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TENSILE PROPERTIES OF PUMPKIN PEEL AND FLESH TISSUE AND REVIEW OF CURRENT TESTING METHODS

M. Shirmohammadi, P. Yarlagadda, Y. T. Gu, P. Gudimetla, V. Kosse

ABSTRACT. *In South and Southeast Asia, postharvest loss causes material waste of up to 66% in fruits and vegetables, 30% in oilseeds and pulses, and 49% in roots and tubers. The efficiency of postharvest equipment directly affects industrial-scale food production. To enhance current processing methods and devices, it is essential to analyze the responses of food materials under loading operations. Food materials undergo different types of mechanical loading during postharvest and processing stages. Therefore, it is important to determine the properties of these materials under different types of loads, such as tensile, compression, and indentation. This study presents a comprehensive analysis of the available literature on the tensile properties of different food samples. The aim of this review was to categorize the available methods of tensile testing for agricultural crops and food materials to investigate an appropriate sample size and tensile test method. The results were then applied to perform tensile tests on pumpkin flesh and peel samples, in particular on arc-sided samples at a constant loading rate of 20 mm min^{-1}. The results showed the maximum tensile stress of pumpkin flesh and peel samples to be 0.535 and 1.45 MPa, respectively. The elastic modulus of the flesh and peel samples was 6.82 and 25.2 MPa, respectively, while the failure modulus values were 14.51 and 30.88 MPa, respectively. The results of the tensile tests were also used to develop a finite element model of mechanical peeling of tough-skinned vegetables. However, to study the effects of deformation rate, moisture content, and texture of the tissue on the tensile responses of food materials, more investigation needs to be done in the future.*

Keywords. *Food processing, Mechanical peeling, Mechanical properties, Postharvest loss, Pumpkin, Tensile test, Tough-skinned vegetables.*

Analyzing the actual behaviors of agricultural and food materials under loading enables researchers and designers to enhance existing industrial food processing technologies and machinery. Agricultural crops undergo different types of loads during postharvest processes such as handling, grading and sorting, cleaning, transporting, and packaging. Depending on the production process and material behavior, the loading source can be categorized as vibration, impact, compression, shear, or tensile. It is usually difficult to evaluate the results of loading on food tissue during processing, as load combinations generally create changes in food materials. Investigating the mechanical properties of agricultural tissues requires a thorough evaluation of the tissue behavior during mechanical operations. Additionally, the nature of food materials creates different responses to the loading source according to the operational conditions and moisture content of the tissue. However, it is possible to classify the processing loads as wanted and unwanted (Shirmohammadi et al., 2012). Wanted loads are those that create desirable changes during the processing stages. For example, during cutting and peeling processes, cutting, shear, and tensile loads can be helpful to cut and peel tissue. However, unwanted loads, such as compression, can create discoloration and bruising on materials, which diminish the quality of food products. These unwanted loads can cause high rates of material damage and loss during postharvest and industrial food processing. Postharvest loss (PHL) causes material waste of up to 66% in fruit and vegetables, 30% in oilseeds and pulses, and 49% in roots and tubers in South and Southeast Asia (Gustavsson et al., 2011). It has been reported that the PHL due to processing operations in potato production can reach 20% of the total product, while in apple production the PHL can rise to 50% of the total product (Shirmohammadi et al., 2011).

Diminishing the rate of loss requires in-depth knowledge of food material behaviors under different types of loading. Previous studies have focused on tensile loading of food material and agricultural crop tissues to describe and calculate mechanical behaviors during food processing operations. However, there is a gap in the literature for the tensile behaviors of tough-skinned vegetables, which could be used to analyze the efficiency of food processing stages for these crops. Such tests are usually designed to test specimens of food materials of a

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given size at a constant loading rate under laboratory conditions. However, the shape and size of the specimen as well as the experimental instruments are critical issues during experimental testing of food materials. Tensile testing can provide useful information about the resilience of food materials, yet it is difficult to choose the best sample size and experimental setup (Luyten et al., 1992), particularly when the shape and size of the crop varies from small (cherry tomatoes) to large (pumpkin and watermelon). Additionally, agricultural crops are soft and juicy, and samples need to be prepared under specific care to prevent sample damage before the loading tests. Tensile testing is usually performed by holding the sample between two clamps and applying the tensile load, a process that may cause the sample to slip as loading starts.

