Effects of Temperature and Loading Characteristics on Mechanical and Stress Relaxation Properties of Sea Buckthorn Berries. Part 2. Puncture Tests.

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ABSTRACT

Puncture force and energy were measured at different loading velocities and probe diameters for two cultivars of sea buckthorn berries of various sizes at several ambient temperatures. In addition to the puncture properties, the firmness-temperature coefficient, the compression coefficient (K_c), shear coefficient (K_s), and the apparent modulus of elasticity were determined. The tests showed that the Sinensis cultivar was generally firmer than the Indian Summer cultivar. With an increase in the berry temperature, the puncture force and energy decreased significantly. The sea buckthorn berry showed a negative firmness-temperature coefficient (FT) which ranged between –0.362 and -0.627% per degree. The puncture force and energy for the large berries of the Sinensis cultivar was significantly higher than that for the small berries. With an increase in loading velocity from 0.3 to 9 mm/s, the puncture force and energy increased significantly. Puncture force and energy also increased as probe diameter increased. As expected, puncture force and energy decreased as storage time increased to 14 d. The mean values obtained for K_c and K_s ranged from –1.079 to -1.575 N/mm^2 and from 0.657 to 0.817N/mm, respectively. The apparent modulus of elasticity of the sea buckthorn berries ranged between 0.24 and 1.25 MPa.

Keywords: Sea buckthorn, firmness, firmness-temperature coefficient, compression coefficient, shear coefficient, modulus of elasticity, puncture properties

Introduction

With the development of mechanical harvesting equipment for the sea buckthorn berry, handling and processing systems should also be considered. New equipment and procedures must be evaluated in relation to their bruising effects and be improved to retain as much of the original firmness of the berries as possible. The development of satisfactory harvesting and processing methods are greatly influenced by the physical and mechanical properties of the product.

Mechanical properties of agricultural products are most conveniently measured with the force-deformation curve. From this curve, a number of mechanical properties can be determined such as maximum force to rupture or puncture, energy, stiffness, and deformation. Three methods have been used to obtain such force-deformation curves (Fischer et al. 1969): i) the compression of fruit by a large flat plate (plate test), ii) the compression of the product by a small flat cylindrical die (plunger test), and iii) the compression of a sample of product cut to uniform size.

Puncture testing is one of the simplest and most widely used methods for objective measurement of the firmness of many food products, including fruit skins (Jackman and Stanley 1994; Holt 1970; Voisey et al. 1970; Bourne 1966). The maximum force required for penetrating the skin is defined as the puncture force. The puncture energy is considered a measure of the resistance of the fruit to mechanical injuries due to tearing and puncturing forces. The results obtained from puncture tests are influenced by probe diameter, loading velocity, cultivar (Holt 1970), stage of maturity, fruit size (Ourecky and Bourne 1968), temperature, and turgid pressure for juicy fruits (Lustig and Bernstein 1987).

The maximum force required to puncture has been considered equal to the sum of compression and shear forces. The compression force should be proportional to the area under the punch and to the compression strength of the food (Bourne 1966). The shear force should be proportional to the perimeter of the punch and to the shear strength of the food (Bourne 1966). Force required to puncture is (Bourne 1966; Jackman and Stanley 1994):

$$F = K_c A + K_s P + C \qquad (1)$$

where: F = puncture force, N
K_c = compression coefficient, N/cm^2
A = area under the punch, cm^2
K_s = shear coefficient, N/cm
P = perimeter of the punch, cm
C = constant, N

In the special case of a punch that is circular in cross-section with diameter D (cm), the puncture force (F) can be written as (Bourne 1966):

$$F = \frac{\pi}{4} K_c D^2 + \pi K_s D + C \qquad (2)$$

If the compression and shear coefficients for a commodity are known, Eq. 2 can be used to calculate the puncture force that will be obtained with a punch of any area and perimeter. Equation 2 can also be used to calculate the puncture force that will be obtained if the punch size is altered.

It has been recognized that the temperature of the commodity at the time of testing affects the firmness (Bourne 1982; Ballinger et al. 1973; Patten and Patterson 1985). Bourne (1982) established a firmness-temperature coefficient (FT) for several commodities using quasi-static firmness measurements. The firmness-temperature coefficient (FT) is defined as the "percentage change in firmness per degree temperature increased" and is written as:

$$\mathrm{FT} = \left[\frac{\text{Firmness at } T_2 - \text{Firmness at } T_1}{\text{Firmness at } T_1 \text{ x} \left(T_2 - T_1\right)} \right] \text{x } 100\% \quad (\text{Degree}^{-1}) \tag{3}$$

where: T_1 = lowest temperature at which the firmness was measured, °C
T_2 = highest temperature at which the firmness was measured, °C.

