Characterization of the mechanical properties of the sweet passion fruit (*Passiflora ligularis* Juss.)

Caracterización de propiedades mecánicas del fruto de la granadilla (*Passiflora ligularis* Juss.)

Jorge Armando Linares[1], Bernardo Castillo[1], and María Teresa Londoño[2]

ABSTRACT

The sweet passion fruit figures prominently among the fruits exported by Colombia. The fruit is an ovoid berry with a thick and brittle peel that changes from green to bright yellow, depending on the degree of maturity. The weight of the fruit is 113 grams on average and about 60% of the fruit is edible. The sweet passion fruit is harvested manually. During the harvest and the subsequent handling and transport to the places of packaging and marketing, the fruit is subjected to multiple loads which may cause deterioration in different ways, resulting in significant product losses. Rheological tests were performed (unidirectional compression, puncture and shear) in order to determine the mechanical response of the fruit to the forces exerted on it during harvest and post-harvest handling. The tests were performed using a texture analyzer (TA.XT Plus of Stable Micro Systems®). For each type of rheological test, the specific conditions of the shape and size of the probe, and the speed and depth of penetration were defined. The tests were carry out with 35 fruits, with and without the polyethylene *mallalon*, at fruit maturity stages 4 and 5. It was found that the firmness of the fruits in the unidirectional compression, longitudinal direction and with a degree of maturity 4, was 117.4 N, similar to that found for the transversal direction but using "mallalón". Under these conditions, the contact stresses should not exceed 600 kPa, while the force required for a transversal shearing of the skin of the fruit was 43.8 N. The mechanical behavior of the sweet passion corresponds to a viscoelastic, anisotropic and variable material.

Key words: rheology, uniaxial compression, shear, harvest, postharvest, handling.

RESUMEN

La granadilla ocupa un lugar destacado entre las frutas exportadas por Colombia. El fruto es una baya ovoide, de cáscara gruesa y quebradiza, que cambia de color de verde a amarillo intenso según el grado de madurez, con peso promedio de 113 gramos de los cuales aproximadamente el 60% es la parte comestible. Su cosecha se realiza en forma manual, durante esta fase de recolección y en las posteriores de manipulación y transporte a los lugares de empaque y comercialización el fruto se ve sometido a múltiples cargas que pueden deteriorarlo de diversas maneras lo que resulta en pérdidas significativas de producto. Se realizaron ensayos reológicos de compresión unidireccional, punción y corte, a fin de caracterizar su respuesta mecánica al tipo de fuerzas que soporta en su manejo cosecha y poscosecha. Los ensayos se realizaron con un analizador de textura TA.XT Plus de Stable Micro Systems®. Para cada tipo de ensayo reológico, se definieron condiciones específicas de forma y tamaño de la sonda, velocidad y profundidad de penetración. Las pruebas se realizaron para 35 frutos con o sin él polietileno de protección (mallalón) en estado de madurez 4 y 5. Se encontró que la firmeza del fruto en compresión unidireccional en dirección longitudinal y para grado de madurez 4 es de 117,4 N, valor similar al que se observa en la orientación transversal pero con mallalón; en estas condiciones los esfuerzos de contacto no deben exceder los 600 kPa, a la vez que la fuerza requerida para cortar transversalmente la cáscara del fruto fue de 43,8 N. El comportamiento mecánico del fruto de la granadilla corresponde a un material viscoelástico, anisotrópico y de muy alta variabilidad.

Palabras clave: reología, compresión unidireccional, corte, cosecha, poscosecha, manejo.

Introduction

The sweet passion fruit is ranked fifth among exotic fruit exports in Colombia for 2007, in which sales were valued at USD 705,701, (Legiscomex, 2008).

This passiflora fruit, native to the tropical Americas, is a perennial, with a climbing habit and rapid growth. The heart-shaped leaves are bright green, the flowers are purple, and the diameter is between 7 and 10 cm. Its fruit is an ovoid berry with a thick and brittle shell, which changes color from green to bright yellow, depending on maturity (Cerdas and Castro, 2002).

