J. Agr. Sci. Tech. (2017) Vol. 19: 809-820

Mechanical Properties of (*Aloe vera* L.) Leaf for Designing Gel Extraction Machines

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ABSTRACT

Compressive and shear properties of (*Aloe vera* L.) leaves were investigated for gel extraction. This information is useful in the design of processing equipment and improving gel production lines in order to decrease losses and enhance product quality. Effects of loading speed (10, 50, and 100 mm min^{-1}), temperature (20, 40, and 60˚C), and diameter of the cylindrical loading head (70, 140, and 210 mm) on the leaf compression properties, as well as the effect of loading speed on the shear properties were examined. The results showed that increasing the temperature would decrease the modulus of elasticity. Loading head diameters had a significant effect on the required force for crushing the leaves and extracting the gel. Based on the results, the best loading combination for extracting *Aloe vera* gel from the leaf is 20˚C temperature, loading head diameter of 14 cm, and loading speed of 100 mm min^{-1}. Shear forces of upper and lower leaf surfaces increased with loading speed. However, speed of loading had no effect on the shear forces at the edges and center of the leaf. The shear force was similar at different speeds for edge and center regions as well as for upper and lower surfaces of the leaf. Two gel extraction machines were developed based on the shear and compression properties of *Aloe vera* leaves.

Keywords: Compression test, Modulus of elasticity, Processing equipment, Shear test.

INTRODUCTION

Aloe vera, from Liliaceae family, is one of the most important and valuable medicinal plants. Nowadays, due to its medical importance, this plant, which is native to south and eastern coasts of Africa, is being cultivated in several countries throughout the world (Tom, 2004; Mirza *et al.*, 2008). Matter sandwiched between the upper and lower surfaces of the leaf consisting of mesophyll or parenchyma is used in the food health and beauty industries (Antonio *et al.*, 2007; Rodriguez *et al.*, 2006). The main industry utilizing *Aloe vera* is cosmetics production. Due to the increasing demand for *Aloe vera*, determination of its mechanical and rheological properties has been the focus of numerous studies. Identifying the physical and mechanical properties of agricultural products and foodstuffs have always been a field of interest for agricultural and food industry researchers. This data is important in the design and development of different parts of harvesting machines, transportation, storage, and processing practices (Azarang and Ziaodin, 2002). Biological materials form a biomechanical set with a complex structure such that their behavior can't be specified using simple physical constants, as in steels, and the materials' structure reacts to factors, such as temperature (Sitkei, 1986). It has been shown that changes in temperature have significant effects on the mechanical properties of agricultural produce. Examples include carrot (Dobias *et al.*, 2006), apple (Baritelle and Hyde, 2001), potato (Blahovec and Lahodova, 2011), and orange (Katsiferis *et al.*, 2008). Mansoori (2006) examined the effect of loading speed and fruit size on the mechanical

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[DOR: 20.1001.1.16807073.2017.19.4.7.8]

properties of two varieties of date fruit. Results showed that loading speed had no significant effect on the mechanical properties of Zahedi variety. However, the effect of speed on Estameran date variety was significant (Mansoori, 2006). The effect of speed on the shear resistance of different parts of *Aloe vera* leaf's rind was found to be significant (Qudsi Babukani, 2011). Determining the modulus of elasticity of agricultural produce is not often an easy task due to their complex shape and their heterogeneous internal structure. Elastic theories have somewhat solved this problem and several studies have been carried out to determine the modulus of elasticity of various agricultural products on this basis (Mirzaee, 2005). Viscoelastic properties can be considered for agricultural products (Shelef and Mohsenin, 1969). The results of these studies indicated the successful implementation of engineering methods on agricultural products (Khazaee, 2003). Since the compressive loading test is representative of the strength characteristics and mechanical properties of the studied sample, the information obtained from the force-deformation curve could be applied in designing and improving processing machinery, such as those used in the gel extraction process of leaves.

The objective of this study was to consider the effects of loading plunger and speed on leaf resistance and the effect of heating on the compression force required for crushing *Aloe vera* leaves. In addition, the effect of shear force on cutting different edges and the longitudinal fillet of *Aloe vera* leaf for extracting its gel out of the leaves was to be considered so as to develop a gel extraction machine for squeezing the gel out of *Aloe vera* leaves.

MATERIALS AND METHODS

Preparation of Samples

Mature *Aloe vera* leaves (*Aloe succotrina*) were randomly selected and picked from the plants in the greenhouse located at the agriculture campus of Tarbiat Modares University, Tehran. Then, the samples were moved to the laboratory where they were washed and placed in a 20°C bain-marie bath for 15 minutes to reach equilibrium.