Bourne (1982) found that most commodities showed a slight linear softening (negative FT) with increasing temperature.

Another important mechanical property of agricultural materials is their modulus of elasticity. Different methods have been employed for the assessment of the modulus of elasticity (Fridley et al. 1968; Timbers et al. 1965; Shelef and Mohsenin 1967). Fridley et al. (1968) and Timbers et al. (1965) used the following relationship (with the plunger test) to obtain the modulus of elasticity of some fruits and vegetables:

$$E = \frac{P(1-\upsilon^2)}{2\,a\,F_d} \tag{4}$$

where: E = modulus of elasticity, Pa
P = maximum force, N
υ = Poisson' ratio
a = plunger radius, mm
F_d = fruit deformation, mm

The objectives of this study were to determine the following properties (using the plunger test) for sea buckthorn berries: i) the puncture force (or firmness) and puncture energy as affected by berry temperature, probe diameter, loading velocity, and storage time; ii) the firmness-temperature coefficient, compression coefficient, and shear coefficient; and iii) the apparent modulus of elasticity as affected by temperature and probe diameter.

MATERIALS and METHODS

Sea buckthorn berries of the cultivars Indian Summer and Sinensis were used in this study. Physical characteristics of the berries are described in Part 1 of this series (Khazaei and Mann 2004). Berries were refrigerated at 6.5°C from the time of harvesting until the time of testing. Indian Summer berries ranged from 7.6 to 8.1 mm (intermediate diameter). “Small” Sinensis berries ranged from 6.8 to 7.2 mm (intermediate diameter) and “large” Sinensis berries ranged from 7.9 to 8.4 mm (intermediate diameter).

The puncture test was used to evaluate the puncture force (firmness) and puncture energy of sea buckthorn berries. For each test, a single berry was placed on its cheek on a flat steel washer beneath the center of the probe. A normal force of 0.04 N was imposed on the berry to establish contact. The berry was then compressed by the probe at a constant loading velocity. A force-deformation curve, as shown in Fig. 1, was obtained for each berry. The first maximum force was defined as the puncture force. The tests were completed using a texture testing machine equipped with a 250 N load cell and having a precision of 0.001 N. The mechanical energy required to puncture the berry (hereafter referred to as puncture energy) was calculated from the area under the force-deformation curve.

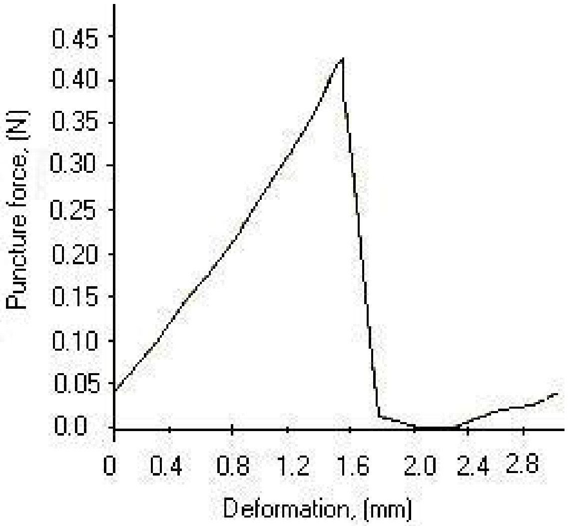


Fig.1 Sample force-deformation curve obtained from a puncture test at a loading velocity of 0.3 mm/s.

Three sets of puncture tests were completed. In the first set, the effect of berry temperature and probe diameter on puncture force and energy was tested. For the Indian Summer cultivar, temperatures of 4.5, 16.5, 25, and 34.5°C and probe diameters of 0.5 and 1.0 mm were used. For the Sinensis cultivar, temperatures of 4.5, 16.5, 25, and 34.5°C and probe diameters of 0.3, 0.5, and 0.67 mm were used. Probe speed was constant at 0.3 mm/s. A randomized full factorial experimental design was used for each of the two cultivars.