The sweet passion fruit has, within its crust, a membranous sac with about 250 small seeds which are gray to dark brown

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1 Program of Agricultural Engineering, Department of Civil and Agricultural Engineering, Faculty of Engineering, Universidad Nacional de Colombia. Bogota (Colombia). bcastilloh@unal.edu.co

2 External consultant. Bogota (Colombia).

and covered with a gelatinous viscous pulp (FAO, 2006). The average weight of one fruit is 113 g, of which approximately 60% is edible. This value varies depending on the stage of development and maturation (Villamizar, 1994).

A month after flowering, the fruit finishes the formation and growth process and initiates the ripening process, which leads to: reactions that convert starches and other polysaccharides into sugars; organic acids react with alcohols to help aroma formation, or simply degrade to carbon dioxide and water; chlorophylls disappear to make way for anthocyanins, carotenoids, xanthophylls and other compounds that cause the characteristic color of the ripe fruit; and pectic and hemicellulose compounds, which are part of the shell, degrade, reducing fruit firmness, favoring softening and improving texture, as published by García (2008).

The detachment of the fruit is carried out by hand or with scissors. The cut is realized in the third node of the peduncle. Once the fruit is removed from the plant, it is placed in a carton, which has an average capacity of 115 passion fruits and achieves a net weight of 13 kg. Usually, four layers are separated by newspaper. Once the fruit is removed from the plant, it is deposited in the collection container and transported to the gathering center.

During collection and later stages of handling, transport, packaging and storage, the fruits are subjected to mechanical loads of various kinds, which can cause significant damage and loss (Mohsenin, 1986; Herold *et al.,* 2001; Ciro *et al.,* 2005; Singh and Reddy, 2006; Ospina *et al.,* 2007; Alamar *et al.,* 2008).

The response of biological materials (fruits and vegetables) to applied loads requires knowledge of their mechanical properties; in addition, the mechanical behavior, or the texture, is a limiting expression which highly influences the quality of fruits and vegetables. (Szczesniak, 2002; Peleg, 2006; Newman *et al.,* 2005; Bentini *et al.,* 2009).

The mechanical characteristic of texture, which is commonly used to describe the rheological behavior of biological materials, is the Firmness (or hardness) and is generally defined as the maximum force required to achieve a specific strain in compression, puncture and cut tests (Rosenthal, 1999; Abbott, 1999; Valero and Ruiz, 2000; Szczesniak, 2002; Tabilo and Barbosa, 2005; Lu *et al.,* 2005; Peleg, 2006). One can actually determine a complete force *vs*. deformation curve for biological materials, in addition to the maximum force, setting parameters such as the bioyield point, the point of rupture or fracture of the material in different tissues and the slope of the curve in several regions of the curve (stiffness or deformability modulus), relating the amount of deformation to an applied force produced according to whether the material behaves as an elastic solid, viscous liquid or as a mixture of the two and generally with large deformations of a plastic nature. If we also take into account the dimensions of the samples tested at each point of the test, a characterization in terms of stress *vs*. strain can be made (Peleg, 1987, 2006; Steffe, 1996; Buitrago *et al.,* 2004; Singh and Reddy, 2006; Aviara *et al.,* 2007).

The firmness of fruits, and generally in all biological materials, is influenced by the anatomy of plant tissues, particularly the size of the cells, their shapes and packaging, by the thickness and strength of the cell walls and by cell adhesion mechanisms in conjunction with the turgor state of the cells (Chanliaud *et al.,* 2002; Waldron *et al.,* 2003; Zdunek and Umeda, 2006; Oey *et al.,* 2007; Van Zeebroeck *et al.,* 2007 and Toivonen and Brummell, 2008).

For the mechanical properties of the sweet passion fruit, references of studies were found only at the National University: one in Medellin: the work of Ciro *et al.* (n.d.), which is about the determination of the surface fracture strength of the passion fruit through unidirectional compression trials of fracture tests for two degrees of maturity and two load application methods; and the works of Bogota: Villamizar (1994) and Mogollón (2010), in the first, Firmness was measured by a puncture test with a manual penetrometer, while the second corresponds to a puncture test with a texturometer (cylindrical probe with a diameter of 4 mm and a speed of 3 mm s^{-1}) during refrigerated storage of the fruit. Furthermore, the firmness values of the NTC 4101 Standard can be added, however this standard does not relate the measuring device used.