This article presents a comprehensive analysis of the literature on tensile testing of agricultural crops in order to classify existing sources of tensile testing. The results of the analysis facilitated the design of an appropriate experimental setup to evaluate tensile properties of pumpkin tissue as an example of a tough-skinned vegetable. Pumpkin is a member of the cucurbit (Cucurbitaceae) family of about 125 genera and 825 species, including cucumbers, gourds, melons, squash, and zucchini (Deyo and O'Malley, 2008). Production of the cucurbit family in Australia reached to 150,728 tonnes in 2007, while pumpkin production was about 114,418 tonnes. The highest pumpkin production rates were in Queensland and New South Wales, with 43,783 and 40,718 tonnes, respectively (Keogh et al., 2010). In this study, tensile testing was performed on pumpkin peel and flesh samples for the first time. Tensile properties were calculated for pumpkin peel and flesh to evaluate the ranges of stress, strain, and Young's modulus before and at the rupture point and were used to develop a finite element model (FEM) of mechanical loading of pumpkin tissue.

EXISTING LITERATURE ON TENSILE TESTING OF FOOD MATERIALS

The analysis of the literature on tensile testing of agricultural and food materials was undertaken with a focus on experimental designs, calculation methods, and final results. This analysis was the basis for developing an experimental protocol for the tensile testing of pumpkin flesh and peel samples. Although there are previous studies on the tensile behavior of different fruit and vegetable tissues, there is no study on the tensile behavior of pumpkin tissue. However, our research group has previously studied the compressive responses of tough-skinned vegetable tissues, including pumpkin and watermelon (Emadi et al., 2005; Emadi et al., 2009). A broad literature review was completed of the available studies on tensile properties of fruits and vegetables, including apple, orange peel, potato, carrot, pear, watermelon, muskmelon, avocado, banana, tomato peel, and onion. Although the available literature is limited, this article lists it in three groups including: (1) apple, pear, potato, tomato, and carrot crops with peel and flesh attached; (2) avocado, orange, banana, and onion with thin peel; and (3) muskmelon, watermelon, and pumpkin as thick-peel fruits and vegetables.

There are studies available on tensile testing of different varieties of apple (Alamar et al., 2005; Clevenger and Hamann, 1968; Harker and Hallett, 1992; Stow, 1989); however, they used different approaches in sample preparation and sizing. Winesap, Red Delicious, and Golden Delicious apples were tested with deformation rates of 5.3 to 21.3 mm min^{-1} (0.21 to 0.84 in. min^{-1}) (Clevenger and Hamann, 1968) using a constant-displacement testing machine. The samples were approximately 2.5 mm (0.098 in.) in width and 27 mm (1.060 in.) in length, and aluminum grips were used to hold the samples and prevent them from breaking close to the grips. An H-shaped sample with a diameter of 14 mm, length of 30 mm, and middle section of 4 mm × 12 mm was cut from each apple to test the tensile properties of Granny Smith apples (Stow, 1989). A 5 mm thick plate attached to a motor platform with a deformation rate of 0.6 mm min^{-1} was used to perform the test. Similarly, Harker and Hallett (1992) used H-shaped samples of 5 mm diameter to study the tensile properties of Golden Delicious apples. Alamar et al. (2005) investigated the tensile behaviors of Jonagored and Braeburn apples using a rectangular sample of 11 mm × 5 mm × 2 mm and loaded at 0.5 mm min^{-1}. The samples were glued to the edge of the grips to stop the samples from slipping. Schoorl and Holt (1983) studied the tensile behaviors of Granny Smith apples by running a series of trial-and-error tests to choose the best sample shape, and a one-sided circular sample of 5 mm middle length was chosen. Each apple was cut into two circular sides approximately 10 mm from the fruit core. A 9 mm diameter circle was then cut from the circular side to create a narrow middle section, which was then placed into the clamps. Minimum pressure was applied on each side of the sample to avoid sample slippage.

