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PHYSICOCHEMICAL AND MECHANICAL-TEXTURAL PROPERTIES OF TOMATOES FOR PROCESSING

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ABSTRACT

Understanding the mechanical responses and physical properties of plant materials can help to improve methods and technologies for reducing post-harvest losses, especially of bulk processed tomato fruits. This study aims to evaluate the biometric physicochemical, and mechanical-textural characteristics of the ripe fruit from five tomato cultivars for processing. The longitudinal, peduncular scar, pericarp and epidermis diameters vary significantly. The ash content of the pulp ranged from 0.40 to 0.92g $100g^{-1}$, and the total pectin from 0.218 to 0.469mg $100g^{-1}$, and all cultivars differed in these parameters. The mechanical-textural properties varied significantly, the firmness of the skin by compression in the standing fruit test correlated negatively with the firmness of the pulp by compression of the fruit in the lying position (-0.79*). The modulus of elasticity of the skin on standing fruit compression ranged from 19.65 to 11.99N mm^{-2}, and correlated positively with the modulus of elasticity of the skin with the fruit in the lying down position (0.79*). Fruits with larger pericarp thickness showed higher skin firmness, lower moisture and higher pectin content. Fruits positioned longitudinally (lying) on the texturometer platform require greater force (N) to break. Firmer fruits in a standing position have a greater skin elasticity modulus. Larger fruits have smaller skin and flesh firmness, and smaller fruits are more recommended for mechanical harvesting. Among the cultivars studied, the ones with the best mechanical properties were TC2736 and CVR2909, which also presented smaller longitudinal diameters, peduncle scar, fresh mass and volume.

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INTRODUCTION

Tomato (*Solanum lycopersicum* L.) is considered an important commodity in Brazil, and the state of Goiás has been prominent in its cultivation, mainly for industrial processing. This fruit is characterized by its high moisture content and high sensitivity to mechanical stress and demonstrates different behavior regarding the type of harvest and transport involved. In tomatoes, the skin has a protective function because it determines their mechanical properties, quality, and their suitability for processing, protecting the soft internal tissues, which affects the integrity of the product (Gladyszewska *et al*., 2011). According to Hetzroni *et al.* (2011), the mechanical properties of tomatoes, such as skin strength and elasticity are important from the point of view of the purposes of both fresh consumption and industrial processing. These properties are also of vital interest to producers. In order to design and optimize a machine for harvesting, transportation and cleaning, the physical attributes of the fruits must be known (Mirzaee *et al*., 2008). The structural complexity of tomatoes and their wide use has created the need to test their physical and mechanical properties (Ponjičan *et al*., 2012b). The physical components of tomatoes vary according to cultivars, i.e. their genetic properties as well as their growing conditions. The structure of the fruit that determines its quality is based on five basic components, which can be distinguished through the cross section of the fruit: skin, outer wall, cavities, placenta with seeds and columella. The most valuable parts of tomatoes with the highest dry matter content are columella and pericarp (Aurand *et al*., 2012). Two forces can be at play during fruit handling and transport stages: compression and puncture.

The internal tissues of fruits subjected to external forces will suffer different degrees of deformation (Sirisomboon *et al*., 2012). Mechanical damage that manifests itself on a macro- scale in fruits is caused by micro-scale cell failure, although cells from different tissues react differently to external forces (Abera *et al*., 2014). Tomato is an agricultural biological material, and these do not behave like perfect plastic or elastic materials, but generally they exhibit both properties simultaneously, being grouped under the definition of viscoelastic materials (Albaloushi, 2013). Therefore. the quality of the fruits can be determined by their external and internal characteristics. Thus, the aim of this study was to evaluate the biometric, physicochemical, and mechanical-textural characteristics of the ripe fruit from five tomato cultivars for processing, in order to correlate the mechanical behaviors with their structural characteristics and to recommend genetic materials that are more resistant to post-harvest operations.

MATERIAL AND METHODS

Materials: Ripe tomatoes from cultivars for processing (IT761, U2006, TC2736, CVR2909 and F3060) were donated by Cargill Agrícola S.A, whose experimental unit. where the cultivation was carried out, is located in the municipality of Hidrolândia, Goiás, Brazil.