The aim of this study was to determine the mechanical properties in compression puncture and shear the fruit of the sweet passion fruit for freshly harvested fruits and will receive further handling to the packaging and marketing process.

Materials and methods

Vegetal material

Sweet passion fruits were used that had a maturity degree of 4 or 5, according to the color chart, to ensure homogeneity in the whole sample and to comply with the general aspects of the NTC 4101 Standard.

The sample size was determined by the procedure of the operation characteristic curves, taking a delta value of 1. There were no statistical tests to compare the values obtained from the two stages of maturity and the two directions of load application.

Rheological testing

A Stable Micro Systems® brand texture analyzer (TA.XT Plus) was used . For the unidirectional compression test in the transversal direction (which is seen along the equator) on fruits, with *mallalon* (polyethylene mesh for packaging protection) and without *mallalon*, and the longitudinal direction (from pole to pole, placing the fruit peduncle opposite the compression plate) for fruits without *mallalon*, a cylindrical probe with a diameter of 75 mm was used at a speed of 2 mm s^{-1}, to a depth of 20 mm, ensuring rupture of the fruit shell. In the puncture test, a cylindrical probe with a 5 mm diameter was used at a speed of 2 mm s^{-1} and a depth of 15 mm so that penetration of the fruit shell was ensured, in both the transversal and longitudinal directions (penetrating through the navel of the fruit), for the fruits without *mallalon*. For the transversal shear test, a probe was used with a cutting edge, made of transparent acrylic, at a speed of 8 mm s^{-1}. All tests were done at fruit maturity stages 4 and 5. The laboratory temperature was between 20 and 22°C.

In all tests, a force-time curve was determined (with deformation measurement) for each of the 35 fruits used in each test (sample size). For the first two trials, the force and deformation values were converted to real stress (σ) versus Hencky deformation (εH) (or Hencky strain) according to the methodology followed by Olivera (2004). For the curves (force-time) in each of the tests, the average maximum force (firmness) was determined and from the true stress *vs*. Hencky deformation curves, the real rupture stresses and break deformations were established.

For the statistical analysis of each test, the samples were divided into two groups of 17 units of product and were tested to validate the correlation between sample independence. The hypothesis was corroborated by the F test and t-test and it was verified that there was no difference between the two samples and ensured that the conclusions of the experiment were valid.

Results and discussion

The maximum forces are the firmness of the fruit for each of the two test types mentioned above: unidirectional compression and puncture. Tab. 1 shows the mean and standard deviation of these maximum forces for each of these tests, including the transversal shear test. Notably, the value of rupture or fracture force in the compression test was greater for the unidirectional load applied longitudinally in comparison with the transversal orientation, for each of the two stages of maturity and without the *mallalon* (117 N *vs*. 107 N for maturity stage 4 and 98 N *vs*. 84 N for grade 5). Also, firmness was greater for compression when comparing the values reached for level 4 of maturity versus state 5. The effect of the fruit *mallalon* for the transversal orientation (as is done in current packaging) shows that the compressive force was increased slightly (114 N *vs*. 107 N) for maturity grade 4. The cause of the firmness value obtained with the transversal compression with *mallalon* and grade 5 maturity is unknown due to the fact that, at 119N, it cannot be solely attributed to the effect of the *mallalon* but can be in the fruit samples with an inferior maturity grade. In any event, these results suggest that fruits, with *mallalon* or not, should be packed longitudinally, but, of course, the problem is the upward stem, which makes it difficult to pack the top layer. The coefficients of variation observed in these tests were high, in the order of 20 to 25%, which are typical of those obtained in tests on biological materials of high heterogeneity.

Comparing with the values reported by Ciro *et al.* (n.d.), the forces of surface fracture were very similar for probe speeds between 1 and 3 mm s^{-1} both in the transversal and longitudinal direction, between 88 and 95 N for fruit maturity degrees 4 and 5 and without *mallalon*, although these authors did not show differences between the two directions of load application.