Asian and European pear behaviors under tensile loading were studied by De Belie et al. (2000) using two special aluminum guides to hold the samples. The pear samples were glued to the guides and placed in a chamber filled with osmotic solution. The tensile loading was applied at a rate of 3 mm min^{-1} using an Instron universal testing machine (Instron, Norwood, Mass.). The load and elongation results were recorded to calculate the tensile properties of pear tissues. Two different shapes, including dumbbell and arc-sided samples, were cut from Kennebec potato and tested; however, results for the dumbbell-shaped samples were unsatisfactory, since the samples failed around the clamp edges instead of in the middle (Huff 1967, 1971). Special clamps were used to squeeze the samples between two grips that were fastened by a right-left screw. The instrument had a weight of about one pound per square inch at the lower clamp, but the effect of this weight on the samples was neglected. Pre-test results of the arc-sided samples, with middle lengths of 76 and 89 mm (3 and 3.5 in.), were used to calculate the tensile properties of the potato samples.

For carrot samples, rectangular shapes of 20 mm × 2 mm × 2 mm were prepared and tested at 1.67×10^{-5} mm s^{-1} using an Instron universal testing machine; the samples had a 1 mm notch in the middle up to the failure point (McGarry, 1995). In a similar approach, Harker et al. (1997) performed tensile tests on carrot and apple tissue using an Instron testing machine. The tests were performed at a deformation rate of 10 mm min^{-1} with samples that were cut in 6 mm × 4 mm blocks and loaded to the point of failure. The force and extension results were used to calculate the tensile properties of the plant tissues. For tomato peel, Rajabipour et al. (2004) used a new approach to measure tensile properties by applying two methods: grip and loop. The grip method was similar to other studies and involved placing a 10 mm wide strip of tomato skin in the Instron grips. The samples were loaded at a rate of 10 mm min^{-1}. Results of the grip method were not satisfactory, as the samples failed near the gripping area but not in the middle section. Consequently, in the loop method, the tomato skin was cut around the equator as a complete loop of 10 mm width and then placed on two parallel cylindrical bars of 4 mm diameter. The results were recorded as a force-extension curve and used to calculate the tensile properties of tomato skins. Bargel and Neinhuis (2005) prepared tomato peel samples of 3 mm × 40 mm from Hazfeuer, Vanessa, and Roma varieties and loaded them at a rate of 2 mm min^{-1} to study the changes in mechanical properties during ripening.

For the tensile properties of orange peel, Churchill et al. (1980) tested Hamlin, Pineapple, and Valencia varieties using a fixed and movable crosshead attached to a universal machine. Orange peel samples were cut into 25 mm wide × 50 mm long pieces with an 8 mm middle section. The tensile properties of unripe avocado and banana were studied using an Instron testing machine at 10 mm min^{-1} (Harker et al., 1997). The samples were 6 mm × 4 mm blocks with notches in the middle length. Harket et al. (1997) used metal strips to place the samples in the Instron jaws. For onion epidermal tissue, due to the soft nature of this material, the micromechanical behavior of the tissue was studied using a miniature tensile stage (Vanstreels et al., 2005). The samples were placed in the 10 mm gap between the clamps. During the test, the samples were humidified with water and humidified air (~90% RH) and loaded at 1 mm min^{-1}.

Harker et al. (1997) tested the tensile response of muskmelon and watermelon tissue under loading. The test results were used to calculate the mechanical properties of the tissues. The samples were prepared as 6 mm × 4 mm blocks with notches in the middle. The results showed a sharp peak for watermelon samples, while the muskmelon samples failed with a gradual increase in force. This study also compared the test results for different plant tissues and reported that watermelon, apple, carrot, and unripe avocado broke apart at the surface of the fracture. Banana cells separated from neighboring cells, and no cell breakage happened. In muskmelon samples, most of the cells broke, and just a limited number of the cells separated from neighboring cells.

Hook's law has been used in the computation of the tensile properties of food samples under tensile loading. The rupture point is defined as the peak of the load-extension curve, which has been reported to be based on a linear relationship between the load and extension values. However, the load-extension curve has also been reported to be slightly different for various samples. In addition, the tensile strength, elastic modulus, and failure modulus of some food material samples have been determined, as mentioned above.

MATERIALS AND METHODS

This study presents experimental results of tensile loading on the Japanese pumpkin variety. The samples were purchased from local suppliers in Brisbane, Australia. Ripe and defect-free pumpkins were selected. Before the tests, the pumpkins were kept in laboratory conditions for 24 to 48 h. For the duration of sample preparation and testing, the humidity and temperature were 20% to 55% and 20°C to 25°C. The tests were performed on 3 mm thick flesh and peel samples. The moisture contents of the flesh and peel samples were determined as 87% and 82.5%, respectively, at 70°C. Flesh samples were cut from the ripe section of tissue under the skin. The peel samples were cut from the darker skin layer and the semi-green layer directly beneath the skin.