Theoretical Principles of Compression Test

One of the most important methods in determining the modulus of elasticity of agricultural produce is the Hertz theory (Arnold and Mohsenin, 1971). This theory, which is suggested for calculating the contact stress of elastic materials, has been applied in four different forms for calculating the modulus of elasticity of agricultural products. In this study the form with two parallel plates was used (Figure 1). Equation (1) was utilized to calculate the whole-leaf modulus of elasticity (Storshine and Hamann, 1994; Mohsenin, 1986),

$$E = \frac{0.388K^{\frac{3}{2}}F(1-\mu^2)}{D^{\frac{3}{2}}}\left[\left(\frac{1}{R_1}+\frac{1}{R_1'}\right)^{\frac{1}{3}}+\left(\frac{1}{R_2}+\frac{1}{R_{21}'}\right)^{\frac{1}{3}}\right]^{\frac{3}{2}} \quad (1)$$

Where, E is the modulus of elasticity of *Aloe vera* leaf in Pascals; F is the compression strength at the yield point on the force-deformation curve in Newtons; the amount of deformation equivalent to force read from the force-deformation curve in

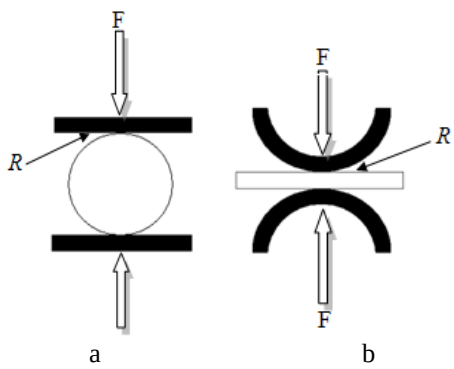


Figure 1. Schematic Hertz theory for calculating modulus of elasticity in case of two parallel plates: (a) Original theory and (b) modified mode (Mohsenin, 1986).

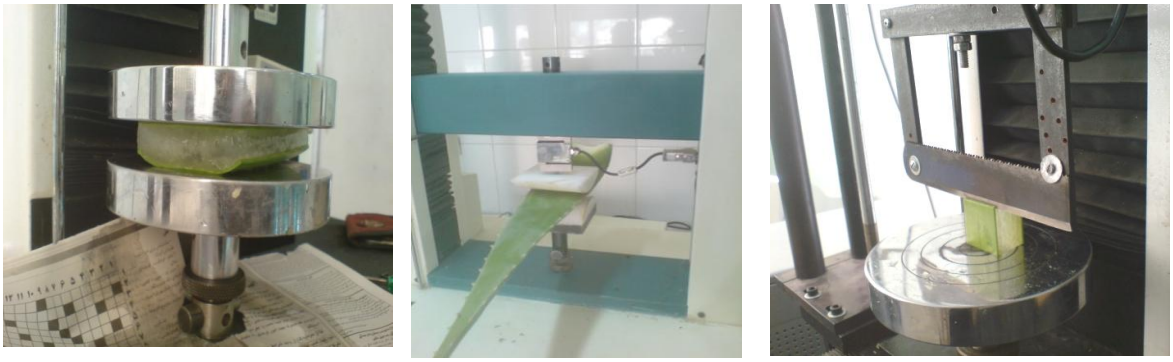
[DOR: 20.1001.1.16807073.2017.19.4.7.8]

millimeter; $R_1$and R_2 are the minimum curvature radii at points of contact with the loading plates in meters; $R'_1$and R'_2 are the maximum curvature radii at points of contact with the loading plate in meters; k is a dimensionless factor which depends on the geometric characteristics of the loading plate (ASAE Standard, 2001), and μ is Poisson's ratio of *Aloe vera* leaves (Warfield *et al.*, 1970).

Compression Test and Shear Force Measurement

Since the loading test usually represents the strength properties of the sample, information obtained from the force-deformation curve could be used in designing and optimizing the parameters involved in processing, packing, and transportation machinery (Afkari Sayyah and Minaei, 2004). In order to measure the compression mechanical properties of *Aloe vera* leaves, a material testing machine (Hounsfield H50K-s model, Britain) with a 50 kN capacity was used. Effects of temperature (20, 40, and 60˚C), loading speed (10, 50, and 100 mm min^{-1}) and loading head diameter (7, 14, and 21 cm) on leaf mechanical strength were studied (Figure 2-a) using a factorial test based on a complete randomized design with eight replications. The obtained data, i.e. modulus of elasticity and yield strength were analyzed using analysis of variance and the means were compared utilizing Duncan's multiple range test. In order to obtain the shear strength between the rind and gel fillet, its corresponding value was measured for the entire leaf width. To do so, a 25 mm long piece was separated from the leaf cross sectional cut (Figure 2-b). It should be noted that the minimum flat surface of the leaf in cross sectional profile was about 25 mm. The test was conducted in three replications at three speed levels, 10, 50, and 100 mm min^{-1}.