The fact that there was greater force in the longitudinal direction may be due to the location of the polysaccharide chains of the cell walls with respect to the load application, as suggested by Vincent (1999), Bruce (2003), Dan and Kohiama (2007) and Mayor *et al.* (2007). It has also been widely reported that as fruit ripeness progresses, water loss occurs, which is associated with a loss of turgor of the cells, a decrease in adhesion between cells and changes in cell wall polysaccharides, among others (Van Linden, 2007; Toivonen and Brummell, 2008; Goulao and Oliveira, 2008).

Moreover, with regard to the results achieved in the puncture test, Tab. 1, it was again shown that the firmness was greater for the longitudinal orientation of the applied load, 44.5 and 28.5 N, when compared to the transversal orientation, 16.8 and 14.3 N for maturity grades 4 and 5 respectively; and the force value for ripeness degree 4 was greater than the force of state 5, which confirms the previously-stated finding of the compression test. Again, there was high variability with the coefficients of variation, between 20 and 25%. The comparison made with the Mogollón (2010) data showed an exact correspondence with fruit ripeness between 4 and 5 for the transversely applied load.

Figure 1 shows the typical stress *vs.* Hencky deformation curve set for a unidirectional compression test in the transversal direction for two degrees of maturity without *mallalon* (top) and (bottom) with *mallalon*.

TABLE 1. Maximum force in mechanical compression, puncture and shear tests in sweet passion fruit.

Test type	Degree of maturity	Maximum force (N)
Transversal compression	4	107.4 ± 19.5
Transversal compression with *mallalon*	4	114.4 ± 23.9
Longitudinal compression	4	117.4 ± 23.7
Transversal compression	5	84.3 ± 18.8
Transversal compression with *mallalon*	5	119.3 ± 29.0
Longitudinal compression	5	98.4 ± 25.1
Transversal puncture	4	16.8 ± 3.6
Longitudinal puncture	4	44.5 ± 11.2
Transversal puncture	5	14.3 ± 3.2
Longitudinal puncture	5	28.5 ± 7.1
Transversal shear	4	43.8 ± 7.6
Transversal shear	5	34.4 ± 7.2

The values presented are means ± standard deviation.

The form of the curves which shows how the fruits were deformed by the transversely-applied unidirectional compressive forces, initially presented an approximately linear behavior (elastic character); although, in the fruits with *mallalon*, an initial deformation was produced that delayed the elastic deformation of the fruits.

In both cases (with and without *mallalon*), a bioyield point was seen, which is associated with tissue microfailures, but which corresponds to the resistance of the exocarp (husk), according to Aviara *et al.* (2007). Furthermore, it could also be said that at this point the internal fluid of a freshly squeezed fruit begins to ooze without tearing the epicarp; the strength then increases to a maximum value at rupture, with a breaking stress that completely breaks the epicarp and releases liquids; and the compression of the fibers are definitely noticeable. We must also add that after the elastic behavior and bioyield, the concavity of the curve is downward, showing that the prevailing situation was the internal fracture of all tissues, particularly the epicarp and mesocarp. Furthermore, it shows that, after yield, there are several peaks, *i.e.* partial ruptures, until reaching final rupture. This behavior has already been reported in biological materials, especially in fruits, by Herold *et al.* (2001), Singh and Redy (2006), Aviara *et al.* (2007), Chassagne-Berces *et al.* (2009) and Nguyen *et al.* (2010). In turn, it is already clear that fruits in maturity 4 have greater resistance than fruits of grade 5 and the *mallalon* effect increases rupture strength and increases deformation at the breaking point, especially for fruits with advanced maturity; see also the rheological parameters of Tab. 2.

Figure 2 shows two typical stress - strain curves for a unidirectional compressive load in the longitudinal direction for the two degrees of maturity considered. In the longitudinal orientation, the bioyield point is not marked or is very close to the peaks of failure or rupture. The breaking stresses in this direction are higher compared to the transversal direction, see Tab. 2.

In Tab. 2, it can again be seen that resistance decreases with the advancement of the maturation process in either of two orientations, although, in the longitudinal orientation, the fruits were not tested with *mallalon* so the Hencky strain at breaking for this orientation is less than 0.10 in the two degrees of maturity, values similar to those achieved in transversal load trials for fruits without *mallalon*.