The literature reports the use of different sample shapes and sizes for tensile testing of agricultural materials. However, there is no similar study on tough-skinned vegetables or pumpkin tissue. Therefore, a series of pre-tests was performed to identify the appropriate peel and flesh sample sizes. The critical issues involved in sample size selection were uneven stress distribution, sample failure at the gripping point, and sample extrusion from the clamps during the test. For this reason, an Instron universal testing machine was used with a 100 N load cell and the clamps (fig. 1) usually used for tensile testing of food materials (FTC, 2012; Instron, 2012). It was crucial to prepare samples without nicks and cuts and with parallel edges in order to eliminate any possible stress concentrations near the gripping edges and necks.

Initially, a set of pilot experiments was conducted to estimate the optimum sample size and possible modes and zones of failure during the testing procedure. It was found that longer and thicker samples failed near the gripping area due to the stress concentration. Pre-tests were performed for dogbone (Luyten et al., 1992), arc-sided (Huff, 1967, 1971), and rectangular (Alamar et al., 2008) samples. Among the different sample shapes tested, the rectangular and dogbone-shaped samples both failed at the

Figure 1. Clamp used for tensile test.

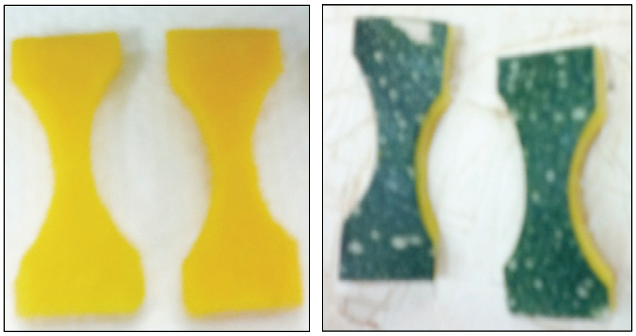


Figure 2. Flesh and peel samples.

gripping edges. For arc-sided samples with a width of 5 mm, breakage happened in the middle as expected, similar to the findings of Huff (1967, 1971). Due to the convex shape of pumpkins, the samples were prepared with 40 mm lengths, as this was the best length for preparing parallel-edge specimens, which also required the width to be 10 mm at the ends (fig. 2).

Sample extrusion from the clamps was eliminated by fastening the grips with high clamping pressure. This high pressure was enough to keep the peel samples fixed. However, with flesh samples, water was exuded when the grips were fastened. To avoid flesh sample extrusion from the grip edges, a very thin layer of tissue was placed between the flesh sample and the grip. Several tests were performed, and the majority of samples failed in the narrow middle length, as expected. After finalizing the sample size and test setup using data from the literature, tensile tests were repeated ten times for peel and flesh samples at a loading rate of 20 mm min^{-1} (Churchill et al., 1980; Holt and Schoorl, 1977; Mohsenin and Mittal, 1977). The time, load, and extension data obtained from the Instron machine were used for further calculation of the tensile properties.

RESULTS

Tensile tests were performed at a loading rate of 20 mm min^{-1} using an Instron universal testing machine to determine the tensile properties of pumpkin tissue. The results were used to evaluate the tensile properties of peel and flesh samples of pumpkin. In the tensile loading curves, shown in figure 3, both peel and flesh had a semi-linear first section, which continued to a peak value at the point of rupture. This pattern was similar to the tensile test results for muskmelon and watermelon tissues (Harker et al., 1997). The rupture force was approximately 8 N for flesh samples and 21 N for peel samples. Rupture in flesh samples occurred at 3.63 mm extension, and rupture in peel samples occurred more quickly at 2.84 mm extension. Stress-strain values were calculated using equation 1; the ultimate strength of the peel and flesh samples were 1.45 and 0.535 MPa, respectively (fig. 4):

$$\sigma = \frac{F}{A},\ \sigma_r = \frac{F_r}{A} \tag{1}$$

$$\varepsilon = \frac{\Delta l}{l_0} \tag{2}$$

$$E = \frac{\sigma}{\varepsilon},\ E_f = \frac{\sigma_r}{\varepsilon_r} \tag{3}$$

where σ is stress (MPa), σ_r is stress at the rupture point, F is load (N), F_r is rupture force (N), A is cross-sectional area (mm^2), ε is strain, Δl is change in length (mm), l_0 is initial length (mm), E is elastic modulus (MPa), E_f is failure modulus (MPa), and ε_r is strain at the rupture point (Huff, 1967, 1971; Mohsenin, 1986; Steffe, 1996; Bargel and Neinhuis, 2005).

