Characterization of the mechanical properties of the cape gooseberry fruit (*Physalis peruviana* L.)

Caracterización de propiedades mecánicas del fruto de la uchuva (*Physalis peruviana* L.)

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ABSTRACT

Colombia is the world's leading producer of the cape gooseberry and it is a crop of great importance due to its high demand in the international market. The fruit, the part that is sold, is an ovoid-shaped, juicy berry, and its harvest starts when the fruit is orange-colored and the cap surrounding the fruit is yellow-colored. This labor is done manually. During this phase of collection, subsequent handling and transport to the places of packaging and marketing, the fruit is subjected to multiple loads which may deteriorate it in different ways, resulting in significant product losses. Rheological tests of unidirectional compression, punctures, and cuts at the peduncle were performed in order to characterize the mechanical response of the fruit to the type of forces exerted at harvest and post-harvest handling. It was found that the fruit's firmness in unidirectional compression in the axial direction, with a ripeness grade of four, was 38.6 N, while the force required to separate the fruit from the peduncle was 15.1 N. The mechanical behavior of the cape gooseberry corresponds to a viscoelastic, anisotropic, highly variable material.

Key words: rheology, harvest, postharvest, handling.

RESUMEN

Colombia es el principal productor mundial de uchuva y constituyéndose en un cultivo de gran importancia por su requerimiento en los mercados internacionales. El fruto, que es la parte que se comercializa, es una baya jugosa en forma de globo u ovoide. Su cosecha se inicia cuando los frutos toman una coloración anaranjada y el capuchón o 'capacho' que encierra la fruta se torna de color amarillo, esta labor 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 en pedúnculo, a fin de caracterizar su respuesta mecánica al tipo de fuerzas que soporta en su manejo durante la cosecha y la poscosecha. Se encontró que la firmeza del fruto en compresión unidireccional en dirección axial y para grado de madurez cuatro es de 38,6 N, a la vez que la fuerza requerida para separar el fruto del pedúnculo es de 15,1 N. El comportamiento mecánico del fruto de la uchuva corresponde a un material viscoelástico, anisotrópico y de muy alta variabilidad.

Palabras clave: reología, cosecha, poscosecha, manejo.

Introduction

Colombia is the main producer of the cape gooseberry (*Physalis peruviana* L.), and for the country, it is the second most important crop of fresh fruit for export, due to its nutritional and medicinal qualities, it is of great appeal to the international market (Salazar *et al.,* 2008).

The fruit, which is the part that is marketed, is a juicy berry, ovoid or balloon-shaped, with an average diameter between 1.3 and 2.1 cm and an average weight of 1.3 to 5.9 g, depending on the production zone of Colombia (Fischer *et al.*, 2007; Bonilla *et al.*, 2008; Herrera *et al.*, 2012). It contains about 245 to 310 small, lentil form seeds in the "Colombia" ecotype (Fischer *et al.*, 2007) that are devoid of a placental thread. The internal structure of the fruit appears to be a miniature tomato; however, the pulp is formed from both the pericarp tissue and placenta, contrary to what happens in tomato pulp which comes mainly from the placenta. The parenchyma of the fruit is not compact and has many gaps (voids) of more than 4 mm in length, the number and size increases as the fruit ripens. The fruit develops for about 60 to 80 d, according to the agro-ecological conditions of the site (Flórez *et al.,* 2000).

The calyx or cap of the cape gooseberry consists of five persistent sepals, and is hairy with prominent veins and a length of about 4-5 cm, completely covering the fruit

Received for publication: 12 December, 2012. Accepted for publication: 29 March, 2013.

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throughout its development and growing after fecundation of the fruit (Flórez *et al.,* 2000). During the first 40 to 45 d of development, it is green, but with fruit ripening, it loses chlorophyll and turns yellow-orange in the end. It is important because it protects the fruit from insects, birds, extreme weather conditions, as well as serving as an indispensable source of carbohydrates for the first 20 d of fruit growth.

The cape gooseberry is considered a climacteric fruit, that is, once separated from the plant, it continues ripening, which is why it is important to identify the right time for harvesting. Harvesting is done when the fruits start taking an orange color and the cap or ”calyx” enclosing the fruit turns yellow. This is done manually.

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

When the cape gooseberry is collected, some harvesters exert pressure on the calyx for removal from the plant, causing compression injuries. It is necessary to be very careful at harvest to avoid tearing and cracking the branches and stems, and to ensure the longevity of the plant and the quality of the harvested fruits.