Berry temperature was modified by immersing the berries in water baths of 4.5, 16.5, 25, and 34.5°C for 15-20 min. Individual berries were removed, drained, and immediately punched. Each combination of temperature and probe diameter was replicated 25 times. A firmness-temperature coefficient (FT) was used to define the percentage change in puncture force per degree of temperature increase.

Using these results, the compression and shear coefficients (K_c and K_s) for the sea buckthorn berry were determined. According to Bourne (1975;1966), by plotting the ratio of puncture force to probe perimeter versus probe diameter and the ratio of puncture force to probe area versus the reciprocal of probe diameter for probes of different diameter, estimates of K_c and K_s may be obtained from the slopes and intercepts of the resulting curves.

The modulus of elasticity of the sea buckthorn berry was obtained by application of the theory of elasticity to a plunger-type test. While the berry was compressed to 0.1 of its original diameter, the maximum force and deformation were recorded and used to calculate the modulus of elasticity using Eq. 4.

In the second set of puncture tests, the effect of loading velocity on puncture force and energy was studied. Tests were conducted using loading velocities of 0.3, 1.5, 3.5, 6, and 9 mm/s at a constant berry temperature of 16.5°C. With each of the five loading velocities, puncture tests were completed using probes of 0.5 and 1.0 mm diameter for Indian Summer berries and probes of 0.3, 0.5, and 0.67 mm diameter for Sinensis berries. Each combination of loading velocity and probe diameter was replicated 25 times.

Finally, the third set of puncture tests was used to study the effect of storage time on puncture force and energy. Berries stored in a refrigerator at 6.5°C were tested at 2 to 3 d intervals for a duration of 14 d. Tests were completed only for the Indian Summer cultivar using a 0.5 mm diameter probe and a loading velocity of 0.3 mm/s. Prior to the test and after a berry was taken out of the refrigerator, it was immersed in a water bath of 16.5°C for about 15 min, then immediately punched.

RESULTS and DISCUSSION

Effect of berry temperature and probe diameter on puncture force and energy

Comparison of the puncture force of the two cultivars for the 0.5 mm diameter probe showed that the Sinensis cultivar was firmer than the Indian Summer cultivar (Table 1). The puncture force of the small Sinensis berries at 4.5, 16.5, 25, and 34.5°C was 2.4, 2.2, 2.1, and 2.3 times higher, respectively, than those of the Indian Summer cultivar. A similar trend was observed for puncture energy (Table 2). Meanwhile, a comparison between small and large berries of the Sinensis cultivar showed that the puncture force of the large berries was higher than that for the small berries (Table 1). This difference was greater for puncture energy (Table 2).

Table 1. Effect of temperature and probe diameter on puncture force (N x 10^{-2}) for sea buckthorn berries.

Cultivar	Probe diameter (mm)	Berry temperature (°C)				Average	*FT* (% per degree)
		4.5	16.5	25	34.5		
Indian Summer	0.5	38.4 (7.4)[+]	38.2 (5.1)	35.8 (6.9)	33.0 (6.6)	36.3	-0.468
	1.0	75.4 (14)	74.0 (10)	69.5 (17)	67.2 (14)	71.5	-0.362
	Average*	56.9 a	56.1a	52.7 ab	50.1 b		
Sinensis Small berries	0.3	59.7 (10.3)	54.3 (6.2)	53.4 (8.4)	50.8 (8.6)	54.6	-0.496
	0.5	92.9 (18)	83.6 (17)	76.6 (14)	75.4 (9.5)	82.2	-0.627
	0.67	100.5 (15)	95.9 (14)	88.6 (18)	82.8 (15)	92.0	-0.587
	Average	84.4 a	78.0 b	72.9 bc	69.7 c		
Sinensis Large Berries	0.3	-	68.9 (12.1)	-	-	68.9	-
	0.5	-	109.3 (17.8)	-	-	109.3	-
	0.67	-	133.2 (27.6)	-	-	133.2	-
	Average		103.8 a				

* In each row, averages with the same letter have no significant difference at the 1% level.

+ Standard deviation

Both puncture force and energy tended to decrease as the temperature increased, however, many of the differences were not significant (Tables 1 and 2). The effect of temperature on puncture force was higher for the Sinensis cultivar. For the small Sinensis berries, the average puncture force decreased 17.4% with an increase in berry temperature from 4.5 to 34.5°C. For the Indian Summer cultivar, the average puncture force decreased 11.9%. The effect of temperature on puncture energy for the Indian Summer cultivar was not significant at the 1% level, but the puncture energy for Sinensis was significantly higher at 4.5°C (Table 2).