Finally, Fig. 3 shows typical stress-strain curves developed from the results of the puncture tests which show the rheological behavior of freshly-harvested sweet passion fruits for the two load application methods: transversely and longitudinally; and for two maturity states: 4 and 5. While there is some similarity in the curves found in the unidirectional compression tests, as for the bioyield and rupture points, the stress values are very different given the probe geometries, which presented the greatest difference between the two load methods. Puncture tests represent a highly localized stress in a small area, while compressive stress is distributed over a larger area. Thus, it is likely that the effect of stacked boxes better fits that represented by the unidirectional compression, while the puncture test might better represent the damage caused by manual handling of the fruits. These values are reported in Tab. 2 and demonstrate the same higher resistance for longitudinally-applied forces and for fruits with a maturity grade of 4. It is notable that the puncture-rupture is set for very small strains, with a delicate behavior.

The values in Tab. 2, in terms of the puncture tests (firmness) expressed as the breaking stress, compare well with the 6 $kg_f\ cm^{-2}$ value reported by NTC 4101 (Icontec, 1997) for grades 4 and 5 of color (except the value obtained in

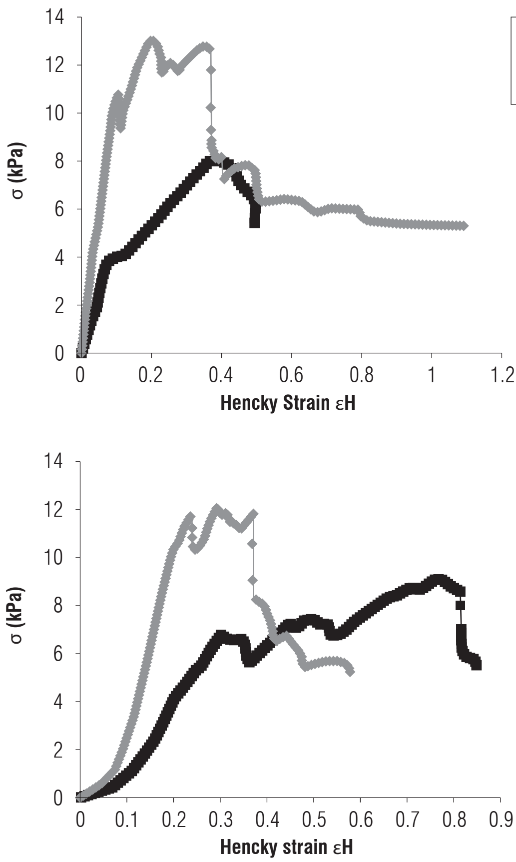

FIGURE 1. Typical real stress-Hencky strain curves for a unidirectional compression test, above: in the transversal direction, degrees of maturity 4 and 5 without *mallalon*; below: with *mallalon*, transversal direction, degrees of maturity 4 and 5 of sweet passion fruit.

TABLE 2. Rheological parameters found with mechanical testing: unidirectional compression and puncture in sweet passion fruit.

Test type	Degree of maturity	σ_R (kPa)	ε_R (adim)
Transversal compression	4	10.9	0.10
Transversal compression with *mallalon*	4	11.6	0.24
Longitudinal compression	4	13.5	0.04
Transversal compression	5	1.3	0.02
Transversal compression with *mallalon*	5	5.4	0.25
Longitudinal compression	5	9.9	0.09
Transversal puncture	4	581	0.01
Longitudinal puncture	4	1260	0.01
Transversal puncture	5	409	0.05
Longitudinal puncture	5	643	0.06

the longitudinal puncture test for maturity 4), but not with the value obtained by Villamizar (1994) of only 12 to 16 lb_f/pulg^2 (0.84 to 1,13 $kg_f\,cm^{-2}$) which depend on the geometry of the probes used in each case.

