

Determination of the physical and mechanical properties of a potato (the Agria variety) in order to mechanise the harvesting and post-harvesting operations

NEGAR AHANGARNEZHAD^{1*}, GHOLAMHASSAN NAJAFI¹, AHMAD JAHANBAKHSHI²

¹Department of Mechanic Engineering of Biosystems, Faculty of Agriculture, Tarbiat Modares University, Tehran, Iran

²Department of Mechanical Engineering of Biosystems, Faculty of Agriculture and Natural Resources, University of Mohaghegh Ardabili, Ardabil, Iran

*Corresponding author: Nahangarnezhad@yahoo.com

Citation: Ahangarnezhad N., Najafi G., Jahanbakhshi A. (2019): Determination of the physical and mechanical properties of a potato (the Agria variety) in order to mechanise the harvesting and post-harvesting operations. *Res. Agr. Eng.*, 65: 33–39.

Abstract: Studying the physical and mechanical properties of agricultural products has been the subject of criticism and discussion for many years already and has attracted the attention of many researchers. The physical and mechanical properties of agriculture products are the most important parameters in the design of agricultural machinery sorting systems, transmissions, processing and packaging systems. The potato is one of the most important agricultural products as a food resource. The aim of this research is to investigate the physical properties and mechanical behaviour of the potato due to its importance and the current inadequate information about it. In this research, some of the physical and mechanical properties of the potato were measured in standard conditions. The length, width, thickness, geometric mean diameter and arithmetical diameter, sphericity, surface area, aspect ratio, mass, volume, bulk density and the projected mean area were included in the physical properties. The mechanical properties of the potato were determined by using a universal testing machine (MRT-5; Santam, Germany) with a uniaxial compression test. Then, the mechanical properties were measured with four repetitions. The physical properties of the potato such as length, width, thickness, mass, volume and geometric mean diameter had a direct relationship, while the density had an inverse relation to the size. The result of the mechanical properties of the sample, such as vertical stress, elasticity module, deformation energy, fracture force and deformation were obtained respectively as 0.34 MPa, 3.09 MPa, 892.02 J, 8.80 N and 207.22 mm. The comparison of the potato's real volume with the standard shapes showed that the potato's shape is similar to an oval due to the largest determination coefficient ($R^2 = 0.86$). The results of this research can be used for the design and optimisation of the processing equipment, as well as the transporting, sorting and packing of the potato crop.

Keywords: potato; engineering properties; post-harvest operations; waste control

The potato with the scientific name of *Solanum tuberosum* is ranked as the fourth most important product after wheat, rice and corn. Potatoes are full of starch, protein and potassium and are considered as high caloric products (ÖZTÜRK, POLAT 2016). Agriculture products from the harvesting time until consumption time undergo different processes and

changing factors. These processes may be simple operations such as cleaning, separating, washing, displacement and weighing and or conversion processes. So, the determination of the different physical and mechanical properties of the agriculture products and finding the ways to protect them from changing are the objectives for keeping the qualita-

tive and quantitative characteristics. Also, discriminating the physical properties is of high importance in designing the separating machines, elevators, washers and agricultural products' processing operations (PELEG 1985; SITKEI 1987). Determination of the dimension, volume and density has an important role in the preservation processes, the silo and bin design, and the external sorting and separating materials (PITTS et al. 1987; MCGLONE et al. 2002). One research studied some of the physical and mechanical properties of onions in Egypt. These properties consisted of the dimensions, geometric mean diameter, arithmetic mean diameter, project area, volume, mass, apparent density, static coefficient of the apparent density, rolling angle, crushing force and hole test (BAHNASAWY et al. 2004). The volume and density of the agricultural products are of great importance in different processes and product quality evaluations, such as fruit ripeness (SITKEI 1987). Some mechanical properties, such as the flesh and skin of an orange, were determined with a compression loading and shearing test. The shear loading test was undertaken by a blade (with 6 mm thickness), then the force and energy values were measured for shearing the orange. The results showed that by increasing the storage period, the force and energy for shearing the orange would be reduced (SINGH, REDDY 2006). One research on the potato was performed in Iran. The physical properties, such as the dimensions, mass, volume, density, geometric mean diameter, sphericity and project area, were determined for four varieties including Vital, Draga, Agria and Ajax (TABATABAEFAR 2000). In another research, the bending and shearing properties of the sunflower's stem was studied. The results showed that by increasing the moisture content, the module of the elasticity and bending stress reduced and the shearing firmness and shearing energy increased (INCE et al. 2005). Numerous studies have been carried out on the physical and mechanical properties of different products, such as the apricot (HASSAN-BEYGI et al. 2009), the strawberry (OZCAN, HACISEFEROĞULLARI 2007), the tomato (TAHERI-GARAVAND et al. 2011), the apple (KHEIRALIPOUR et al. 2008) and the scolymus (JAHANBAKHSI et al. 2016) thus far.