Experimental design and crop management: A completely randomized design was adopted using five treatments (cultivars). The fruits from the third and fourth positions of the third bunch of the plant were sampled. For the study of biometric and physicochemical characteristics three repetitions were used, each with ten fruits, and for mechanical characteristics 10 fruits (experimental unit) for each analysis were used. The soil samples were analyzed in October 2013, before the crop implantation, and placed in the layer (0-20cm): which had a pH 5.8, aluminum contents of 0.0cmolc dm^{-3}, calcium 3.1cmolc dm^{-3}, magnesium 1.0cmolc dm^{-3}, potassium 0.30mg dm^{-3}, phosphorus 53.1mg dm^{-3}, cation exchange capacity (CTC) 6.57g dm^{-3}, organic matter of 17.4dag dm^{3},a percentage of sand, silt and clay, respectively of 300.0g kg^{-1}, 80.0g kg^{-1}, 620.0g kg^{-1}. While in the 20-40cm layer there was a pH of 5.4, 0.0cmolc dm^{-3}of aluminum. calcium of 1.6cmolc dm^{-3}, magnesium of 0.5cmolc dm^{-3}, potassium of 0.23mg dm^{-3}, phosphorus of 27.3mg dm^{-3}, CTC 5.26g dm^{-3} and organic matter of 19.0g dm^{-3}, with sand, silt and clay of 280.0g kg^{-1}, 75.0g kg^{-1} and 650.0g kg^{-1}, respectively.

Soil correction was performed on November 20, 2013, with dolomitic limestone (3t ha^{-1}) based on soil analysis and the recommendation described by the Goiás Soil Fertility Commission (1988). The soil was prepared with a cross plowing harrow. Seedling production occurred in greenhouses using coconut fiber substrate. Nitrogen foliar fertilization as well as spraying with fungicides and insecticides were performed weekly (forumplus and nomolt150, respectively). The seedlings were transplanted on March 15, 2014. For the control of whitefly.Mospilan was sprayed and for the control of septoriosisBravonil fungicide was applied. The formulation NPK 4-39-16 (1.300kg ha^{-1}) was used at planting. The herbicides Secor (0.8L ha^{-1}) and Boral (0.1L ha^{-1}) were applied to the area. Sprinkler irrigation occurred on April 7, 23 and 28; May 4, 8, 15, 18, 24, and on June 3, 10 and 18, totaling 147.60mm, and was spread uniformly over all plots. Manual harvesting of the fruits took place from June to September 2014, and the tomatoes were packed in low density polyethylene (LDPE) bags, coded and transported to the Laboratory of Processing of Vegetable Products of the School of Agronomy of the Federal University of Goiás, in Goiânia, GO. Then, the fruits were selected for appearance, absence of damage,rot and the degree of ripeness,and then subjected to manual washing and sanitization in sodium hypochlorite solution at 150mg L^{-1} for 20min and dried naturally.

Biometric Characteristics: Measurements of longitudinal diameter, transverse diameter, peduncular scar and fruit pericarp thickness were obtained with the aid of a digital caliper.

Fruit volume was determined by immersing the fruit in water contained in a 1L graduated beaker, while the fresh mass was put into a digital analytical balance, and the density calculated by the mass to volume ratio (Mattietto *et al*., 2010). A 1.00g tomato pulp sample, 1 x 1 x 0.5 cm (length x width x height), was taken from the equatorial area of the fruit, with a scalpel, fixed in FAA 70g 100^{-1} (formaldehyde of 40g per 100mL^{-1},5mL; ethanol of 70g per 100mL^{-1}, 90mL; glacial acetic acid. 5mL) for 72h and stored in 70g 100^{-1} of alcohol according to the methodology reported by Johansen (1940). Cross-sectional and longitudinal sections were obtained with a razor blade, stained with astra blue and basic fuchsin dyes, and mounted on semi-permanent blades with 50g 100g^{-1} glycerin solution. Photographic recording was obtained by optical microscopy (Leica Microsystems, LAD EZ.Wetzlar, Germany). Measurements of the epidermis were collected on photo microphotographs at a magnification of 300 times with ImageJ software (Schneider *et al*., 2012). Ten readings were taken for each sample.