In order to measure the shear strength of the edges, the sample was cut 5 mm from the edge as shown in Figure 3-a. As a result, the two surfaces of the leaf diverged and the gel fillet thickness reached 2 mm. If the leaf is cut at known distance, the minimum gel losses can be obtained. To determine the maximum required force to cut the product, 35 mm of the product should be cut (Singh and Reddy, 2006). But this cutting thickness might be insufficient and ineffective in flattening the leaves' surfaces by the compression force. Thus, it increases the probability of losses from the lower and upper rind (as indicated in Figures 2-c and 3) and/or increase non-removed excess rinds on gel fillet, despite decreasing the gel losses from the edges. Thus, according to Figure 3b, in order to ensure the maximum required force for cutting edges, an experiment was conducted to measure the required shear force for cutting the thickest part of the leaf. In most leaves, the thickest part is about 15 to 20 mm. The experiments



(a) (b) (c)

Figure 2. Compression test setup (a and b) and removal of the leaf upper rind (c).

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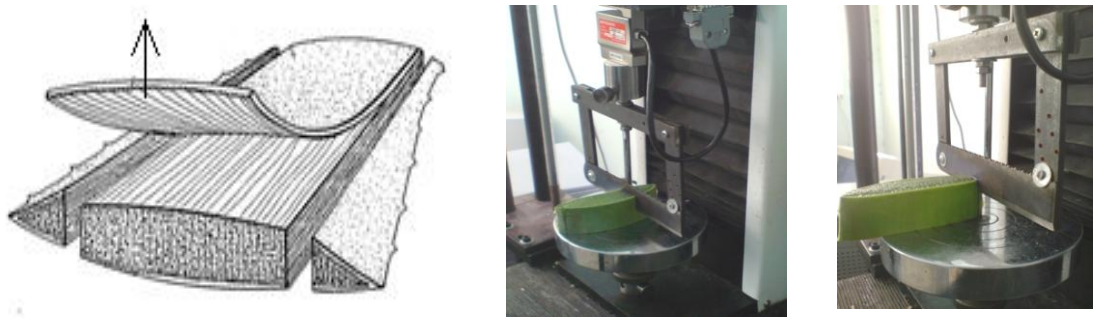

(a) (b) (c)

Figure 3. (a) Lower and upper rind; (b) Sample under edge cutting, (c) Cutting perpendicular to the cross sectional profile of leaf.

related to the edge cuttings were carried out in 4 replications and at three speed levels of 10, 50, and 100 mm min^{-1} (Qudsi Babukani, 2011).

RESULTS AND DISCUSSION

Schematic diagram of the force-deformation curve for *Aloe vera* leaves under compression test (at 20˚C, loading speed of 50 mm min^{-1} and loading head diameter of 21 cm) is presented in Figure 4.

With increasing the compression force up to the yield point, the gel inside the rind is compressed. After yielding of the first part of the leaf width and due to continuous decrease of the distance between the loading jaws, the applied force remains nearly constant. An increase in the engagement area of the loading jaw increases leaf rupture, until this engagement reaches its maximum. Finally, with the full extraction of gel from the leaf, only two rinds remain between the upper and lower jaws of the compression device.

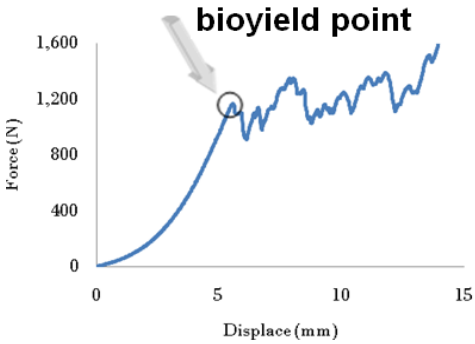

Figure 4. Force-deformation curve obtained from compression test of *Aloe vera* leaf (at 20˚C, speed of 50 mm min^{-1}, and loading head diameter of 21 cm).

Data Analysis

Two experiments were carried out in order to study the properties of *Aloe vera* leaf. The effect of two parameters including the diameter and loading speed on the mechanical properties of *Aloe vera* leaf were studied during the first experiment and the results are presented in Table 1 and Figures 5 and 6. Both diameter and speed had significant effects on all the studied characteristics, at probability level of 1%. This is in line with the results reported by Canet *et al.* (2007). During the second experiment, the effects of diameter and temperature on mechanical properties of *Aloe vera* leaves were studied and the results are presented in Table 2 and Figures 5 and 6. As it can be seen from Table 2, the effect of temperature on modulus of elasticity is significant at 1% probability level. The effects of temperature on the mechanical properties of agricultural products such as carrot (Dobias *et al.*, 2006), potato (Blahovec and Lahodova 2011), and orange (Katsiferis *et al.*, 2008) were reported to be significant, which is in complete accordance with the present study. The interaction effect of the rupture force and temperature was not significant as

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Table 1. Analysis of Variance results for diameter and loading speed on compression mechanical properties of *Aloe vera* leaf (8 replications).