Table 2. Effect of temperature and probe diameter on puncture energy (N· mm) x 10^{-2} for sea buckthorn berries.

Cultivar	Probe diameter (mm)	Berry temperature (°C)				Average
		4.5	16.5	25	34.5	
Indian Summer	0.5	24.2 (6.7)+	26.7 (4.5)	25.3 (5.5)	21.0 (4.1)	24.3
	1.0	67.4 (13)	68.4 (12)	70.7 (19)	65.6 (12)	68.0
	Average*	45.8 a	47.5 a	48.0 a	43.3 a	
Sinensis Small berries	0.3	33.4 (7.6)	27.4 (6.1)	28.1 (6.8)	27.8 (6.8)	29.2
	0.5	57.1 (13)	53.2 (11)	48.1 (7.9)	46.3 (8.9)	51.2
	0.67	70.0 (18)	65.4 (13)	63.2 (19)	57.4 (14)	64.0
	Average	53.5 a	48.7 ab	46.5 b	43.8 b	
Sinensis Large berries	0.3	-	56.4 (13.5)	-	-	56.4
	0.5	-	101.8 (25.8)	-	-	101.8
	0.67	-	135.9 (30.4)	-	-	135.9
	Average		98.0 a			

* In each row, averages with the same letter have no significant difference at the 1% level.
+ Standard deviation

Puncture energy is a function of two parameters; puncture force and berry deformation, which change with increasing berry temperature. It was just shown that puncture force decreases with temperature. On the other hand, berry deformation has an increasing trend with temperature up to a threshold temperature. Beyond this threshold temperature, berry deformation decreases because skin strength decreases. These variations of the force and deformation of the berry influenced the puncture energy (Table 2).

Table 1 shows that the sea buckthorn berry has a negative firmness-temperature coefficient (FT) because increasing the berry temperature had a decreasing effect on puncture force. Bourne (1982) reported that the firmness-temperature coefficient varied from commodity to commodity, from cultivar to cultivar, and from year to year. He expressed that most fruit had a negative FT coefficient between -0.1% and -1% per degree. The values obtained for FT coefficient in this experiment fall within the same range.

With these data, it is possible to predict the amount of puncture force at any temperature between 4.5 and 34.5°C. For example, if the puncture force for the Indian Summer cultivar at a temperature of 4.5°C is known, the puncture force at a temperature of 30°C for a probe of 0.5 mm is predicted to be 33.8×10^{-2} N using Eq. 3. The higher FT coefficient for the small Sinensis berries shows that these berries are more sensitive to temperature than the Indian Summer berries.

Probe diameter had more effect on puncture force and energy than temperature (Tables 1 and 2). For the Indian Summer cultivar, increasing the probe diameter from 0.5 to 1.0 mm increased the mean puncture force and energy 2.0 and 2.8 times, respectively. For the small Sinensis berries, increasing the probe diameter from 0.3 to 0.67 mm increased the puncture force and energy 1.7 and 2.2 times, respectively. Corresponding values for the large Sinensis berries were 1.9 and 2.4 times, respectively.

Representative plots of the data for the small Sinensis berries are shown in Figs. 2 and 3. Similar plots were obtained for the large Sinensis berries. The good agreement of the experimental data with Eq. 2 establishes the validity of this equation in describing the forces involved in a puncture test. If Eq. 2 is correct, a plot of F/A versus 1/D should be rectilinear if C is small, with slope $4K_s$ and intercept on the ordinate of $K_c+4C/\pi D^2$. Also, a plot of F/P versus D should be rectilinear if C is small, with slope $K_c/4$ and intercept on the ordinate of $K_s = C/\pi D$.