Chemical Composition: Moisture and ash content were obtained according to AOAC (2012) methods, the first by drying in an oven with air circulation at 105ºC, at constant weight, and the second from the samples used for moisture determination in a muffle furnace for six hours at 550ºC. The pectin content was obtained according to (Mccready and Mccomb, 1952), and the total pectin content spectrophotometrically, according to the technique of Blumenkrantz and Asboe-Hansen (1973), expressed in 100g^{-1} fruit mgalcidgalactid. Then 50g of tomato pulp, homogenized in a domestic blender with 50mL of ethanol (absolute), was weighed, ground for 3min and allowed to stand for 12 hours. After that, filtration was performed on Whatman N^{o}. 2 paper. 40mL of ethanol (80g 100^{-1}) was added and it was taken to the boiling water bath for 20min. It was then filtered and washed three times each with ethyl alcohol (80g 100^{-1}), absolute alcohol and acetone, leaving it then to evaporate. The filter residue was transferred to an amber glass and 50 ml of distilled water was added. It was then stirred for 1h on a magnetic stirrer and filtered. The residue was taken to the oven at 105 ° C for 6h, then dried and 50mL of distilled water was added, stirred for 1h, and further filtered. Afterwards a 0.5mL of diluted solution and acid solution were added and a solution of sulfuric acid / tetra borate (0.0125M) in an ice bath, and stirred slightly. The vial was kept in a water bath for 10min, cooled in an ice bath, added to with 3 drops of carbazole (125mg in 100mL of methanol), kept in a water bath at 80ºC for 15min, cooled in an ice bath for 30min, and the reading was performed in a spectrophotometer at 530nm.

Mechanical-textural properties: Immediately after harvest, the mechanical-textural properties of the fruits were determined on a texturometer (TextureAnalyser, TA-XT Plus, Surrey England) by compressing the fruit in the lying and standing positions and by puncturing the tomato lying down through an application of a normal force in its equatorial area. The deformation was 50% in relation to the initial height of the fruit. The pre-test, test and post-test speeds were, respectively. 2mm s^{-1}, 1mm s-1 and 10mm s^{-1}, while the average height of the standing fruit sample was 100mm, and the lying down fruit was 70mm. The probe, with cylindrical geometry and a 100mm diameter (P100) was used in the tomato compression test, while the 5mm (P5) cylindrical probe was used in the puncture test. The analyzes were performed at 25ºC. The firmness of the whole fruit for compression, as well as skin and pulp puncture was calculated by equations 1 and 2, respectively. The modulus of elasticity (ME) (Equation 3) was also calculated.

Equation1: $F = \frac{Fm}{\Delta}$

Equation2: $F = \frac{Lm}{\Delta}$

In which: firmness (N mm -1); Fm = breaking force of the fruit epidermis (N); and Lm = fruit pulp breaking force (N). Δ = fruit displacement or deformation (mm).

Equation 3: $ME = 9.8\sqrt{\left[1.25(1-\mu^2)^2 \ \frac{\Delta F^2}{D^3(\Delta D/10)}\right]}$

Where: µ = Poisson's ratio, D = equatorial fruit diameter (mm), ΔF = force variation between the beginning of compression and the maximum force point, ΔD = deformation from the beginning of compression to the point of compression. Maximum force 9. 8 = acceleration force due to gravity (m s^{-2}). Poisson's ratio (dimensionless) was also calculated (Equation 4). This ranges from 0 to 0.5 Kojima (1983) considered this to be because of the difficulty in measuring this coefficient in fruits and vegetables, the Poisson's ratio of water in fruit was 0.5 and that of pulp dry matter was 0.1.

Equation 4: $CP = \frac{0.5M+0.1(100-M)}{100}$

In which: CP = Poisson's ratio (dimensionless), M = average moisture content of fruits and vegetables (g $100g^{-1}$).

Statistical Analysis: The results were submitted to analysis of variance (ANOVA) and the Tukey test at 5% of significance. Pearson's correlation was established between all variables. Free software Assistat7.7 beta was used.