Independent variables	Degrees of freedom	Rupture force (N)	Coefficient of elasticity (Pa)
Diameter	2	10^3×1002**	10^6×1143**
Speed	2	10^3×165**	10^6×466**
Diameter ×Speed	4	10^3×21^{ns}	10^6×13^{ns}
Error	56	10^3×34	10^6×20
CV		21.1	30.42

** Significant at the 1% level, *ns*: Not significant.

Table 2. Analysis of Variance results (mean squares) for compressive mechanical properties of *Aloe vera* leaf (8 replications).

Independent variables	Degrees of freedom	Rupture force (N)	Coefficient of elasticity (Pa)
Diameter	2	10^3×693**	10^6×147**
Temperature	2	10^3×60^{ns}	10^6×459**
Diameter×Temperature	4	10^3×41^{ns}	10^6×156**
Error	56	10^3×23	10^6×3
CV		17.71	24.55

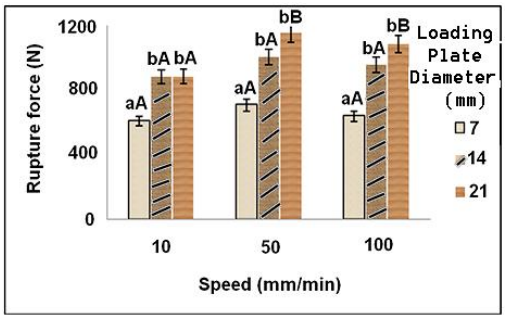

Figure 5. Effect of loading head diameter and speed on the rapture force of *Aloe vera* leaves, at 20°C. Different letters in each column indicate significant differences at 1% probability level (LSD).

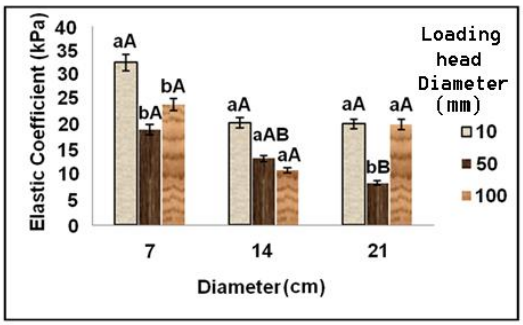

Figure 6. Variation of elasticity coefficient with loading head diameter and speed at 20°C. Different letters in each column indicate significant difference at 1% probability level (LSD).

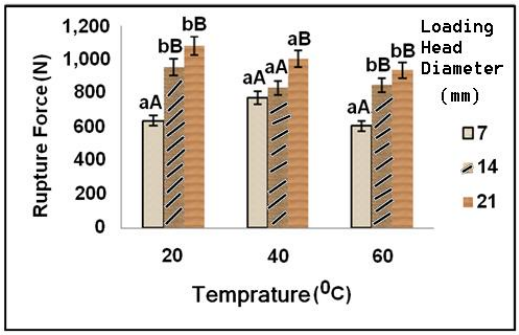

Figure 7. Interaction effect of temperature and loading head diameter on the rapture force of *Aloe vera* leaves at loading speed of 10 mm min^{-1}. Different letters in each column shows significant difference at 1% probability level (LSD).

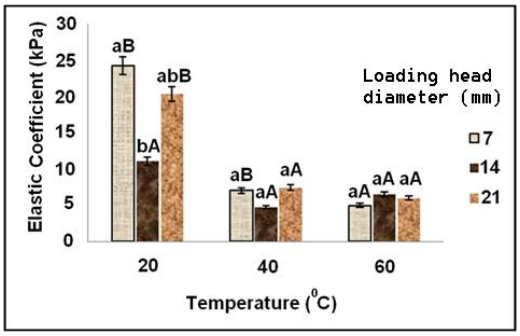

Figure 8. Effects of temperature and loading head diameter on the elastic coefficients at loading speed of 10 mm min^{-1}. Different letters in each column shows significant difference at 1% probability level (LSD).

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studied and reported elsewhere (Baritelle and Hyde, 2001).

Results show that increasing the temperature would decrease the modulus of elasticity. In addition, loading head diameter had a significant effect on the required force for crushing the leaves and extracting the gel. Based on the results, the best loading combination for extracting the gel from *Aloe vera* leaves was 20˚C temperature, speed of 100 mm min^{-1}, and using 14 cm loading head (this combination yielded maximum gel extraction). Increasing the loading speed led to an increase in shear forces in the leaf upper and lower surfaces; however, speed variations had no significant effect on the edge and center shear forces of *Aloe vera* leaves. Also, the shear force was similar at different speeds for edge and center regions as well as for upper and lower surfaces.