The objective of this research is to determine some of the physical and mechanical properties of a potato (the Agria variety). The results can be useful for reducing the harvesting losses and for mechanising the harvesting and post-harvesting operations.

MATERIAL AND METHODS

In order to determine the physical properties, 100 potato samples of the Agria variety were randomly selected and hand-picked to undergo experiments. The samples were kept in cold storage at 4°C before the test. The mass of samples was determined with an electronic balance with 0.01 g of sensitivity. To determine the average size of the potatoes, three linear dimensions, namely the length (L , mm), width (W , mm), and thickness (T), were measured by using a digital calliper (DC-515; Taiwan) with an accuracy of 0.01 mm. The geometric mean diameter (D_g , mm, Eq. 1) and the arithmetic mean diameter (D_a , mm, Eq. 2) were calculated (MOHSENIN 1986):

$$D_g = \sqrt[3]{LWT} \quad (1)$$

$$D_a = \frac{L+W+T}{3} \quad (2)$$

The sphericity (ϕ), which is defined as the ratio of the surface area to the sphere, has the same volume as that of the fruit to the surface area of the fruit, was determined by Eq. 3 (MOHSENIN 1986):

$$\phi = \frac{D_g}{L} \quad (3)$$

The surface area (S , mm²) of the potato was calculated by Eq. 4 (MOHSENIN 1986):

$$S = \pi(D_g)^2 \quad (4)$$

The aspect ratio (R_a) was calculated by Eq. 5 (OMOBUWAJO et al. 2000):

$$R_a = \frac{W}{L} \quad (5)$$

To determine the volume of each potato, a water container was put on the scale, then the potato samples were floated in the container then the mass of the displaced water (w_w , g) was determined. The water temperature was kept constant at 25°C. The volume of the displaced water was equal to the potato volume (V , cm³), which was calculated by Eq. 6 (MOHSENIN 1986):

$$V = \frac{w_w}{\rho_w} \quad (6)$$

where: ρ_w – water bulk mass (g·cm⁻³)

The water bulk mass at 25°C is equal to 0.9971 g·cm⁻³ and the true bulk mass (ρ_p , g·cm⁻³) was defined by Eq. 7:

<https://doi.org/10.17221/122/2017-RAE>

$$\rho_t = \frac{m}{V} \quad (7)$$

where: m – potato mass (g)

Because of the importance of the apparent shape in the separation stage of the products from the external materials and sort them according to the mass and product quality, the potatoes similarity was studied with standard estimated shapes. In this research, standard estimated shapes such as an elliptical spheroid volume (V_e , Eq. 8), a prolate spheroid volume (V_p , Eq. 9), an oblate spheroid volume (V_o , Eq. 10) were calculated (MOHSEIN 1986; STROSHINE 2004):

$$V_e = \frac{4}{3} \pi abc \quad (8)$$

$$V_p = \frac{4}{3} \pi ab^2 \quad (9)$$

$$V_o = \frac{4}{3} \pi a^2 b \quad (10)$$

where: a, b, c – half of the main axes of the prolate spheroid

Each potato's projected area was taken and recorded by an Area Measurement System Delta Tenglandt apparatus (Iran) with an accuracy of 0.05 mm^2 (Fig. 1). Then, the projected areas in three perpendicular directions were calculated by Matlab software (Version R2012a). The criteria projected area (CPA) was defined by Eq. 11 (MOHSEIN 1986):

$$\text{CPA} = \frac{\text{PA}_1 + \text{PA}_2 + \text{PA}_3}{3} \quad (11)$$

where: $\text{PA}_1, \text{PA}_2, \text{PA}_3$ – first, second and third projected areas (mm^2), respectively