RESULTS AND DISCUSSION

Biometric Features: Fruit biometric parameters, such as longitudinal, peduncular scar diameter, pericarp thickness and epidermis thickness varied significantly, except for the transverse diameter. The longitudinal diameter of tomatoes varied 24.0%. from 63.6 to 78.8mm, and the highest value was observed in cultivar F3060. However, the other cultivars did not differ from each other. The cross-sectional diameter of the fruit varied only 1.8%, from 48.5 to 49.9mm, with no significant difference between cultivars (Table 1). Longitudinal diameter correlated negatively with transverse diameter and positively with scar diameter, fresh mass, volume and density (-0.73*, 0.75*, 0.91**, 0.92** and 0.72*, respectively), thus, the larger the longitudinal diameter, the greater the mass, volume and density, and the smaller the transverse diameter. Rodica *et al*. (2011) also observed significant positive correlations between longitudinal diameter and the fresh weight of table tomatoes (0.95**). According to these authors both mass and diameter were strongly negatively correlated with fruit shape, which means that heavier fruits had a flat shape. Tiwari and Upadhyay (2011) reported that longitudinal and transverse diameters were directly responsible for tomato yield, which corroborates the results observed in the present study. Fruit shape and mass dimensions are focused on tomato growers, geneticists and industry, probably due to the correlation of these parameters with post-harvest mechanical strength (Nascimento *et al*., 2013). The fruits of the cultivars of the present study were classified as oblong, since all presented larger longitudinal diameters than the transverse ones (Ferreira *et al*., 2010). The oblong format is more suitable for production of whole peeled fruits and diced tomatoes. The peduncular scar measured from 7.0 to 8.6mm, and the variation between cultivars was 22.6%. Cultivars F3060 and TC2909 presented with the largest diameters for peduncular scar and CVR2909, IT761 and U2006 the smallest ones (Table 1).

Table 1. Biometric characteristics of five industrial tomato cultivars (Solanum lycopersicum), Goiânia, GO, Brazil

Cultivar	Ø longit.[1]	Ø transverse.[2]	Ø ped. scar[3]	Peric. Thick.[4]	Skin thick.[5]
IT761[6]	63.6b±5.6	49.1a±3.7	7.5bc±1.0	8.2ab±0.6	39.5a±2.1
U2006	65.2b±4.2	49.9a±2.8	7.5bc±1.1	7.2c±0.8	31.9b±3.2
TC2736	64.5b±5.7	48.8a±3.4	7.9ab±1.1	8.5a±0.5	36.4ab±2.0
CVR2909	66.7b±4.7	48.9a±3.0	7.0c±1.1	7.8b±0.8	32.8ab±2.1
F3060	78.8a±5.6	48.5a±2.8	8.6a±0.7	7.2c±0.6	37.5ab±14.8
CV[7]	7.7	6.5	12.8	8.7	31.3

[1]Longitudinal diameter (mm); [2]transverse diameter (mm); [3]peduncle scar (mm); [4]pericarp thickness (mm); [5]skin thickness (mm); [6]Means in the same column followed by different letters differ by Tukey test at 5% level; [7]Coefficient of variation (%).

The peduncular scar positively correlated with fresh mass and volume, (0.83* and 0.85*, respectively),i.e. the larger the mass and volume the greater the scar. Smaller peduncular scar diameter may be one of the factors involved in lower post-harvest water loss, as most tomato gas exchange (up to 97%) occurs through this structure (Khaleghi *et al*., 2013). It would be more advantageous for larger tomato mass and smaller peduncular scar, According to Araújo (2013), table tomato genotypes with potential for adaptation to the organic cropping system, which presented a small scar, were firmer. Thus, the fruits of the cultivars CVR2909, IT761 and U2006, because they have scar diameters between 7.0 and 7.5mm, have an advantage over the others in post-harvest operations since a very large scar can make the product less turgid more quickly, which may facilitate fruit collapse or crushing during transport.

The thickness of the pericarp oscillated from 7.2 to 8.5mm, and the variation was 18.3%. The cultivars TC2736 and TC761 had the highest thickness values, while cultivars F3060 and U2006 had the lowest. The thickness of the pericarp correlated negatively with the density and ash of the tomatoes (-0.83* and -0.84*, respectively), because thicker pericarps may have larger cells, and consequently lower ash density and content. According to Mousawinejad *et al*. (2014), tomato cultivars with thicker pericarp, small locules and smaller seeds are more suitable and produce better results for industrial processing. Fruits with thicker pericarps are more resistant to long-distance transport and remain firmer for a longer period (Kumari and Sharma, 2011). From this point of view, the cultivars TC2736 and IT761 would have advantages over the others, because they have the thickest pericarp. Henareh*et al*. (2015) reported on the thickness of the commercial tomato pericarp as having an average of 7.8mm. While Lahaye*et al*. (2013) found a variation between 5.2 and 9.3mm, values that corroborate the present study. However. Ahmad *et al*. (2011) found smaller values, between 4.74 and 5.97mm, for different table tomato cultivars, showing that genetic material is very important for determining this parameter. The thickness of the epidermis measured between 31.9 and 39.5µm, with a variation of 23.6% (Table 1).