Compression Mechanical Properties

The mean comparison of mechanical properties was performed using the Duncan's multiple range tests. Table 3 shows that difference in the required crushing force in all speed levels is significant between the loading factors of 7, 14, and 21 cm diameters. Due to the distribution of compression force over a smaller area, the force required to cause leaf rupture was smaller for 7 cm diameter in comparison with the other diameters. Moreover, there were significant differences between loading speeds at different diameters. As the speed increased to 50 mm min^{-1}, the crushing force increased temporarily. Then, it decreased with further speed increase. The probable reason could be that at very low speeds, the gel has enough time to create a small opening in the rind and exude out through it. However, it was a little lower at speed of 100 mm min^{-1} than 50 mm min^{-1}. This was because of the fact that the gel inside the leaf moved with a high speed and created momentum force, therefore, the leaf could be cracked with a smaller force and, as a result, the gel could be extracted easily.

Modulus of elasticity increases with loading speed (Storshine and Hamann, 1994; Najafi *et al*., 2015). The schematic longitudinal view of how the gelatinous material of *Aloe vera* shift the pressure range to the lower surface of the upper rind is given in Figure 9.

Table 4 presents the mean comparison of variations in temperature. Quasi-static penetration tests on intact apple fruit showed that the force values equivalent to the yielding point increase with temperature. Meanwhile, fruit rigidity is higher at lower temperatures while its resistance against intracellular failure is lower due to lower

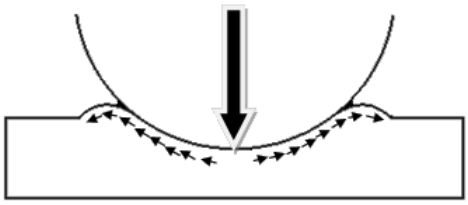

Figure 9. The schematic longitudinal view of how gelatin materials of *Aloe vera* shift the pressure range to the lower surface of the upper rind

Table 3. Comparison of the means of mechanical properties for *Aloe vera* leaves as affected by loading head diameter and speed.[a]

Treatment	Rupture force (N)	Elasticity coefficient (Pa)
7 cm	651b	22585a
14 cm	949a	11680b
21 cm	1042a	9801b
10 mm min^{-1}	792b	19728a
50 mm min^{-1}	956a	12798b
100 mm min^{-1}	894ab	11545b

[a] Different letters (a, b and ab) indicate significant difference at 1% probability level (LSD).

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Table 4. Comparison of the means of mechanical properties for *Aloe vera* leaves as affected by loading head diameter and temperature.

Rupture force (N)	Elastic coefficient (Pa)	Treatment
673c [a]	10291a	7 cm
880b	6575b	14 cm
1009a	5608b	21 cm
893a	12538a	20ºC
870ab	4916b	40ºC
798b	5019b	60ºC

[a] Letters show significant difference

force value. Higher yielding stress at higher temperatures could decrease cell swelling (turgidity) which allows cells to accept deformation (Mohsenin, 1986). The findings of this paper are in line with these results. By increasing temperature from 20 to 40˚C, the modulus of elasticity would decrease dramatically. This phenomenon could be explained by the notion that elasticity increases with temperature and, as a result, the loading head penetrates deeper in the leaf. Considering that there is no significant change in the modulus of elasticity value from 40 to 60˚C, it can be concluded that the increase in temperature had no significant effect on the leaf modulus of elasticity (Karimi Akandi, 2011).

Mechanical Properties of Leaf under Shear Test

Figure 10 shows a force-deformation curve for *Aloe vera* leaves under shear test at loading speed of 50 mm min^{-1}. As shown in this figure, applying the maximum force of the cutting blade to the leaf tears the rind apart and penetrates through it. This force decreases as the dynamic movement of the blade continues.

Figure 11 shows the shear force curve of upper and lower rinds of *Aloe vera* leaf. The shear force curve of edge and center parts of *Aloe vera* leaf is also presented in Figure 12. As shown in Figure 11, increasing the loading speed leads to an increase in shear force. However, according to Figure 12, any increase in the loading speed would decrease the shear force. In cutting the lower and upper surfaces of *Aloe vera* leaves, the continuity boundary is placed between the gel and leaf's rind, which, in this case, according to their physical combination, the gel is getting cut. However, in cutting the edges, the rind is getting cut. The rind's

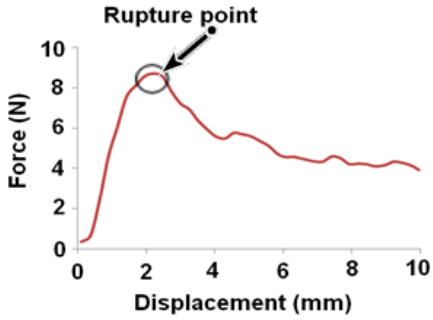

Figure 10. An example of force-displacement curve of *Aloe vera* leaf during shear testing.