The ratio of tensile stress over strain in the elastic zone was also calculated as the elastic modulus of the samples. The elastic modulus of peel (25.2 MPa) was much higher than that of flesh (6.82 MPa). The failure modulus was calculated as the ratio of stress over strain at the failure point (Huff, 1967, 1971); the values for flesh and peel were 5.90 and 20.40 MPa, respectively. The flesh and peel samples both failed after a clear breaking noise, and the failed section revealed an uneven line (fig. 5). The required energy for failure, calculated as the area under the load

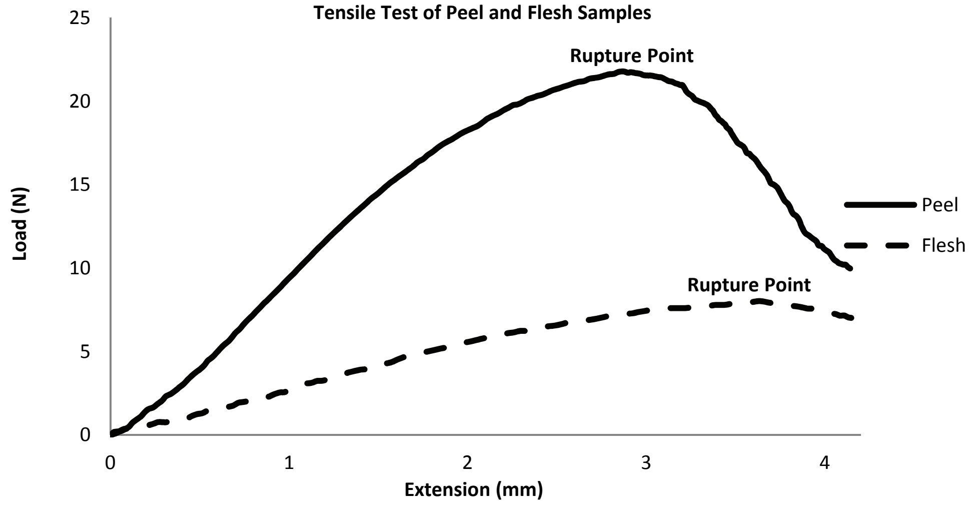


Figure 3. Load-time curves for flesh and peel samples.

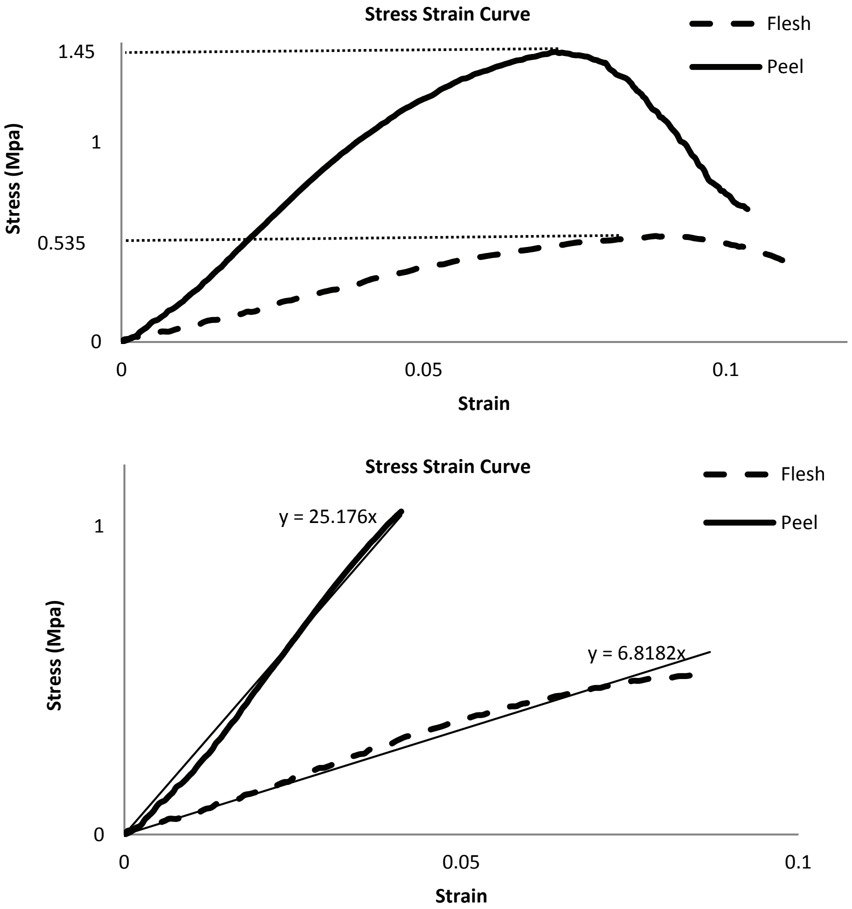
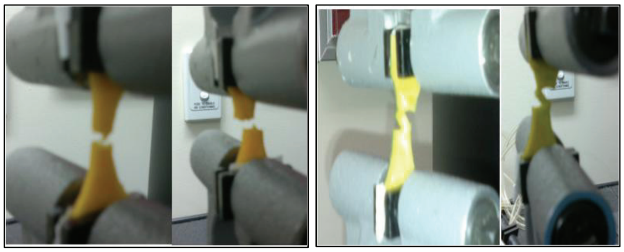