The IT761 cultivar presented greater epidermis thickness only in relation to the U2006 cultivar, while the TC2736, CVR2909 and F3060 cultivars did not differ from the two previously mentioned cultivars. The thickness of the epidermis was negatively correlated with the elasticity of the skin to the puncture of the tomato (-0.83*), that is, the thicker epidermis presented less elasticity of the skin by puncture. Firmness is largely determined by anatomy, particularly cell size, shape, cell wall thickness, and the extent of cell-to-cell adhesion, along with the state of turgidity. Many of these factors are interrelated, for example, small cell tissues tend to have a higher cell wall content, lower cytoplasm and vacuole content, larger cell-to-cell contact area, and a low amount of air in the intercellular space, making the fabric firmer (Toivonen and Brummell, 2008). From this point of view, in tomato for processing with an epidermis made up of smaller cells, it could have greater mechanical resistance in post-harvest handling. The table tomato epidermis has no stomata (Chaïb*et al*., 2007), which was also verified in the tomato for processing (Figure 1). All cells in frontal view have different sizes and shapes, but all are polygons that look alike, have at least four to six distinct sides, and are thick from the lateral view (Figures 1A and 1B, respectively). As noted by Devaux*et al*. (2008), tomato tissues were heterogeneous, with thickened and paved epidermal cells. They showed that below the epidermis, smaller cells that provide greater mechanical resistance to fruits exist. and more internally in the pericarp, larger cells with thin walls. Most of these cellular characteristics were observed in the present work in different tomato cultivars for processing (Figure 1B). There were significant differences between fresh tomato masses, with fruit averages ranging from 82.9 to 102.5g (23.6%). The cultivar F3060 stood out with the highest value and the others being smaller (Table 2). Fresh mass correlated positively with volume and density, and negatively correlated with firmness of the pulp by compression with the fruit in the standing position, i.e. greater fresh mass higher volume and

Table 2. Fresh mass, Volume, density, moisture, ash and pectin of five tomato cultivars for processing (*Solanum lycopersicum*), Goiânia, GO, Brazil

Cultivar	Fresh weight[1]	Volume[2]	Density[3]	Moisture[4]	Ash[4]	Pectin[5]
IT761[6]	82.9b±18.3	87.0b±18.3	0.96a±0.13	95.9a±0.4	0.40d±0.05	0.26c±0.004
U2006	88.9b±12.3	91.1b±13.0	0.98a±0.05	95.9a±0.4	0.92a±0.04	0.23d±0.003
TC2736	89.6b±13.3	91.7b±11.6	0.97a±0.05	95.2b±0.5	0.61c±0.11	0.47a±0.003
CVR2909	87.9b±14.3	90.0b±12.9	0.97a±0.03	95.8a±0.3	0.72b±0.09	0.22e±0.003
F3060	102.5a±15.1	102.9a±13.9	0.99a±0.04	96.1a±0.3	0.85a±0.04	0.36b±0.004
CV[7]	16.4	15.1	7.2	0.4	10.1	1.1

[1]g; [2]cm^3; [3]g cm^{-3}; [4]g $100g^{-1}$; [5]mg $100g^{-1}$; [6]Averages followed by different letters in the same column differ by the Tukey test at 5% probability; [7]Coefficient of variation %.

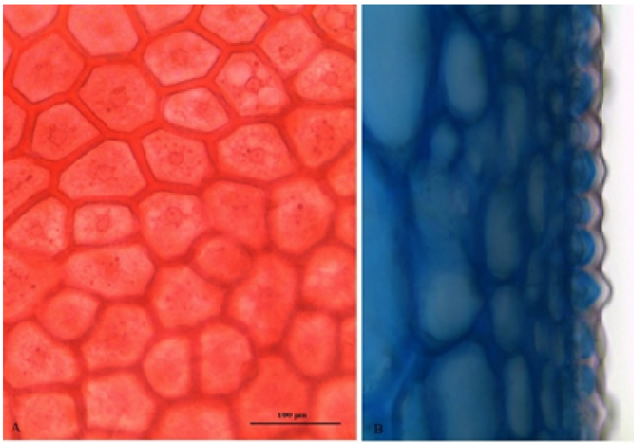

Figure 1. Epidermis of mature tomato (*Solanumlycopersicum* L.) in safranin-stained paradigm, cultivar U2006 (A) and cross-section stained with astra blue showing, from right to left, the epidermis, hypodermis and parenchyma, cultivar F3060 (B)