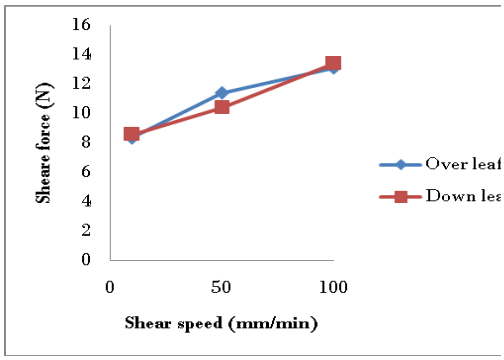

Figure 11. Shear force of upper and lower rinds of *Aloe vera* leaf.

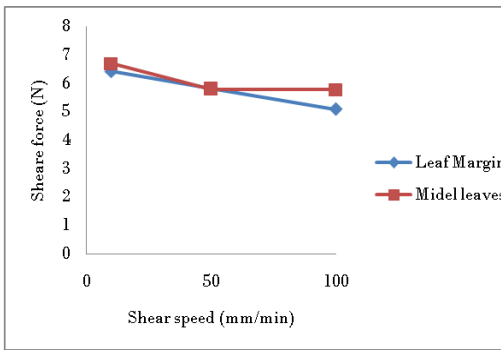

Figure 12. Shear force of edges and center of *Aloe vera* leaf.

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material is more wooden and rigid than the gel fillet; so, as the speed increases, the blade's thickness imposes a torque force to both sides of the rind, thereby decreasing the shear force. However, since the gel is softer, it couldn't transmit the torque force (Qudsi Babukani, 2011). Therefore, increasing the loading speed due to an increase in the force required to break the cellular tissue requires larger amounts of shear force. Since thickness differences do not influence the rind's shear strength (Fidelibus *et al.*, 2002), there is no difference between the shear strength of leaf edge and center.

Results obtained from measuring the crushing force due to contact with cutting edges showed that the amount of this force was 220 N. Thus, three compression forces of 60, 120, and 180 N were applied to evaluate the device at three speed levels of 5, 15, and 25 mm min^{-1} (Qudsi Babukani, 2011).

Development and Testing of *Aloe vera* Gel Extraction Machines

Based on the information obtained from the shear and compression tests, two gel extraction machines were designed and developed for gel extraction from *Aloe vera* leaves: one for extracting intact gel fillet and the other for extracting crushed gel (liquid form). The development process for the two machines is shown in Figure 13.

Experiments were carried out to find the effect of different parameters on the final gel extraction performance. The different components of gel extraction machine are springs, a belt, shaft, cutting edges, etc. (Figures 14 and 15). Schematics as well as photographs of the developed machines are shown in Figure 14 while Figure 15 shows the gel extraction process.

Comparing Machine Method with Manual One

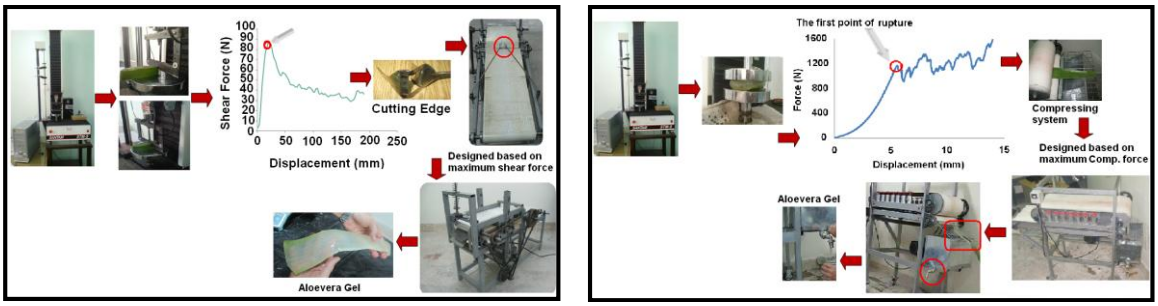
Finally, the results were compared with manual method to evaluate the machine's performance (Figure 16). Summarized results have been presented in Table 5. The efficiency of device in terms of the percentage of gel fillet impurities is calculated using Equation 2 (Shelef and Mohsenin, 1969):

$$\mu(\%) = \frac{A-B}{(A-B)+(C-D)} \times 100 \qquad (2)$$

Where, A is the weight of gel fillet and rind remaining on it; B is the weight of rind remaining on gel fillet; C is the weight of upper, bottom, and side rinds (with gel residue); and D is the weight of upper, bottom, and side rinds (without gel residue).