The response of biological materials (fruits and vegetables) to applied loads requires knowledge of their mechanical properties, in generic terms, it is essential to study the rheological behavior, in addition, the mechanical behavior better expresses the quality of fruits and vegetables, that is, the texture (Szczesniak, 2002; Peleg, 2006; Newman *et al.,* 2005; Bentini *et al.,* 2009).

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

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

For the mechanical properties of the cape gooseberry, study references were only found at the Universidad Nacional de Colombia, Medellín: The study of Ciro *et al.* (2007), in which a rheological characterization of the cape gooseberry through unidirectional compression strength and fracture tests, for three degrees of maturity and days after harvest was carried out, and the research of Ciro and Osório (2008), which determined rupture and firmness forces using destructive techniques and low compression unidirectional loads with a constant speed. On the international scope, Gutiérrez *et al.* (2008) described a test of firmness (not clear whether it was compression or puncture) with an Instron® universal machine (Barcelona, Spain) and a flat probe of unspecified dimensions, at a very low speed of load application to four degrees of maturity of the cape gooseberry.

The aim of this study was to determine the mechanical properties in compression, punctures and cuts of the peduncle of the cape gooseberry for freshly harvested fruits that will receive further handling in the packaging and marketing processes.

Material and methods

Plant material

Cape gooseberry “extra” fruits were used in which cap defects did not exceed 5% of the total area, there was an average equatorial diameter of 18.22 mm, the fruits were fully intact, with uniform coloration, stored in an environment free of excessive humidity and average temperatures of 18°C, with stem lengths ranging from 0.2 to 1.0 mm; these fruits were grouped by two degrees of maturity, determined by the color according to the NTC 4580 Standard (Icontec, 1999): with a color 4 description of light orange fruits and a color 5 description of orange fruits; to better identify this product, a sample of 400 g was taken and the process described in the NTC 756 Standard (Icontec, 1977) was performed.

The sample size was determined by the procedure of the operation characteristic curves, taking a delta value of 1. Statistical tests to compare the values obtained from the two stages of maturity and the two directions of load application were not done.

Rheological tests

A Brookfield® (Middleboro, MA) texture analyzer was used with TexturePro CT V1.2 Build 9 software, and a load cell of 5,000 g force. For testing unidirectional compression, a TA25/100 acrylic cylindrical probe with a diameter of 50.8 mm, length of 20 mm, at a speed of 2 mm s^{-1} was used. In the puncture test, a TA 39 steel cylindrical probe with a diameter of 2 mm, length of 20 mm, at a rate of 2 mm s^{-1} was used. For the shear stem test, a TA7 cutting edge probe, with a width of 60 mm, made of transparent acrylic, at a speed of 8 mm s^{-1} was used. In the first two tests, two perpendicular directions were set to apply force: axial and radial. All tests were done with fruits with the cap.

In all trials by the software mentioned, a Force - Time (with deformation measurement) curve was determined for each of the 50 fruits used in each test (sample size). For the first two trials, the force and deformation values were converted to real stress (σ) *vr.* Hencky strain (εH) according to the methodology followed by Olivera (2004). From the force versus time curves for each test, the average maximum force (firmness) was determined and from the true stress versus Hencky strain curves, the actual rupture stresses and deformations at the break were established.

Results and discussion

Maximum forces are the firmness of the fruit according to each of the two types of tests mentioned above. Tab. 1 shows the mean and standard deviation of these maximum forces for each of these tests, including the shear test of the peduncle from an assay as displayed and with a typical curve.

The shape of the curve for the unidirectional compression test initially has an approximately linear behavior (elastic character) with increased resistance to the maximum rupture value. This value corresponds to the resistance of the exocarp (shell), including the defense provided by the calyx, which is consistent with what was found by Ciro and Osório (2008). The tissues that make this shell are parenchyma and sclerenchyma, the latter with cells that have secondary cell walls reinforced with lignin, as discussed by Chiarini and Barboza (2009), referring to the fruits of the Solanaceae Family and the comments of Waldron *et al.* (2003). Then, after this failure, resistance completely decreases when the placental tissue and pulp (mesocarp) have low or no resistance to compression, with a rapid and complete fracture. Defining a bioyield point is difficult because there may be gradient increases at the end of the elastic, small part or close to the point of rupture after resistance. Bioyield is associated with a micro tissue failure when the cells begin to break down and the rupture