This function was estimated as Eq. 12:

$$Y = b_0 + b_1 x_1 + b_2 x_2 + \dots + b_n x_n \quad (12)$$

where: Y – dependent variable such as the mass; $b_0, b_1, b_2, b_3, \dots, b_n$ – curve fitting parameters which are different in each equation; x_1, x_2, \dots, x_n – independent variables such as the dimensions

One evaluation of the goodness of fit is the value of the coefficient of determination. In general, in the case of regression equations, the nearer R^2 is to 1.00, the better the fitness curve is (STROSHINE 2004).

Determination of the mechanical properties

To determine the mechanical properties of the potato samples, a universal testing set (MRT-5; Santum, Germany) was used with the uniaxial com-

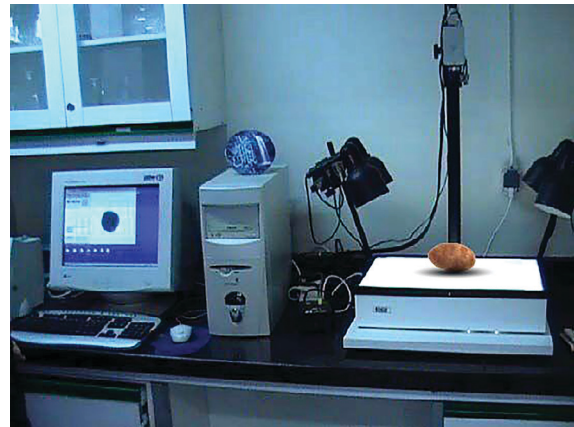


Fig. 1. The apparatus for measuring the projected area. The potato is positioned in the centre of the horizontal plate directly under the vision of the camera

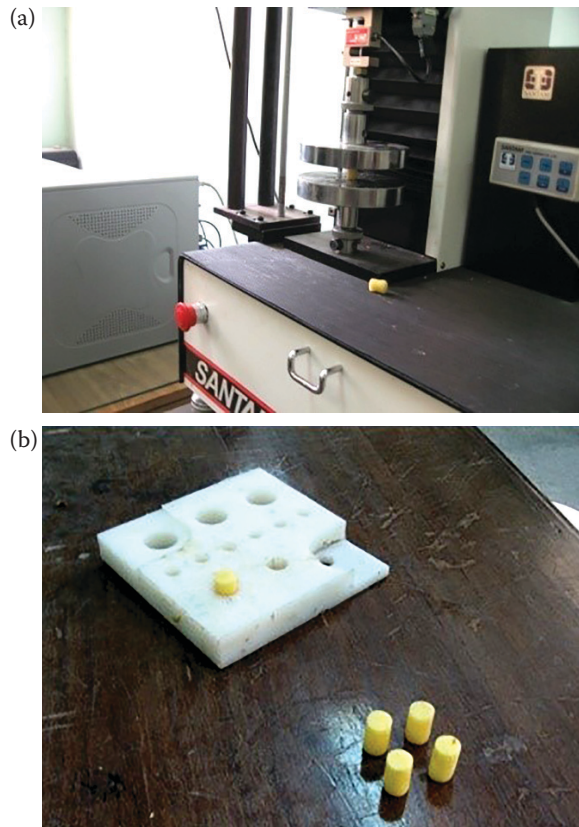


Fig. 2. The universal testing machine (MRT-5; Santum, country?) (a), the prepared potato samples for measuring the modulus of elasticity (b)

pression test (Fig. 2a). The objective of this test is to draw the force-deformation diagram of the safe samples between two parallel plates. The loading speed was set as $20 \text{ mm} \cdot \text{min}^{-1}$. Also, for determining the modulus of elasticity, cylindrical samples 14 mm in diameter and 28 mm in height were pre-

pared after flattening the bottoms and tops of the samples with a thin blade, the required parameters were extracted from the mechanical properties according to the ASTM D 790-03 standard (Fig. 2b) (KARAJ, MÜLLER 2010; JAHANBAKHSHI et al. 2016; JAHANBAKHSHI 2018). Each test was undertaken with four repetitions.