CONCLUSIONS

The compression and shear properties of *Aloe vera* leaves were investigated to design and fabricate a gel extraction machine. The effect of speed (10, 50, and



(a) (b)

Figure 13. The development process of designing and manufacturing of the *Aloe vera* gel extraction machines (a) Cutting system, and (b) Compressing system, based on leaf mechanical properties.

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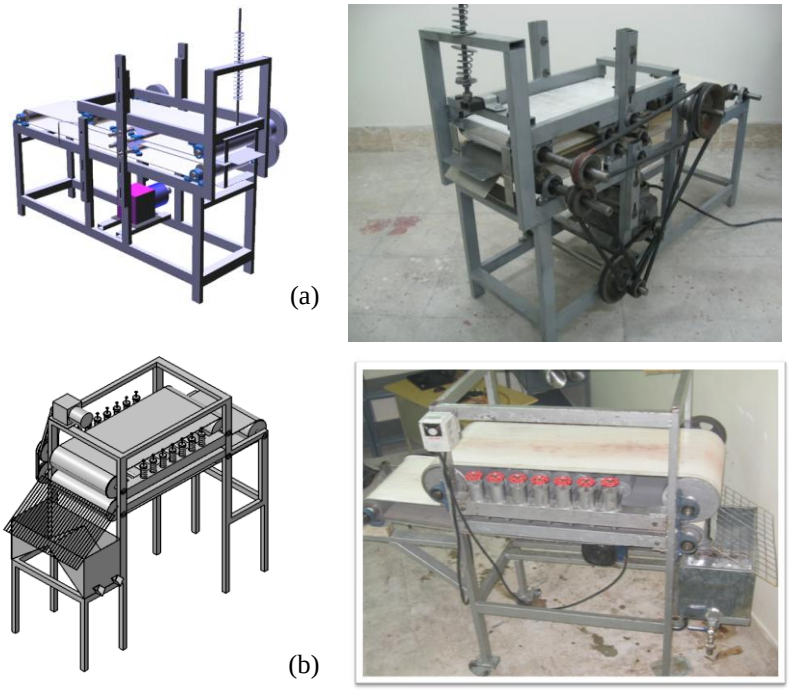

Figure 14. Gel extraction machines including: (a) Cutting system, (b) Compressing system.