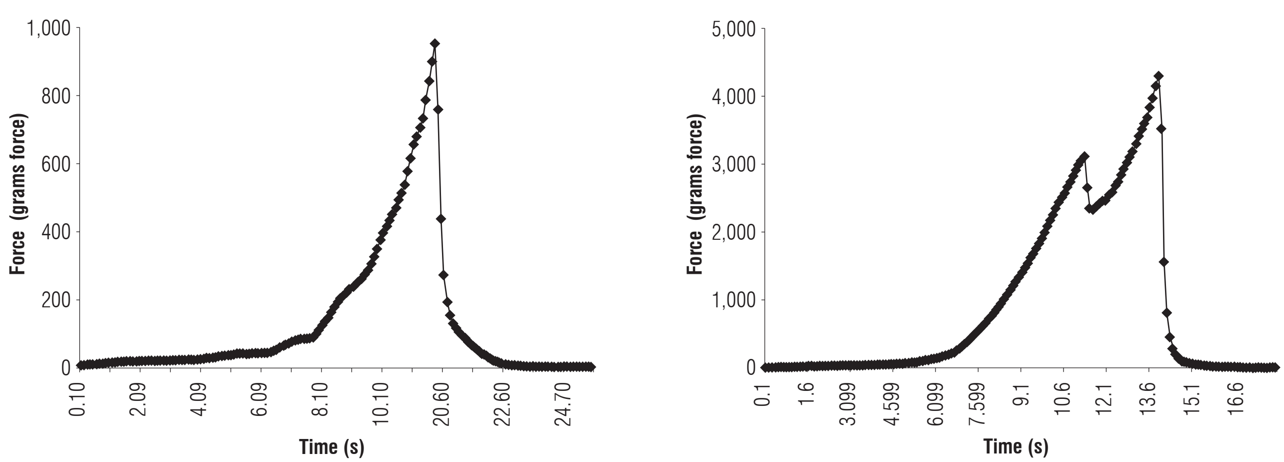

FIGURE 1. Typical force - time curve, for a unidirectional compression test, above: radial direction, degree of maturity 4, bellow: axial direction, degree of maturity 4 of cape gooseberry fruit.

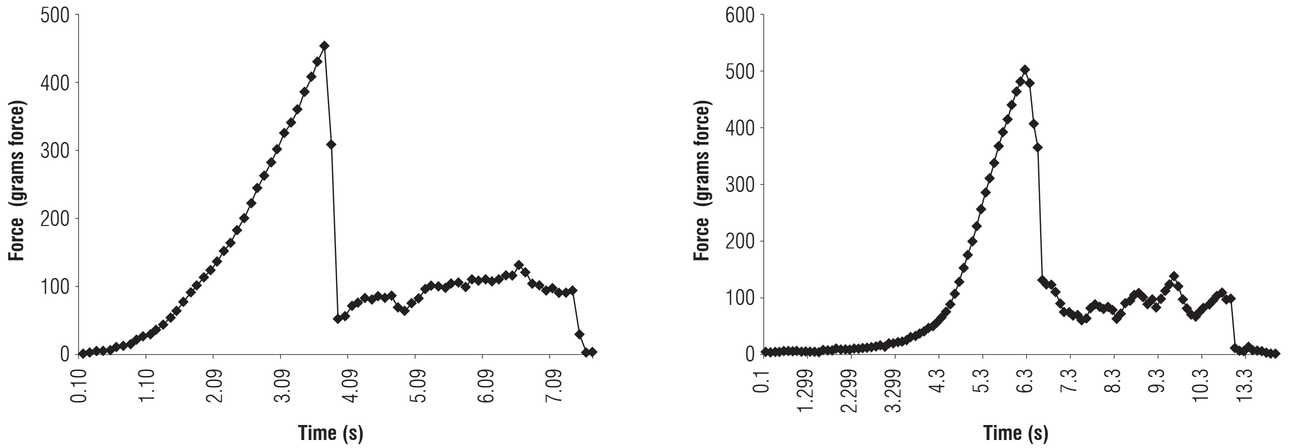

FIGURE 2. Typical force - time curve for a puncture test, above: radial direction, degree of maturity 4, bellow: axial direction, degree of maturity 4 of cape gooseberry fruit.

point is a macro failure of tissues (Mohsenin, 1986; Van Linden, 2007).

