10 % for the lowest impact (13.7 N) to only 2 % for highest impact (49.4 N).

The tomato as a group is very responsive to high temperature exposure, such as delays between harvests and cooling. The single fruit tissue properties are heterogeneous and depend mainly on the number of locules in tomato fruits. Existing results in literatures about temperature effects on tomato bruising are inconsistent. Van Zeebroeck et al. (2007a) reported that tomatoes at room temperature (20 °C) absorb less energy (and consequently bruising is low) than tomatoes at 15 °C, they maintained that the higher firmness of tomatoes at 20 °C leads to lower absorbed energy. A possible explanation is that the higher absorbed energy of colder tomatoes is mainly due to the higher viscous energy component (lower temperature leads to higher viscosity) and not to plastic deformation (plastic energy component) (Van Zeebroeck et al. 2007a). This statement verifies our observation about temperature effect. Van Linden et al. (2006a) observed more external tomato bruising for tomatoes at room temperature compared to those at 12 °C. The influence of temperature on tomato damage bruise susceptibility can be expounded by its effect on tomato elasticity and viscosity. Temperature affects stiffness via the activity of enzymes which degrade the cell wall. As the cell walls viscosity rose with reduction of temperature, the cell walls might get to be more fragile leading to an increased stiffness but decreasing the cell wall inflexibility (Hertog et al. 2004). On the other hand, the modulus of elasticity (stiffness) reduces with the increase of apple temperature and the modulus of elasticity is positively related to the fruit bruise damage (Van Lancker 1979; Van Zeebroeck et al. 2007c). The fruit temperature generally influenced both tension (strength) of tissue and viscosity of cell wall

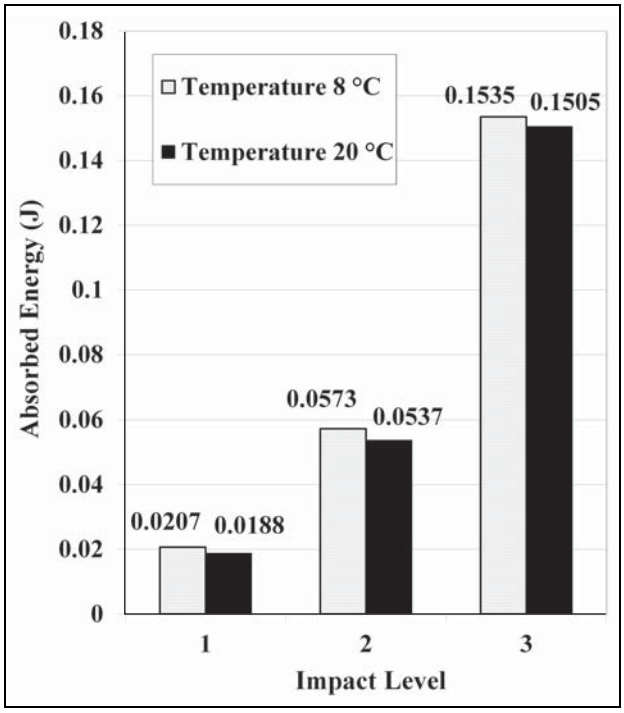


Fig. 4. Effect of temperature on the absorbed energy (J) of tomato for each impact peak contact force level.

(Bajema et al. 1998). With the rise of the fruit temperature, failure stress of tissue decreases and failure strain increase; therefore, the elastic modulus and consequently some sacrifice strength of tissue are reduced (Baritelle and Hyde 2001). Depending on the type of fruit and its physiological status, the relative contributions of temperature and the mechanical rigidity of the cell wall to stiffness might vary. However, metabolic activity and thus softening rate increase with the increase in the storage temperature (Chiesa et al. 1998).

Conclusions

The results of our study show that upon mechanical impact of tomato, specific texture changes started. These texture changes include mainly the bruising of fruit, which cause severe changes during fruit primary metabolism. A bruise prediction model was constructed for the tomato, with impacts controlled by a pendulum. In this work, physical (radius of curvature and tomato temperature), physiological (acoustic stiffness or ripeness) of fruit characteristics and impact property (peak contact force) are considered to characterize the bruising mechanism. Absorbed energy is a good estimation property for quantify bruise damage in tomato. The effect of the tomato properties on the absorbed energy was distinguished. Softer tomato developed a higher amount of the absorbed energy. At low temperatures, tomatos absorbed more energy than at high temperature. Higher radii of curvature led to more bruise damage.

References

Ahmadi, E., H.R. Ghassemzadeh, M. Sadeghi, M. Moghadam and S. Zarif Neshat 2010: The effect of impact properties and fruit properties on the bruising of peach. J. Food Eng. **97**, 110–117.

Ahmadi, E. 2012: Bruise susceptibilities of kiwifruit as affected by impact and fruit properties. Res. Agric. Eng. **58**, 107–113.