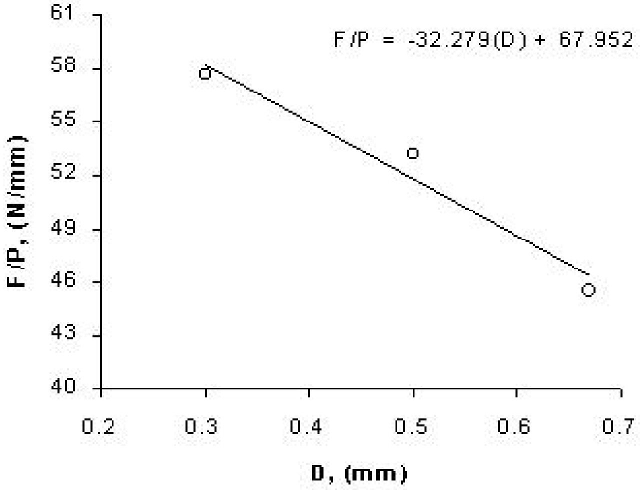


Fig. 2. The ratio of puncture force/probe perimeter versus probe diameter for small berries of the Sinensis cultivar at 16.5°C.

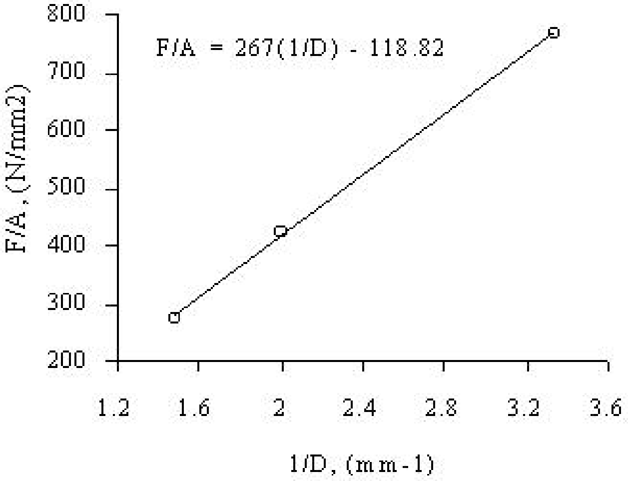


Fig. 3. The ratio puncture force/probe area versus the reciprocal of probe diameter for small berries of the Sinensis cultivar at 16.5°C.

From Table 3, the sea buckthorn berry had a negative compression coefficient. The positive or negative value of K_s and K_c depends on the mechanical properties of the products. For instance, Bourne (1966), reported a negative value for K_s in a puncture test of carrot. In this research**,** because small-diameter probes were used, the resistance to compression of the berry was too small to be detected. Therefore, K_cD^2 (in Eq. 2) showed a negative effect on the puncture force. Thus it can be assumed that the total puncture force was equal to the force required to shear the skin which depends on the tensile and shear strength of the skin. As temperature increases, K_s decreases showing that the shear and tensile strength of the skin decreased as temperature increased. The mean value of K_s and K_c for the large Sinensis berries at 16.5°C was 21.4% and 12.9% higher, respectively, than that for the small Sinensis berries.

Table 3. Values of K_s (N/mm) and K_c (N/mm^2) coefficients for sea buckthorn berries of the Sinensis cultivar.

Cultivar	Berry temperature (°C)	K_c (N/mm^2) Intercept F/A vs. 1/D	K_c (N/mm^2) 4×(Slope F/P vs. D)	K_c (N/mm^2) Mean value	K_s (N/mm) $\frac{1}{4}$×(Slope F/A vs. 1/D)	K_s (N/mm) Intercept F/P vs. D	K_s (N/mm) Mean value
Sinensis Small berries	4.5	-1.460	-1.664	-1.562	0.747	0.771	0.759
	16.5	-1.188	-1.291	-1.239	0.667	0.679	0.673
	25	-1.575	-1.574	-1.575	0.684	0.684	0.684
	34.5	-1.467	-1.562	-1.515	0.651	0.662	0.657
Sinensis Large berries	16.5	-1.034	-1.124	-1.079	0.812	0.822	0.817

Effect of loading velocity on puncture force and energy

The force-deformation curve had a different form depending on the loading velocity. As illustrated in Fig. 4, the force-deformation curve showed a small initial peak at loading velocities above 3.5 mm/s. Based on Hertz's theory, it may be due to failure caused by excessive internal shear stresses which could detach the skin and internal layer of the fruit.

Analysis of variance (ANOVA) showed that the loading velocity had a significant effect on puncture force and energy for the two cultivars (p=0.01), except for the puncture force of the small Sinensis berries (Tables 4 and 5).