In this research, the analysis of the measured data was performed making use of MS Excel (Version 2013) and Minitab software (Version 2014).

RESULTS AND DISCUSSION

A summary of the physical properties of the potato is shown in Table 1. According to the results, the mean length, width and thickness, geometric mean diameter and arithmetic mean diameter, sphericity, project area, aspect ratio, mass, volume, true density, first project area, second project area, third project area and project area mean were 91.23 mm, 63.17 mm, 52.43 mm, 66.85 mm, 68.94 mm, 74.09%, 14,452.02 mm², 0.70, 185.62 g, 179.11 mm³, 1.05 g per mm³, 6,276.18 mm², 5,480.74 mm², 4,414.85 mm², and 5,390.59 mm², respectively. The results showed that the length is not significantly different to the width and thickness, so it can be concluded that potato has a high sphericity equal to 74.09. The vol-

ume and area of the product are applied in the modelling matters and heat transfer during the drying or freezing processes. Knowing the information about geometric mean diameter and arithmetic mean diameter can be considered useful parameters in designing the sorting and packaging machines, especially for products with irregular geometric shapes. Part of the losses of the agriculture products are related to the incorrect packaging method and inadequate transportation facilities. The packaging should be provided with the transportation and marketing needs in terms of mass, dimension and shape of agriculture products, so this requires knowing the physical and mechanical properties. The information obtained in this research can be used in this regard. The true density of the potato was 1.05 g·mm⁻³ and this property can be used in designing the transfer, displacement and sorting systems. In a similar research, CELİK et al. (2007), GOYAL et al. (2007) and JAHANBAKHSHI et al. (2016, 2018) have discussed and stressed upon the importance of these properties in determining the size of the machines, particularly that of the separation, transfer and sorting equipment.

According to the results shown in Table 2, the relationship between the *S* level and the main dimensions of the potato with the correlation coefficient of 99% was the best regression model. Among the physical characteristics, the mass, the volume and

Table 1. Some physical properties of the potato (Agria variety)

Parameter	Mean	Maximum	Minimum	SD	CV (%)
Length (mm)	91.23	126.51	50.47	18.16	19.90
Width (mm)	63.17	97.20	35.01	12.96	20.51
Thickness (mm)	52.43	74.93	33.02	9.68	18.46
Geometric mean diameter (mm)	66.85	88.89	38.79	11.66	17.44
Arithmetic diameter (mm)	68.94	91.67	39.50	12.03	17.44
Sphericity (%)	74.09	92.96	56.03	8.13	10.97
Surface area (mm ²)	14,452.02	24,810.23	4,723.51	4,723.45	32.68
Aspect ratio	0.70	1.05	0.42	0.12	17.14
Mass (g)	185.62	419.19	38.68	80.60	43.42
Volume (mm ³)	179.11	417.40	29.20	77.78	43.42
True density (g·mm ⁻³)	1.05	1.95	0.70	0.14	13.33
First project area (mm ²)	6,276.18	11,082.00	3,717.10	2,041.59	32.52
Second project area (mm ²)	5,480.74	9,881.00	3,468.40	1,661.71	30.31
Third project area (mm ²)	4,414.85	6,551.60	2,871.70	1,038.22	23.51
Project area mean (mm ²)	5,390.59	9,171.53	3,472.23	1,550.57	28.76

SD – standard deviation, CV – coefficient of variation

<https://doi.org/10.17221/122/2017-RAE>

Table 2. The best models and their constant values for the volume, mass and surface area based on three linear dimensions

Regression model	Constant value				R^2
	b_0	b_1	b_2	b_3	
$\ln V = b_0 + b_1 \ln L + b_2 \ln W + b_3 \ln T$	-6.12	1.24	0.25	1.17	0.91
$m = b_0 L + b_1 W + b_2 T$	-239.74	2.52	-0.27	4.01	0.86
$S = b_0 L + b_1 W + b_2 T$	-14,331.10	101.32	150.72	192.23	0.99