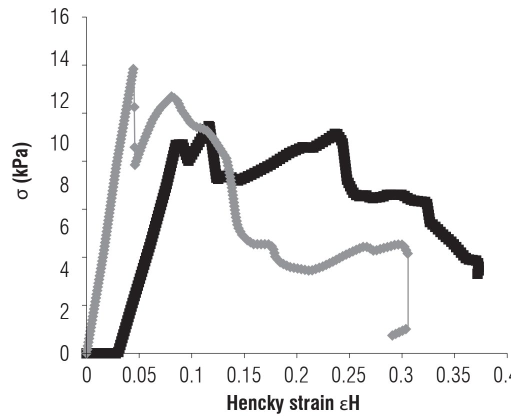

FIGURE 2. Typical real stress-Hencky strain curves for unidirectional compression test, longitudinally, degrees of maturity 4 and 5 of sweet passion fruit.

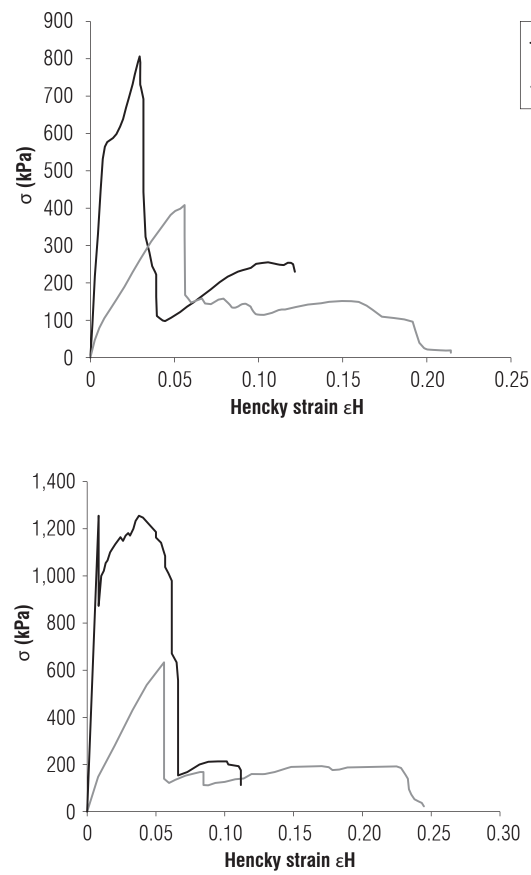

FIGURE 3. Typical real stress-Hencky strain curves for puncture test, above: transversely, degrees of maturity 4 and 5; below: longitudinally, degrees of maturity 4 and 5 of sweet passion fruit.

In summary, this fruit, as with most biological materials, in particular fruit and vegetables, behaves as a nonlinear, viscoelastic material which, according to Peleg (2006), when subjected to large deformations, may suffer important internal, structural changes.

At the time of collection of the sweet passion fruit, the operator must manipulate the fruit lengthwise and take care not to exceed contact stresses of around 600 kPa for fruits with maturity 4 and 400 kPa for grade 5 mature fruits. The stacking of containers or boxes must be configured for pressures below 5 kPa and the fruit should be positioned longitudinally, with *mallalon* and preferably a fruit ripeness of 4.

It should be noted that the values listed here make no reference to dynamic loading or impact or considerations on the effect of bruising in fruits.

Any cutting device for the separation of the fruit from the plant stalk must exert a shear force of 35 and 45 N for fruit maturity grades 5 and 4 respectively.

Conclusions

The sweet passion fruit, when subjected to quasi-static loads, behaves as a viscoelastic material with highly variable, anisotropic properties. The firmness values obtained for both the unidirectional compression test and puncture test corresponded to the resistance of the fruit exocarp (shell). The polyethylene *mallalon* used in some marketing systems contributes to a greater strength of the fruits against breakage and to an increase in fruit deformation before this point. SI Harvest and postharvest management must be done with fruits that do not exceed maturity 4 (NTC 4101). Sweet passion fruit manipulation must be done in the longitudinal direction with contact stresses that do not exceed 600 kPa. Similarly, when fruits are stacked in containers or boxes, they must be configured so that the fruits are oriented lengthwise, with the stem directed upwards and with pressures below 5 kPa. For the packaging design, direct contact should be avoided between the stem and peel of fruits that are stacked in layers.

Literature cited

Abbott, J.A. 1999. Quality measurement of fruits and vegetables. Postharv. Biol. Technol. 15, 207-225.