For most tests, an increase in the loading velocity from 0.3 to 6.0 mm/s increased the puncture force and energy of sea buckthorn berries. There was a decrease in puncture force and energy for a loading velocity of 9 mm/s, except for the large Sinensis berries (Tables 4 and 5). For the large Sinensis berries, loading velocity showed a continuous increasing trend on puncture force and energy. With increasing the loading velocity from 0.3 to 9 mm/s, the mean puncture force for the Indian Summer, small Sinesis, and large Sinensis berries increased 26, 3.9 and 12.8%, respectively. Corresponding values for puncture energy were 28, 12.7 and 24%, respectively.

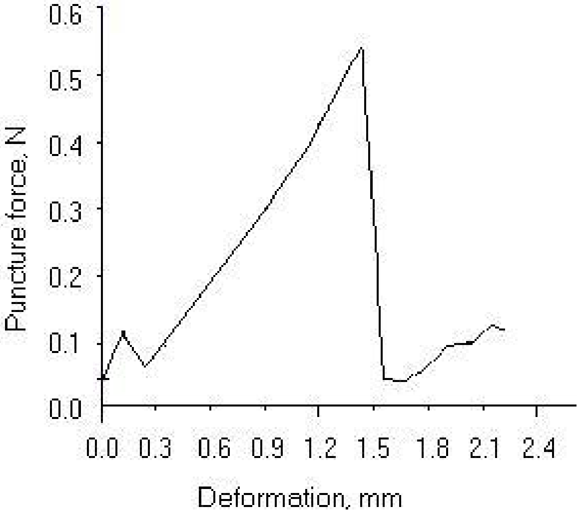


Fig. 4. A typical puncture force-deformation curve for a sea buckthorn berry at loading velocities above 3.5 mm/s.

Table 4. Effect of loading velocity on puncture force (N x 10^{-2}) of sea buckthorn berry.

Cultivar	Probe diameter (mm)	Loading velocity (mm/s)					
		0.3	1.5	3.5	6	9	Average
Indian Summer	0.5	38.2 (5.1)$^{+}$	38.9 (8.1)	43.3 (7.4)	51.4 (7.6)	49.7 (7.7)	44.3
	1.0	74.0 (10)	86.7 (16)	97.2 (15)	93.7 (13)	91.8 (13)	88.7
	Average*	56.1 c	62.8 b	70.3 a	72.6 a	70.8 a	
Sinensis Small berries	0.3	54.3 (6.2)	54.9 (9.5)	56.3 (13)	64.1 (9.8)	53.1 (12)	56.5
	0.5	83.6 (17)	87.1 (19)	93.1 (20)	88.0 (19)	90.2 (16)	88.4
	Average	69.0a	71.0 a	74.7 a	76.1 a	71.7 a	
Sinensis Large berries	0.3	69.0 (12.0)	64.7 (12.1)	68.8 (13)	72.8 (16.6)	76.4 (13.5)	70.5
	0.5	109.3 (17.8)	114.1 (19.4)	116 (20.1)	116.6 (19.8)	123.5 (23.8)	115.9
	Average	89.1 b	89.4 b	92.4 ab	94.7 ab	100.5 a	

* In each row, averages with the same letter have no significant difference at the 1% level.
\+ Standard deviation

Table 5. Effect of loading velocity on puncture energy (N·mm)x10^{-2} of sea buckthorn berry.

Cultivar	Probe diameter (mm)	Loading velocity (mm/s)					
		0.3	1.5	3.5	6	9	Average
Indian Summer	0.5	26.7 (4.5)	24.7 (6.6)	31.3 (6.0)	36.5 (6.9)	34.7 (6.6)	30.8
	1.0	68.4 (12)	90.4 (16)	103.4 (19)	91.0 (15)	87.4 (17)	88.1
	Average*	47.6 c	57.6 b	67.4 a	63.8 ab	61.1 ab	
Sinensis Small berries	0.3	27.4 (6.1)	29.6 (5.7)	31.4 (6.8)	33.8 (5.2)	30.7 (5.4)	30.6
	0.5	53.2 (11)	60.4 (12)	64.5 (16)	59.5 (15)	60.1 (9.9)	59.6
	Average	40.3 b	45.0 ab	48.0 a	46.7 a	45.4 ab	
Sinensis Large berries	0.3	56.4 (13.5)	54.7 (13.2)	54.7 (13.4)	55.0 (12.9)	57.4 (13.5)	55.8
	0.5	101.8 (25.8)	114.3 (29.1)	118 (25)	118.4 (21.8)	138.5 (27.8)	118.2
	Average	79.1 b	84.5 b	86.4 b	86.7 b	98.2 a	