V – volume; b_0, b_1, b_2, b_3 – curve fitting parameters which are different in each equation; L – length; W – width; T – thickness; m – potato mass; S – surface area

Table 3. Comparing the potato's real volume with standard geometric shapes' volume

Standard shape	R^2	Standard error
Oval	0.86	26.68
Prolate spheroid	0.78	32.97
Oblate spheroid	0.83	33.09

the level of the image of the fruit are more important in the design of the equipment associated with the separation systems. In a similar research for these purposes, researchers have proposed models for predicting the dimensions of different agricultural products (LORESTANI, TABATABAEEFAR 2006; SHAHBAZI, RAHMATI 2013; TAGHIZADEH, JAJARMI 2015; ZIARATBAN et al. 2017).

The irregular shape of most agricultural products, such as the potato, is the reason for measuring its volume by the water displacement method. The tuber volume can be determined with similar methods through the geometric shapes such as an oval, a prolate spheroid and an oblate spheroid. The descriptive criterion of shape and size with geometric shapes was used for describing the agriculture products. The result of the comparison of potato's real volume to its approximate volume that is measured by using standard geometric

shapes (oval, oblate spheroid and prolate spheroid) is shown in Table 3. Oval standard shape had the largest correlation coefficient, so the potato shape is similar to an oval with ($R^2 = 0.86$). In addition, the approximated volume with an oval against an oblate spheroid and a prolate spheroid showed the maximum correlation and minimum standard deviation.

The results of the determination of the potato's mechanical properties during quasi static loading are shown in Table 4. The results for the mechanical properties such as vertical stress, elasticity module, deformation energy, force and sample deformation were 0.34 MPa, 3.09 MPa, 892.02 J, 8.8 N, and 207.22 mm, respectively. These properties are considered as the basic information needed in designing the machinery and equipment used during the harvesting and post-harvesting operations of a potato in order to reduce waste. Also, in order to minimise the mechanical damage and to reduce losses, the pressure forces caused during the transfer and packaging of the potato must be reduced to the minimum rate possible (lower than 8.8 N). The modulus of elasticity is one of the parameters that can be used to measure the product's tissue hardness. The higher the modulus of elasticity is, the harder the product tissue will be.

Table 4. The mechanical properties of the potato (Agria variety)

Parameter	Average	Maximum	Minimum	SD	CV (%)
Vertical stress (MPa)	0.34	0.4	0.3	0.04	11.76
Elasticity module (MPa)	3.09	3.7	2.66	0.43	13.91
Deformation energy (J)	892.02	916.02	861.08	23.09	2.58
Force (N)	8.8	9.7	7.42	1.05	11.93
Deformation (mm)	207.22	229.8	198.9	15.07	7.27

SD – standard deviation, CV – coefficient of variation

CONCLUSION

The first step in achieving qualitative standards for agriculture products, such as the potato, is to know the importance of the physical and mechanical properties and their changes because of the variety factors. In this research, some physical and mechanical properties of a potato (Agria variety) were investigated. The results of this research are listed below:

- (i) The length, width, thickness, mass, volume and geometric mean diameter had a direct relationship to the potato size, while the density had an inverse relationship;
- (ii) Comparison of the potato's real volume with standard geometric shapes (oval, oblate spheroid and prolate spheroid) showed the largest correlation coefficient with the oval, so the potato's shape is similar to an oval with ($R^2 = 0.86$);
- (iii) The potato samples had a relatively large mean sphericity and true density, equal to 74.09% and $1.05 \text{ g}\cdot\text{mm}^{-3}$, respectively;
- (iv) The vertical stress and modulus of elasticity were obtained as 0.34 MPa and 3.09 MPa, respectively, and the fracture force was equal to 8.8 N. The obtained deformation energy and the deformation of the potato were 892.02 J and 207.22 mm, respectively;
- (v) The physical and mechanical properties can be considered as useful parameters in designing the washing, sorting, grading and packaging equipment to avoid the product being crushed during the storage of the potato.

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Received for publication November 24, 2017

Accepted after corrections November 16, 2018