Bajema, R.W. and G.M. Hyde 1998: Instrumented pendulum for impact characterization of whole fruit and vegetable specimens. Trans. ASAE **41**, 1399–1405.

Bajema, R.W., G.M. Hyde and A.L. Baritelle 1998: Turgor and temperature effects on dynamic failure properties of potato tuber tissue. Trans. ASAE **41**, 741–746.

Baritelle, A.L. and G.M. Hyde 2001: Commodity conditioning to reduce impact bruising. Postharvest Biol. Technol. **21**, 331–339.

Chiesa, A., L. Diaz, O. Cascone, K. Panak, S. Camperi, D. Frezza and A. Fraguas 1998: Texture changes on normal and long shelf-life tomato fruit ripening. International Postharvest Science Conference Postharvest 96. Acta Hort. **464**, 488–489.

Duprat, F., M. Grotte, E. Pietri and D. Loonis 1997: The acoustic impulse response method for measuring the overall firmness of fruit. J. Agric. Eng. Res. **66**, 251–259.

Garcia, C., M. Ruiz and P. Chen 1988: Impact parameters related to bruising in selected fruits. ASAE Paper No. **88–6027**. Amer. Soc. Agr. Eng., St. Joseph, Mich.

Halsey, L.H. 1955: Preliminary studies of bruising of 'turning' and 'pink' tomatoes caused by handling practices. Proc. Fla. State Hort. Soc. **68**, 240–243.

Hertog, M.L.A.T.M., R. Ben-Arie, E. Róth and B.M. Nicolai 2004: Humidity and temperature effects on invasive and non-invasive firmness measures. Postharvest Biol. Technol. **33**, 79–91.

Hetong, L., X. Fang and C. Shaojun 2002: A review of enzymatic browning in fruit during storage. J. Fuzhou Univ. **30**(supp.), 696–700.

Holt, J.E. and D. Schoorl 1982: Mechanics of failure in fruit and vegetables. J. Text. Stud. **13**, 83–97.

Menesatti, P., C. Beni, G. Paglia, S. Marcelli and S. Dandrea 1999: Predictive statistical model for the analysis of drop impact damage on peach. J. Agric. Eng. Res. **73**, 275–282.

Moretti, C.L., S.A. Sargent, D.J. Huber, A.G. Calbo and R. Puschmann 1998: Chemical composition and physical properties of pericarp, locule, and placental tissues of tomatoes with internal bruising. J. Am. Soc. Hort. Sci. **123**, 656–660.

Olorunda, A.O. and M.A. Tung 1985: Simulated transit studies on tomatoes: effect of compressive load, container, vibration and maturity on mechanical damage. J. Food Technol. **20**, 609–678.

Opara, L.U. 2007: Bruise susceptibilities of 'Gala' apples as affected by orchard management practices and harvest date. Postharvest Biol. Technol. **43**, 47–54.

Sargent, S.A., J.K. Brecht and J.J. Zoellner 1992: Sensitivity of tomatoes at mature-green and breaker ripeness stages to internal bruising. J. Am. Soc. Hort. Sci. **117**, 119–123.

Strehmel, N., U. Praeger, C. Konig, I. Fehrle, A. Erban, M. Geyer, J. Kopka and J. Dongen 2010: Time course effects on primary metabolism of potato (*Solanum tuberosum*) tuber tissue after mechanical impact. Postharvest Biol. Technol. **56**, 109–116.

Van Lancker, J. 1979: Bruising of unpeeled apples and potatoes in relation with temperature and elasticity. Lebensm.-Wiss. u. -Technol. **12**, 157–161.

Van Linden, V., B. De Ketelaere, M. Desmet and J. De Baerdemaeker 2006a: Determination of bruise susceptibility of tomato fruit by means of an instrumented pendulum. Postharvest Biol. Technol. **40**, 7–14.

Van Linden, V., N. Scheerlinck, M. Desmet and J. De Baerdemaeker 2006b: Factors that affect tomato bruise development as a result of mechanical impact. Postharvest Biol. Technol. **42**, 260–270.

Van Zeebroeck, M., V. Van Linden, P. Darius, B. De Ketelaere, H. Roman and E. Tijskens 2007a: The effect of fruit properties on the bruise susceptibility of tomatoes. Postharvest Biol. Technol. **45**, 168–175.

Van Zeebroeck, M., V. Van Linden, P. Darius, B. De Ketelaere, H. Roman and E. Tijskens 2007b: The effect of fruit factors on the bruise susceptibility of apples. Postharvest Biol. Technol. **46**, 10–19.

Van Zeebroeck, M., V. Van Linden, H. Roman, J. De Baerdemaeker, B.M. Nicolai and E. Tijskens 2007c: Impact damage of apples during transport and handling. Postharvest Biol. Technol. **45**, 157–167.

Xiubing, Z., W. Aoxue and L. Jingfu 2009: Progress on cell wall hydrolase of tomato fruit. J. NE. Agr. Uni. **40**, 128–132.

Received 08/26/2012 / Accepted 07/18/2013

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