Alamar, M.C. E. Vanstreels, M.L. Oey, E. Moltó, and B.M. Nicolaï. 2008. Micromechanical behaviour of apple tissue in tensile and compression tests: storage conditions and cultivar effect. J. Food Eng. 86, 324-333.

Aviara, N.A. S.K. Shittu, and M.A. Haque. 2007. Physical properties of guna fruits relevant in bulk handling and mechanical processing. Int. Agrophysics 21, 7-16.

Bentini, M., C. Caprara, and R. Martelli. 2009. Physico-mechanical properties of potato tubers during cold storage. Biosyst. Eng. 104, 25-32.

Bruce, D.M. 2003. Mathematical modelling of the cellular mechanics of plants. Phil. Trans. R. Soc. Lond. B 358, 1437-1444.

Buitrago, G.V., A.P. López, A.P. Coronado, and F.L. Osorno. 2004. Determinación de las características físicas y propiedades mecánicas de papa cultivada en Colombia. Rev. Bras. Eng. Agríc. Ambient. 8 (1):102-110.

Cerdas, M. and J.J. Castro. 2002. Descripción botánica. pp. 13-15. In: Cerdas, M. and J.J. Castro (eds.). Manual práctico para la producción, cosecha y manejo poscosecha del cultivo de granadilla (*Passiflora ligularis* Juss). Convenio Poscosecha CNP-UCR, San Jose.

Chanliaud, E., K.M. Burrows, G. Jeronimidis, and M.J. Gidley. 2002. Mechanical properties of primary plant cell wall analogues. Planta 215, 989-996

Chassagne-Berces, S., C. Poirier, M. Devaux, F. Fonseca, M. Lahaye, G. Pigorini, C. Girault, M. Marin, and F. Guillon. 2009. Changes in texture, cellular structure and cell wall composition in apple tissue as a result of freezing. Food Res. Int. 42, 788-797.

Ciro, H.J., D.L. Vahos, and C.J. Márquez. 2005. Estudio experimental de la fuerza de fractura en frutas tropicales: el tomate de árbol (*Cyphomandra betacea* Sendt). Dyna. 72 (146): 55-64.

Ciro, H.J., D.L. Vahos, and E. Cortés, (n.d.) Fuerza de fractura superficial engranadilla (*Passiflora ligularis* Juss) y tomate de árbol (*Cyphomandra betacea* Sendt): Estudio experimental. Department of Agricultural Engineering and Food, Universidad Nacional de Colombia, Medellin, Colombia.

Dan, H. and K. Kohiama. 2007. Characterization of cucumber cultivars by mechanical stress distributions during the compression process. Rev. JARQ 41(2), 115-121.

FAO. 2006. Fichas técnicas, productos frescos y procesados: GRANADILLA (*Passiflora ligularis*). In: http://www.fao.org/inpho_archive/content/documents/vlibrary/ae620s/pfrescos/GRANADILLA.HTM; consulted; June, 2013.

García, M.C. 2008. Manual de manejo cosecha y poscosecha de la granadilla. Corpoica; Fontagro, Bogota.

Goulao, L.F. and C.M. Oliveira. 2008. Cell wall modifications during fruit ripening: when a fruit is not the fruit. Trends Food Sci. Techl. 19, 4-25

Herold, B., M. Geyer, and C.J. Studman. 2001. Fruit contact pressure distributions - equipment. Comput. Electron. Agr. 32, 167-179.

Icontec, Instituto Colombiano de Normas Técnicas y Certificación. 1997. Norma Técnica Colombiana NTC. 4101. Frutas frescas. Granadilla. Especificaciones. Bogota.

Legiscomex. 2008. Inteligencia de mercados - Frutas exóticas en Colombia. In: http://www.legiscomex.com/BancoMedios/Documentos%20PDF/est_col_frutas_exot_6.pdf; consulted: June, 2013.

Lu, R., A.K. Srivastava, and R.M. Beaudry. 2005. A new bioyield tester for measuring apple fruit firmness. Appl. Eng. Agr. 21(5), 893-900.

Mayor, L., R.L. Cunha, and A.M. Sereno. 2007. Relation between mechanical properties and structural changes during osmotic dehydration of pumpkin. Food Res. Int. 40, 448-460.