density, and lower firmness of the pulp with the fruit standing, (0.99**, 0.91** and -0.96**, respectively). Fresh paste is the best way to express fruit size indirectly and constitutes an important parameter related to quality, as well as being a relevant component of industrial production. The fresh mass of tomato fruits is influenced by several factors, such as irrigation and nutrient availability for the plant, and in this research, these factors were the same for all cultivars (Koetz *et al*., 2010). The industry's preference is for genotypes with higher transport resistance, which according to Filgueira (2008), are those whose fruits have an average weight between 50 and 100g; of all cultivars evaluated in this research, only cultivar F3060 is not within this range. The largest fruit volume was determined for cultivar F3060, which differed significantly from all other cultivars, with a variation of 18.26% (Table 2). Fruit density did not differ significantly between cultivars, and its variation was 3.12%, from 0.96 to 0.99g cm^{-3}. Density correlated positively with ash, fruits with higher density had more minerals in their composition, and negatively with firmness of the pulp by standing fruit compression (0.87* and -0.85*, respectively). According to Nascimento *et al*. (2013), higher fruit density values are more desirable, since the transport yield increases, as well as the resistance against kneading during harvest and transport operations, an aspect not observed in the present study regarding the firmness of the fruit pulp in compression. The tomato cultivars presented significantly different moisture, ash and pectin contents. Humidity ranged from 96.1 to 95.2g 100^{-1} (Table 2). The cultivars IT761, U2006, CVR2909 and F3060 did not differ from each other, differing only from cultivar TC2736, which presented the lowest value for moisture, despite the fact that water is the largest component of this fruit. Given the above, high humidity favors the mechanical conservation of the fruit at harvest, since the moisture correlated positively with the firmness of the skin by pressing the standing tomato and with the pulp with the fruit lying down (0.97** and 0. 90*, respectively). In addition to the structural components of the cell wall, cell turgidity also contributes to fruit firmness. The mechanical resistance of tomatoes can be decreased by temperature and enzymatic activity, whereas turgidity by water loss as a function of temperature and relative humidity, because of tissue water vapor permeability (Hertog *et al*., 2004).

Different moisture contents have an effect on the mechanical, electrical, thermal and chemical properties of agricultural products (Mohsenin, 1986). The ash content of the fruits oscillated by 130.0%, and the highest were observed in cultivars U2006 and F3060, with the lowest in cultivar IT761. In tomatoes, Monteiro *et al*. (2008) reported ash content of 1.89 g $100g^{-1}$, concluding that the highest mineral content is in the bark and seeds. This value is much higher than that found for tomato ash in the present research, using only the fruit pulp in the analysis. The differences between cultivars are due to the distinct genetic material, because the cultural treatments were the same for all. Total pectin content ranged by 115.1%, from 0.22 to 0.47mg $100g^{-1}$, and all cultivars differed. The cultivar TC2736 presented the highest value while CVR2909 the lowest (Table 2). The values found in this research corroborate with Canteri *et al*. (2012), who cited in their work values from 0.2 to 0.6mg $100g^{-1}$ for fresh matter of tomato fruit. Pectin is a natural component of tomatoes which acts as a cementing agent and is present among fleshy tissue cells (Butt *et al*., 2004). Variation in the cohesion of pectin molecules in soft fruits such as tomatoes regulates the ease with which one cell can separate from another, affecting the final firmness of the fruit (Sibomana *et al*., 2015). According to Li *et al*. (2015), tomato firmness is gradually diminished due to several coordinated processes, including disassembly of primary cell wall and middle lamella polysaccharides, and loss of turgidity by fruit perspiration. According to Hyodo*et al*. (2013), changes during tomato fruit ripening may differ between the pericarp and internal tissues (locular and placenta tissues), suggesting that changes in pectin during fruit ripening differ in each tissue. Thus, probably the cultivar TC2736, which presented higher pectin content at the same maturity stage as the other cultivars, has better regulation in the degradation process for this polysaccharide.

Mechanical-textural characteristics: The firmness of the skin on standing fruit compression varied by 20.9%, between 5.3 and 6.4N mm^{-1}, and the highest value was found in cultivar TC2736, while the lowest was F3060; The other cultivars were intermediate and did not differ from each other (Table 3). Pulp firmness in relation to standing fruit compression ranged from 1.27 to 1.7N mm^{-1} (33.33%), and cultivar IT761 had the highest value, differing only from cultivar

F3060 which also presented the lowest firmness value for the pulp. In the compression test, the application of an increasing force perpendicular to the longitudinal direction (standing fruits) of the fruit causes an increase in internal pressure and deformation of the fruit until the epidermis ruptures. At this microstructural level, according to Mayor *et al*. (2007), what can be acknowledged as relevant to the firmness is the structure and thickness of the cell wall, the pressure of cell turgidity, as well as the mechanical resistance and type of adhesion between cells, which may be the causes of differences observed for skin and pulp firmness between the cultivars analyzed in this study.