* In each row, averages with the same letter have no significant difference at the 1% level.
\+ Standard deviation

Again, the difference between the two cultivars is clear. For a probe of 0.5 mm in diameter, the puncture force of the small Sinensis berries at loading velocities of 0.3, 1.5, 3.5, 6, and 9 mm/s were 22.9, 13, 6.2, 4.8, and 1.3% higher, respectively, than those for the Indian Summer berries (Table 4). Meanwhile the average puncture force of the large Sinensis berries at loading velocities of 0.3, 1.5, 3.5, 6, and 9 mm/s were 58.8, 42.3, 31.4, 30.4, and 42% higher, respectively, than those for the Indian Summer berries. Similar trends existed for puncture energy (Table 5).

Comparison of the results shows that the small and large Sinensis berries had a different behavior under loading, especially at higher velocities. Meanwhile, the mean puncture forces for the large berries at 0.3, 1.5, 3.5, 6 and 9 mm/s were 29.1, 25.9, 23.7, 24.4, and 40.2% higher, respectively, than those for the small berries. Corresponding values for puncture energies were 96.3, 87.7, 80.0, 86, and 116.2% higher, respectively.

Effect of storage time on puncture force and energy

Storage time showed a significant effect on puncture force and energy. As storage time increased, both puncture force and energy decreased (Fig. 5). With an increase in the storage time from 3 to 6, 9, 11, 12, and 14 d, the puncture force decreased 7.5, 26.3, 28.9, 34.8, and 32.2%, respectively, for Indian Summer berries. The corresponding values for the puncture energy were 13, 33, 35.3, 47, and 45.6%.

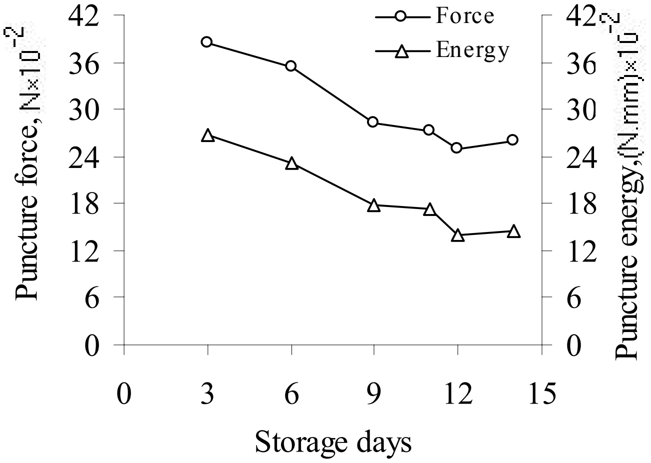


Fig. 5. Effect of storage time on puncture force and energy for the Indian Summer cultivar. Temperature of 16.5°C, probe diameter of 0.5 mm, and loading velocity of 0.3 mm/s.

Modulus of elasticity of the berries

To use Hertz's theory to calculate the modulus of elasticity (Eq. 4), it is necessary to have a value for Poisson's ratio. Since the value of this factor for a sea buckthorn berry was not available, a value of 0.5 was used based on the fact that Poisson's ratio for most fruits and vegetables varies between 0.45 and 0.5 (Timbers et al. 1965; Finney and Hall 1967). To determine the modulus of elasticity, it was necessary to use a low loading velocity. As indicated previously, when the velocity was higher than 3.5 mm/s, the force deformation curve had an initial peak (Fig. 4) which made it difficult to calculate the modulus of elasticity.