Mogollón, M.R. 2010. Informe técnico de pruebas de laboratorio de poscosecha: Granadilla (*Passiflora ligularis* J.). Department of

Agricultural Engineering and Food, Universidad Nacional de Colombia, Bogota.

Mohsenin, N. 1986. Physical properties of plant and animal materials: structure, physical, characteristics and mechanical properties. Gordon and Breach Science Publishers, New York, NY.

Newman, J.M., H.W. Hilton, S.C. Clifford, and A.C. Smith. 2005. The mechanical properties of lettuce: A comparison of some agronomic and postharvest effects. J. Mater. Sci. 40, 1101-1104.

Nguyen, L.T., A. Tay, V.M. Balasubramaniam, J.D.Legan, E.J. Turek, and R. Gupta. 2010. Evaluating the impact of thermal and pressure treatment in preserving textural quality of selected foods. LWT - Food Sci. Technol. 43, 525-534.

Oey, M.L. E. Vanstreels, J. Baerdemaeker, E. Tijskens, H. Ramon, M.L.A.T.M. Hertog, and B. Nicoläi. 2007. Effect of turgor on micromechanical and structural properties of apple tissue: A quantitative analysis. Postharv. Biol. Technol. 44, 240-247.

Olivera, L.M. 2004. Efecto del tratamiento térmico sobre la textura de la Murta (*Ugni molinae* Turcz) definida como resistencia a la ruptura. Ungraduate thesis. Universidad Austral de Chile, Valdivia, Chile.

Ospina, D.M., H.J. Ciro, and I.D. Aristizábal. 2007. Determinación de la fuerza de la fractura superficial y fuerza de firmeza en frutas de lulo (*Solanum quitoense* x *Solanum hirtum*). Rev. Fac. Nal. Agr. Medellín 60(2), 4163-4178.

Peleg, M. 1987. The basics of solid food rheology. pp. 3-34. In: Moskowitz, H.R. (ed.). Food texture: Instrumental and sensory measurement. Marcel Dekker, New York, NY.

Peleg, M. 2006. On fundamental issues in texture evaluation and texturization-A view. Food Hydrocoll. 20, 405-414.

Rosenthal, A.J. 1999. Food texture: measurement and perception. Food Science and Technology, International Series Academic Press, London.

Singh, K.K. and B.S. Reddy. 2006. Post-harvest physico-mechanical properties of orange peel and fruit. J. Food Eng. 73, 112-120.

Szczesniak, A.S. 2002. Texture is a sensory property. Food Qual. Prefer. 13, 215-225.

Steffe, J.F. 1996. Rheological methods in food process engineering. Freeman Press. East Lansing, MI.

Tabilo, G. and G.V. Barbosa. 2005. Rheology for the food industry. J. Food Eng. 67, 147-156.

Toivonen, P.M.A. and D.A. Brummell. 2008. Biochemical bases of appearance and texture changes in fresh-cut fruit and vegetables. Review. Postharv. Biol. Technol. 48, 1-14.

Valero, C. and M. Ruiz. 2000. Técnicas de medida de la calidad de frutas. Vida Rural 116, 60-64.

Van Linden, V. 2007. Identification of fruit parameters responsible for impact-bruising of tomatoes. Ph.D. thesis. Katholieke Universiteit Leuven, Leuven, Belgium.

Van Zeebroeck, M., V. Van Linden, H. Ramon, J. De Baerdemaeker, B.M. Nicolaï, and E. Tijskens. 2007. Impact damage of apples during transport and handling. Review. Postharv. Biol. Technol. 45, 157-167.

Villamizar, F. 1994. La granadilla, su caracterización física y comportamiento poscosecha. Ing. Investig. 28, 14-23.

Vincent, J.F.V. 1999. From cellulose to cell. J. Exp. Biol. 202, 3263-3268.

Waldron, K.W., M.L. Parker, and A.C. Smith. 2003. Plant cell walls and food quality. Comp. Rev. Food Sci. Food Saf. 2, 101-119.

Zdunek, A. and M. Umeda. 2006. Extension and fracture of cell walls after parenchyma tissue deformation. Biosyst. Eng. 93(3), 269-278.