Table 3. Skin (Fc_{skin}) and flesh (Fc_{pulp}) compression firmness of tomato fruits (*Solanum lycopersicum*) of five cultivars for processing, maintained in standing and lying positions. Goiânia, GO, Brazil

Cultivar	Fruit stand		Fruitlying	
	Fc_{skin}	Fc_{pulp}	Fc_{skin}	Fc_{polpa}
IT761[1]	5.6ab±0.7	1.7a±0.39	7.4a±0.9	2.1a±0.4
U2006	5.6ab±0.5	1.5ab±0.39	4.7b±1.6	2.0a±0.4
TC2736	6.4a±1.2	1.5ab±0.33	4.9b±1.2	1.7a±0.4
CVR2909	5.5ab±0.7	1.5ab±0.24	7.0a±1.5	1.8a±0.2
F3060	5.3b±0.8	1.3b±0.17	6.8a±1.4	2.1a±0.2
CV[2]	14.3	21.4	21.9	17.9

[1]Fruit compression standing; [2]compression lying fruit; [3]Mean values followed by different letters in the same column differ among themselves by Tukey test at 5% level; [4]Coefficient of variation (%).

The skin protects the soft tissue of the fruits and the mechanical properties of this structure are important considerations as they affect the quality of the final product, its processing and the design of harvesting machines and devices (Hertog *et al*., 2004). The firmness of the skin on compression of the lying fruit was significant, it oscillated 58.0%, between 4.7 and 7.4N mm^{-1}, with the highest values in cultivars IT761, CVR2909 and F3060, and the lowest in cultivars U2006 and TC2736. Compression tests showed statistically higher puncture values for tomato fruits for processing, which corroborate with Ponjičan *et al*. (2012a), who found 4.91N mm^{-1} and 1.44N mm^{-1}, respectively. However, in the present study, values higher than those found by these authors were verified. For the firmness of the pulp the compression with lying fruit did not differ between the cultivars. However, this property was negatively correlated with the skin elasticity and puncture of the standing fruit (-0.73* and -0.74*, respectively), i.e. the higher the firmness the lower the skin elasticity.

According to Chaïb *et al*. (2007), the firmness attribute in tomatoes evolves differently, depending on the genetic background of the material, and each cultivar has its inheritance in relation to this parameter. The firmness of the skin by compression in the standing fruit test correlated negatively with the firmness of the pulp by compression of the fruit in the lying position (-0.79*). This negative correlation between the firmness of the skin on compression with the standing fruit and the pulp from the lying fruit may be due to the location of the cell wall polysaccharide chains with respect to force application, as suggested by Dan and Kohyama (2007). Skin firmness at puncture in the equatorial area of fruits varied 26.31% (Table 4). The highest value was found in cultivar CVR2909, which differed significantly only from the value of U2006, which presented the lowest degree of firmness. The firmness of the pulp by puncture differed significantly between cultivars. Skin firmness by puncture was positively correlated with firmness by puncture of the fruit pulp, and skin elasticity with the fruit lying down, as well as flesh firmness with skin elasticity with the fruit lying down (0. 91**, 0.92** and 0.92**, respectively). Researching tomato, Chaïb *et al*. (2007) found a positive correlation between fruit firmness and skin toughness (0.83**), and a negative correlation between fruit firmness and juiciness (-0.73*). The positive correlations found in the present research may be related to cellular heterogeneity in the pericarp and small cells in the epidermis, as described by these authors. Idah *et al*. (2007) revealed that the severity of mechanical damage in fruits is related to the vibration level and to the stage of maturity.

Table 4. Skin (Fp_{skin}) and flesh (Fp_{pulp}) puncture firmness of tomato fruits (*Solanum lycopersicum*) for processing, maintained in the lying down position. Goiânia, GO

Cultivar	Fp_{skin}[1]	Fp_{pulp}[2]
IT761[3]	2.1ab±0.44	0.21a±0.014
U2006	1.9b±0.26	0.21a±0.023
TC2736	2.0ab±0.45	0.21a±0.020
CVR2909	2.4a±0.39	0.22a±0.016
F3060	2.0ab±0.33	0.21a±0.022
CV[4]	18.20	9.06

[1]Puncture of the skin; [2]pump function; [3]Averages followed by different letters in the same column differ by the Tukey test at 5% probability; [4]Coefficient of variation %.