Figure 4. Stress-strain curves for peel and flesh samples.



(a) **(b)**

Figure 5. Breakage section of samples: (a) flesh and (b) peel.

extension curve (Schoorl and Holt, 1983), was 30.88 and 14.51 N·mm for peel and flesh samples, respectively.

DISCUSSION

Tensile testing of pumpkin flesh and peel samples was performed using an Instron universal testing machine. The results demonstrated a linear relationship between load and extension up to the rupture point for both the peel and flesh samples. However, unlike apple and watermelon samples, which had a sharp peak (Harker and Hallett, 1992; Schoorl and Holt, 1983), rupturing of pumpkin flesh and peel samples occurred gradually, similar to muskmelon and carrot samples (Harker et al., 1997). Unfortunately, there is no previous study on the tensile properties of tough-skinned vegetables such as pumpkin; therefore, the results were compared with available data in the literature for other vegetable tissues.

The comparison between peel and flesh results indicates a more linear stress and strain relationship in the flesh samples than the peel samples (fig. 4). The natural convex shape of pumpkin could be the reason for this phenomenon, which was also observed in Huff's study of the tensile properties of potato peel (Huff, 1967, 1971). The rupture load reached 21 N for pumpkin peel samples, which was higher than the rupture loads for tomato (Rajabipour et al., 2004) and potato skin (Huff, 1967, 1971) but lower than that for apple (Schoorl and Holt, 1983) and for orange peel, which had a rupture load of 22.5 N (Churchill et al., 1980). These results indicate the resistance of pumpkin peel to external sources of tensile loading. For the pumpkin flesh samples, the maximum load was 8 N, which was lower than the pumpkin peel rupture force but higher than the value reported for pear tissue (De Belie et al., 2000). The flesh samples failed after a larger deformation of 3.63 mm; however, the peel samples ruptured after 2.84 mm and displayed a tougher behavior. This behavior indicates a more brittle characteristic of pumpkin peel in comparison with pumpkin flesh. Under tensile loading, potato peel (Huff, 1967, 1971) failed at 3.05 mm (0.12 in.), while tomato peel samples (Rajabipour et al., 2004) failed at 6 mm elongation when applying the loop method. Investigating the response of pumpkin flesh and peel samples to tensile loading is a new approach, and there was no similar study on pumpkin in the literature with which to compare the results of this study.

The gripped cross-sectional area was determined as the thickness multiplied by the average sample width in the middle length at the narrowest part (Mohsenin, 1986) and was used to evaluate stress. For strain calculation, the extension values were divided by the initial length of the samples (Vanstreels et al., 2005). The resulting stress-strain curves are shown in figure 4. The ultimate tensile stress in flesh and peel were 0.535 and 1.45 MPa, respectively. The maximum stress values for Braeburn and Jonagored apples were reported as 0.22 and 0.24 MPa (Alamar et al., 2008), and carrot tissue 91 days after drilling had a minimum stress value of 0.501 MPa (McGarry, 1995).