TABLE 1. Maximum force in mechanical tests. Compression, puncture and shear of cape gooseberry fruit.

Test type	Degree of maturity	Maximum force (N)*
Axial compression	4	38.6±6.2
Radial compression	4	9.4±0.2
Axial compression	5	34.9±4.5
Radial compression	5	32.5±8.1
Axial puncture	4	4.9±1.4
Radial puncture	4	4.7±1.5
Axial puncture	5	4.9±1.2
Radial puncture	5	3.5±2.2
Peduncle shear	N/A	15.1±8.1

*The values presented are means ± standard deviation.

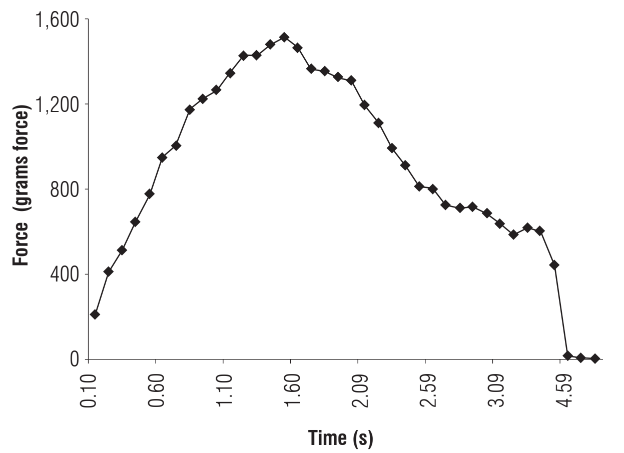

FIGURE 3. Typical force - time curve, for a shear test on the peduncle of cape gooseberry fruit.

Table 1 shows that this rupture or fracture in the unidirectional compression test is similar for both directions of load application and the two stages of maturity (the radial compression value for maturity four was not take into account and the cause is unknown, outside of the normal value, thus corresponding to a state of very mature fruit), although slightly higher for axial compression and stage 4 maturity (greener). In Comparison with the values reported by Ciro and Osório (2008), they agree as to degree of maturity between green and "pintón" and in the axial direction reported by these authors, *i.e.* the order of 35 N and high values of coefficient of variation (20%), which isn't surprising in biological materials, which are very uneven. The fact that it has greater strength in the axial 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 Kohyama (2007) and Mayor *et al.* (2007). Besides, it has been sufficiently reported by Van Linden (2007), Toivonen and Brummell (2008), Goulao and Oliveira (2008) that as ripeness of the fruits proceeds, there is a loss of water associated with a loss of turgor of the cells, a decrease in adhesion between cells and changes in cell wall polysaccharides.

Puncture tests produced the force - time curves, which have similarity with the unidirectional compression, although the decrease in the shell´s firmness corresponding to the value of the resistance force exerted on the pulp is notable, as reported by Ciro and Osório (2008), however, the initial elastic character in the axially oriented load curve with stage four maturity is not evident. Again, the firmness values recorded in the puncture tests are consistent with those obtained by Ciro and Osório (2008) for gooseberries with a state of maturity between green and "pintón", around 4.5 N, with a coefficient of variation of 30%, as can be noted in Tab. 1. Similarly, the results are consistent with that