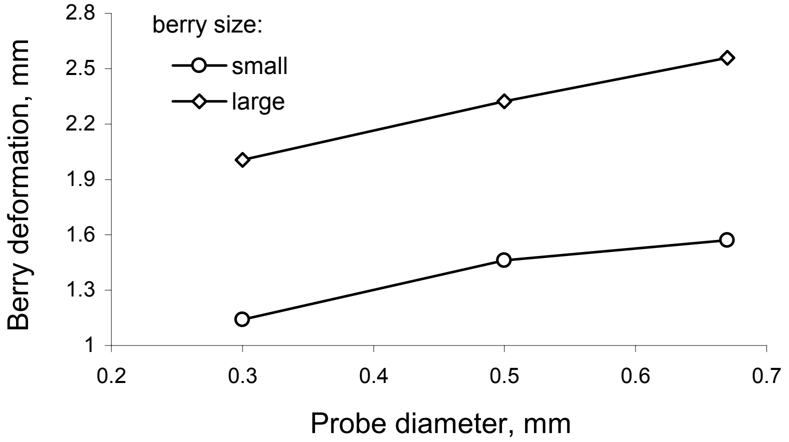
There was a significant difference in the moduli of elasticity calculated for different probes. As probe diameter increased, the modulus of elasticity decreased significantly. The inconsistent results may be attributed to the fact that the fundamental assumptions such as elasticity, homogeneity, and being a semi-infinite body were not met (Shelef and Mohsenin 1967). For the semi-infinite body assumption, the diameter of the probe must be small compared with the diameter of the fruit. In the original work by Hertz, the ratio of the circle of pressure to the radius of the spherical body under load was considered less than 1/10 (Shelef and Mohsenin 1967). Thus, a probe diameter of 0.5 and 0.3 mm was the best selection for the Indian Summer and Sinensis cultivars, respectively. Under these conditions the berries can be considered to be semi-infinite bodies. Also, it must be accepted that the assumption of homogeneity for a sea buckthorn berry is not true. Thus, one cannot speak of a true modulus of elasticity for a sea buckthorn berry. The modulus calculated according to Eq. 4 can, at best, be termed the apparent modulus of elasticity.

Modulus of elasticity of the sea buckthorn berry decreased with increasing berry temperature, however, many of the differences were not significant (Table 6). The Sinensis cultivar had a higher modulus of elasticity than the Indian Summer cultivar. For the 0.5 mm diameter probe, the mean modulus of elasticity of the small Sinensis berries was double the modulus of elasticity of the Indian Summer cultivar.

The results showed that there was a signifficant difference between modulus of elasticity of the large and small Sinensis berries at 16.5 ^{o}C. The mean modulus of elasticity for the small Sinensis berries was 1.2 times than that for the large Sinensis berries. Based on Eq. 4, the modulus of elasticity is a function of puncture force and berry deformation. The large berries had a higher puncture force than the small berries, but based on Fig. 6, they also had a higher deformation than the small berries.

Table 6. Effect of temperature and probe diameter on apparent modulus of elasticity (MPa) of the sea buckthorn berry.

Cultivar	Probe diameter (mm)	Berry temperature (°C)				Average*
		4.5	16.5	25	34.5	
Indian Summer	0.5	0.45	0.40	0.38	0.38	0.40 f
	1.0	0.27	0.27	0.24	0.24	0.25 g
	Average**	0.36 a	0.34 a	0.31 a	0.31 a	
Sinensis Small berries	0.3	1.25	1.24	1.16	1.09	1.19 a
	0.5	0.93	0.87	0.78	0.78	0.84 c
	0.67	0.72	0.67	0.60	0.56	0.64 ed
	Average	0.97 a	0.93 ab	0.85 ab	0.81 b	
Sinensis Large berries	0.3	-	0.94	-	-	0.94 b
	0.5	-	0.74	-	-	0.74 d
	0.67	-	0.61	-	-	0.61 e
	Average		0.76			



* In average column, data that have a similar letters have no significant difference at 1% level.
** In each average row, data that have a similar letters have no significant difference at 1% level.

Fig. 6. Effect of probe diameter on berry deformation for small and large Sinensis berries at 16.5 ^{o}C.

CONCLUSIONS

From this study, the following conclusions were drawn for sea buckthorn berries:

- as berry temperature increased, both puncture force and energy decreased; yielding a negative firmness-temperature coefficient
- as probe diameter increased, both puncture force and energy increased
- as loading velocity increased, both puncture force and energy increased
- as storage time increased, both puncture force and energy decreased
- for the Sinensis cultivar, both puncture force and energy increased as berry size increased
- overall, the Sinensis cultivar was firmer than the Indian Summer cultivar
- the sea buckthorn berry had a negative compression coefficient and a positive shear coefficient
- the apparent modulus of elasticity decreased with increasing berry temperature
- for the Sinensis cultivar, apparent modulus of elasticity decreased as berry size increased
- overall, the Sinensis cultivar had a higher apparent modulus of elasticity than the Indian Summer cultivar

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