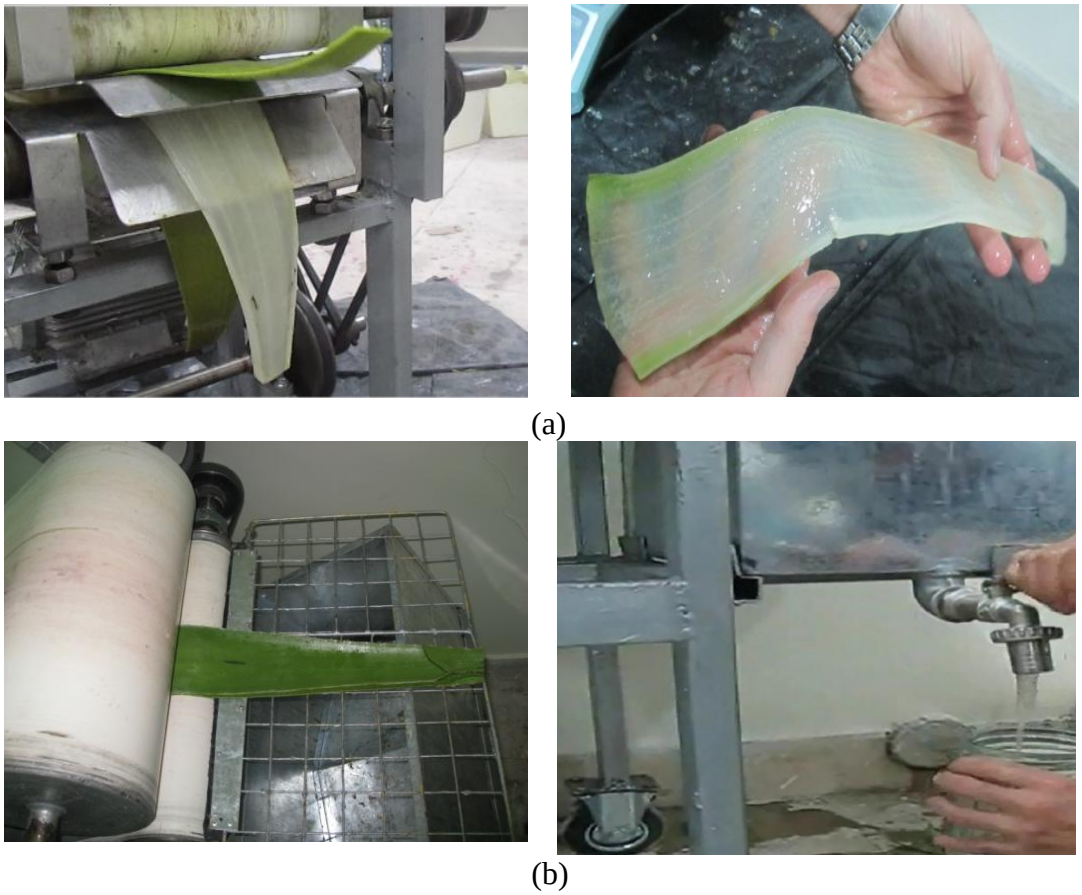

Figure 15. Extracted gel in two forms: (a) Fillet using the cutting machine, (b) Gel by the compression

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(a) (b) (c)

Figure 16. (a) Manual method of extracting the *Aloe vera* gel; (b) Gel fillet by cutting machine, (c) Gel by compressing machine.

Table 5. Comparison of two methods for gel extraction.

Spec.	Compression machine	Cutting machine		Manual method
Speed	40 m/min	15 m/min	5 m/min	
Capacity (Piece of leaf/hour)	2400	900	300	150-200
Efficiency (%)	79	82	89	93

100 mm min^{-1}), temperature (20, 40, and 60˚C), and diameter of the cylindrical loading head (70, 140, and 210 mm) on the leaf mechanical properties, as well as the effect of loading speed (10, 50, and 100 mm min^{-1}) on the shear properties, were examined. Results of statistical analysis showed that increasing the temperature up to 40˚C would decrease the modulus of elasticity, but its increase over this limit has no significant effect. In addition, loading head diameter had a significant effect on the required force for crushing the leaves and extracting the gel. The minimum crushing force was obtained at loading speed of 100 mm min^{-1}, temperature of 20˚C and loading head diameter of 7 cm. The minimum crushing force was 0.5 kN. The shear forces of upper and lower leaf surfaces decreased as the speed increased. Changes in loading speed had no significant effect on the shear force of leaf edges and center. Based on the results, the best combination of parameters for extracting gel from *Aloe vera* leaves was as follows: temperature of 20˚C, speed of 100 mm min^{-1}, and loading head diameter of 14 cm. Increasing speed led to an increase in shear forces of upper and lower surfaces of leaves. However, speed variations had no effect on the leaf edge and center shear forces. Moreover, the shear force was similar at different speeds for leaf edge and center regions as well as for upper and lower surfaces. Two gel extraction machines were designed and fabricated based on the mechanical properties (shear and compression properties) of *Aloe vera* Leaves. The efficiency of the leaf cutting machine was between 82-89% with a maximum capacity of 900 leaves hour^{-1}, while the efficiency of the compression machine was around 79% with the maximum capacity of 2,400 leaves hour^{-1}.

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[DOR: 20.1001.1.16807073.2017.19.4.7.8]

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خواص مکانیکی برگ صبر زرد به منظور طراحی دستگاه استخراج ژل

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چکیده

در این مطالعه خواص فشاری و برشی برگ صبر زرد مورد بررسی قرار گرفت. این خواص برای کاهش ضایعات و افزایش ظرفیت کاری خطوط فرآوری برگ صبر زرد مورد نیاز می‌باشد. اثر پارامترهای سرعت با سه سطح 10 mm/min، 50 و 100 و دما با سه سطح 20 ^{o}C، 40 و 60 و سه اندازه فک لهنده استوانه‌ای ساخته شده با اقطار 7 cm، 14 و 21 بر روی خواص مکانیکی فشاری و اثر پارامتر سرعت با سه سطح 10 mm/min، 50 و 100 بر روی خواص مکانیکی برشی بررسی گردید. نتایج نشان داد با افزایش دما ضریب کشسانی کاهش یافت. همچنین اقطار مختلف فک‌ها بر روی نیروی مورد نیاز برای لهیدن برگ و استخراج ژل اثر معنی‌داری داشت. بر اساس نتایج، بهترین ترکیب بارگذاری برای استخراج ژل برگ صبر زرد عبارتند از: دمای 20 ^{o}C، سرعت 100 mm/min و فک با قطر 7 cm. با افزایش سرعت نیروی برشی سطح رویی و زیری برگ افزایش یافت ولی تغییر سرعت بر نیروی برشی حاشیه و وسط برگ تاثیری ندارد. همچنین نیروی برشی در سرعت‌های مختلف برای حاشیه و وسط برگ و نیز برای سطوح رویی و زیری برگ یکسان بدست آمد. همچنین دو دستگاه استخراج ژل آلوئه ورا بر اساس خواص فشاری و برشی طراحی و ساخته شدند.

[DOR: 20.1001.1.16807073.2017.19.4.7.8]