Hook's law was applied to measure the elastic modulus of pumpkin tissues, which was 25.2 MPa for peel samples and 6.81 MPa for flesh samples. These values were relatively higher than the value reported by Alamar et al. (2008) for apple tissue (3.91 MPa) but close to the value reported by Kramer and Szczesniak (1973) for raw carrot, i.e., 20 MPa (2×10^8 to 4×10^8 dyne cm^{-2}). Additionally, the ratio of stress over strain at the failure point was 5.90 MPa for potato flesh samples and 20.40 MPa for potato peel samples (Huff, 1967, 1971).

The samples failed with a clear breaking noise midway along their length, and the broken cross-section was uneven for both flesh and peel (fig. 5). This was similar to what was reported by Huff (1967, 1971) for potato peel, where samples did not detach completely. Pumpkin flesh tissues separated into two pieces just after rupturing (fig. 5). However, for peel samples, cracks developed around mid-length and the samples failed along the cracks thereafter. In tensile testing of apple tissue (Schoorl and Holt, 1983), the pattern of crack development occurred after a sharp failure noise. The tests were performed at one deformation rate, and it has been reported that the deformation rate affects the formation of cracks; more cracks are created with slower rates (Huff, 1967, 1971).

The energy dissipated in tensile loading was calculated as approximately 30.88 and 14.51 N·mm, respectively, for peel and flesh samples using the definition given by Emadi et al. (2009) and Schoorl and Holt (1983). Clearly, failure in peel samples required higher energy, so more time was required to reach that energy level. Moreover, lower rates of loading take longer to reach the rupture point, when cracks develop in the tissue. The energy required for rupture of the flesh and peel tissues of pumpkin under tensile testing was significantly lower than the values under compression loading (Emadi et al., 2009; Shirmohammadi and Yarlagadda, 2012). Therefore, regardless of samples size and shape, the susceptibility of pumpkin tissue to compression loading is relatively higher than tensile loading. This indicates that processes involving tensile loads can create higher rates of damage to pumpkin tissue than processes involving compressive loads.

CONCLUSION

Analysis of the behavior of food materials under mechanical loading assists researchers in categorizing tissue damage, determining PHL rates, and measuring energy consumption. Due to the diversity of food industry operations and the nature of food materials, there is a lack of knowledge about the mechanical responses of food materials under tensile loading. Computational methods can partly address this lack by defining the effects of processing stages on food materials so as to diminish the rate of loss and enhance the quality of the final product. Therefore, developing a finite element model (FEM) of mechanical peeling of tough-skinned vegetables, and determining the mechanical properties of the flesh and peel layers, was essential. To develop appropriate material models for pumpkin flesh and peel, tensile loading tests were performed. Flesh and peel tissues were examined as two materials, and the properties of each material were calculated separately. The maximum tensile stress for flesh and peel was 0.535 and 1.45 MPa, respectively, while the elastic modulus was 6.82 and 25.2 MPa, respectively. The failure modulus was calculated as 14.51 and 30.88 MPa for flesh and peel samples, respectively. Comparable with previous studies on different agricultural products, the results of these tensile tests on pumpkin samples indicate tougher material behavior for the peel as compared to the flesh. Values of force and stress at the rupture point were also higher for the peel layer compared to the flesh tissue.

FUTURE WORK

The tensile testing performed in this study was one of few experiments on pumpkin peel and flesh samples. However, the effects of different loading rates on the tensile behaviors of these tissues can be studied further. The different responses of the peel and flesh samples to loading rates, considering ripeness, toughness, and moisture content as influential factors, need to be addressed in future studies. Additionally, samples cut close to the stem end of the pumpkin have different mechanical behavior in comparison to samples from the bottom end. This difference needs to be considered in the processing stages, particularly in handling and packaging operations. The different responses of peel and flesh samples are only one parameter that needs to be addressed to identify the more susceptible sections of this crop to loading. The effects of moisture content during processes such as storage must also be included in future studies, as the moisture content potentially affects the response of a food material to loading. Microstructural changes and discoloration occurring during postharvest processing stages of agricultural crops can also be investigated in future work.

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