Table 5. Modulus of elasticity of five tomato cultivars for processing (*Solanum lycopersicum*), Goiânia, GO, Brazil

Cultivar	Modulus of elasticity		
	Fc_{stand}[1]	Fc_{lying}[1]	Fp[1]
IT761[2]	12.0c±1.7	12.0b±0.5	0.78b±0.2
U2006	13.5bc±2.9	9.3c±1.5	1.16a±0.4
TC2736	17.8ab±5.1	13.1b±0.7	1.18a±0.4
CVR2909	19.7a±2.2	19.3a±3.9	1.30a±0.3
F3060	16.3abc±6.8	12.5b±1.0	0.79b±0.3
CV[3]	25.5	14.8	26.5

[1]Elasticity module (N/mm^2);[2]Means in the same column followed by different letters differ from each other by the Tukey test at 5% probability;[3]coefficient of variation %.

Since tomato fruits intended for processing are transported in bulk, with excessive load height and vibration during transport, they may suffer more compression and consequently more damage. However, Li and Thomas (2014) reported that the greater the amount of intercellular space present in fresh fruit tissue, the more damage and bruising will occur, because damage is initiated in or near these weakened tissue air spaces. In this work, these intercellular spaces were not measured. The modulus of elasticity is defined in dictionaries as a magnitude proportional to the firmness of a material when it is subjected to an external compression or tensile stress without undergoing permanent deformation. According to Rojas *et al*. (2001), this quantity is measured through the stress-strain curve at the moment of fruit rupture. The modulus of elasticity to compression of the skin on fruit in the standing position ranged from 11.99 to 19.65mm^{-2} (65.89%). The highest value was observed in cultivar CVR2909, followed by TC2736, the lowest in cultivar IT761, followed by U2006, and cultivar F3060 presented an intermediate value (Table 5). For the fruit in the lying position. the elasticity of the skin to compression ranged from 9.29 to 19.30N mm^{-2} (107.75%), and the cultivar CVR2909 presented the highest value. while the U2006 the lowest. Skin elasticity modulus with standing fruit correlated positively with the skin elasticity modulus of fruit in the lying position (0.79*). For puncture, the cultivars CVR2909, TC2736 and U2006 presented the highest values of modulus of elasticity, and the cultivars IT761 and F3060 the smallest, ranging from 0.78 to 1.30N mm^{-2} (66.66%). There was a difference for the modulus of elasticity for standing and lying fruit only for cultivars U2006 and TC2736.

The significant difference was for fruit position in compression, only for cultivars U2006 and 2736, with a tendency to higher values for fruits in the longitudinal position, unlike Masoudi *et al*. (2007), who reported higher modulus of elasticity for radial apple fruit (lying down) compared to vertical fruit (standing). Sirisomboon *et al*. (2012), evaluating both table tomatoes and those for processing, found modulus of elasticity for the puncture test (0.90N mm^2) in completely mature tomatoes for processing, but an intermediate value to those found in the present study. According to Vieira *et al*. (2019) the mechanical characteristics of the fruits depend on the cultivar, i.e. its genetic characteristics. In mechanical tests, part of the applied energy is permanently stored in the fruit due to plastic deformation of the tissue or cell structure, and this absorbed energy is channeled to the bruises (Van Zeebroeck *et al*., 2007). The results indicated that the cultivar CVR2909 for all elastic modulus parameters presented the highest values, suggesting that this cultivar has the highest skin firmness. In this research, the fruits of all cultivars were at similar stages of maturity, and it can be inferred that the differences in the modulus of elasticity between them are related to higher moisture content, smaller size and lower pectin content in the fruits (Bourne, 2002).

CONCLUSION

Fruits with larger pericarp thickness (8.5mm) have greater skin firmness, higher moisture and higher pectin content. Fruits positioned longitudinally (lying) on the texturometer platform require greater force (N) to break. Firmer fruits in the standing position have greater elasticity modulus of skin. Larger fruits have smaller skin and flesh firmness, and smaller fruits are more recommended for mechanical harvesting. Among the cultivars studied, the ones that presented the best set of mechanical properties were TC2736 and CVR2909, which also presented lower longitudinal diameters, peduncle scars, fresh mass and volume.

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