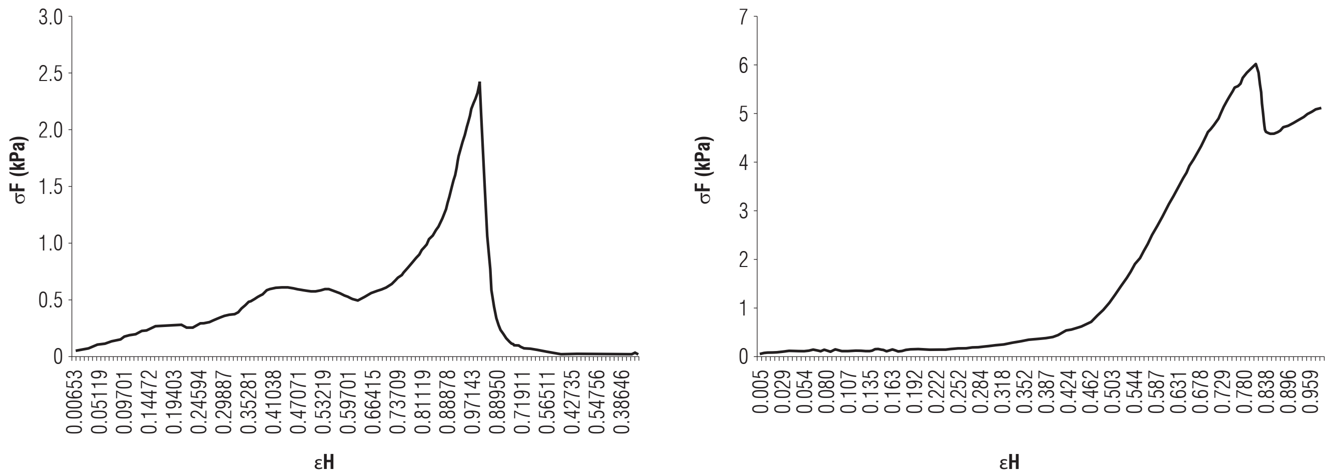

FIGURE 4. Typical stress – Hencky strain curve for unidirectional compression test, above: radial direction, degree of maturity 4, below: axial, degree of maturity 4 of cape gooseberry fruit.

reported by Gutiérrez *et al.* (2008) who tested for firmness (assumed to be with punctures) for stage three maturity, *i.e.*, yellow fruit, which is comparable to stage four of this paper. It is emphasized again that this value corresponds to the strength of the shell with the same connotation made in the unidirectional compression. The decrease until a residual force that can characterize the resistance force of the pulp, although not statistically recorded, was also consistent with that found by Ciro and Osório (2008), *i.e.* around 0.5 N. It should be noted that increasing maturity produces softening only for the radial direction of the load application, which does not seem logical in light of the physicochemical changes that occur in this process.

Figure 3 shows a typical Force - Time curve for a cutting test at the peduncle. Tab. 1 records the average value of the maximum shear force: 15.1 N and a coefficient of variation of 53.6%.

Finally, Fig. 4 shows typical curves developed from the results of the unidirectional compression tests, which show the rheological behavior of freshly harvested cape gooseberry fruits with caps with a Stress – Hencky strain curve in order to determine the mechanical parameters of this fruit as a biological material. Such values are listed in Tab. 2 which also shows these values for the puncture test. From the curves shown in Fig. 4, it may be noted that there is an initial strip more or less elastic, of very low stiffness, up to 20 to 50% of the strain; this stiffness is then increased until rupture at strains of 40 to 90%. No attempt was made to calculate a modulus of elasticity or apparent deformability of the cape gooseberry as a fruit with calyx, given the irregular behavior thereof. The mentioned curves exhibit an upward concave curvature for compressible materials,

TABLE 2. Rheological parameters from mechanical testing of unidirectional compression and punctures of cape gooseberry fruit.

Test type	Degree of maturity	σ_R (kPa)	ε_R (adim)
Axial compression	4	6.0	0.83
Radial compression	4	2.8	0.41
Axial compression	5	5.5	0.89
Radial compression	5	3.4	0.35
Axial puncture	4	440	0.53
Radial puncture	4	32.5	0.72
Axial puncture	5	140	0.41
Radial puncture	5	62.0	0.48

partly due to the increasing cross-section which supports the load and the nonlinearity of the strain, as stated by Peleg (1987).

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

For the cape gooseberry fruit, when subjected to quasi-static loads, such as those of collectors at the time of harvest, or when layers of cape gooseberry fruits are statically stacked, loads should not exceed 3-4 N when applied in puncture form or 20 to 30 N when applied in compression form, provided the degree of maturity does not exceed four. Previous values involve actual compression stresses of 3 kPa (axial direction), 1.5 kPa (radial direction) and 200 kPa (axial direction), 15 kPa (radial direction) for puncture loads and stage four maturity fruit. From the above, it is necessary that the stacking of fruits, if possible, be done with axially oriented fruits.

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

Any cutting device for the separation of the fruit from the plant peduncle must exert a shearing force in the range of 5 to 25 N.

Conclusion

The cape gooseberry fruit, when subjected to quasi-static loads, behaves as a viscoelastic material with high variability of anisotropic properties. The values obtained for firmness, both for the unidirectional compression and puncture tests, correspond to the resistance of the exocarp (shell) of the fruit, including the cap. Harvest and postharvest management must be done with fruits that do not exceed stage four maturity, according to NTC 4580. Similarly, when stacked, fruits should be axially oriented.

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