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The physical and mechanical properties of potato (*Solanum tuberosum* L.) tubers as related to the automatic separation from clods and stones

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Abstract: In the current research, some of the mechanical and physical properties of two industrial varieties of potato tubers that have a prominent role in the mechanised separation process from clods and stones were investigated. These properties include the physical dimension, mass, volume, sphericity, surface area, density, projected areas and Young's modulus. In addition, the static coefficient of friction and rolling resistance for tubers on five surface materials were determined. The tuber's size positively affected the physical and mechanical properties of the tubers. The frictional properties of the tubers were affected by the tuber size, the surface type, and the interaction between them. The results showed that most of the apparent properties for the Sante variety were greater than those of the Marfona variety. The static coefficient of friction for the tubers on a wood surface was the maximum and was the minimum value on a galvanized sheet, but for the tuber's rolling resistance, the results were inversed. The results proposed that the automatic separation of the potato tubers from the impurities using the properties of the crop is possible.

Keywords: mechanical damage; separation process; postharvest; frictional properties

Following rice, wheat and corn, potatoes (*Solanum tuberosum* Linnaeus) are one of the world's main crops in terms of calories, and play a dominant role in the world food production (Ichiki et al. 2013). According to the annual report of the Food and Agricultural Organization (FAO), the total potato production in 2016 was 375 million t for the world, and Iran's contribution was about 5.2 million t over 162 thousand ha (FAOSTAT 2016). The physical and mechanical characteristics of the agricultural crops are considerable as the most critical factors for designing the packaging, processing, conveying, and grading systems. Among the physical properties, mass, volume, projected area and centre of gravity are the most important ones in the handling systems (Wright et al. 1986). The coefficient of static friction is substantial in designing the conveyors and chutes because friction is essential to hold the potato tuber onto the conveying surface without slipping and sliding backward and in addition, to determine the angle at which the chutes must be positioned in order to achieve a consistent flow of materials through the chute (Razavi et al. 2007; Bishop et al. 2012). Density information on the food is essential in the separation processes, such as centrifugation and sedimentation, and in the pneumatic and hydraulic transport of granular materials (Sahin, Sumnu 2006; Chakespari et al. 2010). Until now, many researchers have studied the physical and mechanical properties of fruits, nuts, grains and seeds (Masoumi et al. 2006; Isik, Izli 2007; Jahromi et al. 2008; Bakhtiari, Loghavi

https://doi.org/10.17221/24/2018-RAE

2009; de Figueiredo et al. 2011). Despite the other agricultural products, the physical and mechanical properties of potato tubers have not been well perused and data about them are lacking in the literature , probably due to the high inhomogeneity of tubers in terms of the shape and size (Tabatabaeefar 2002; Dalvand 2011; Yurtlu et al. 2011; Bishop et al. 2012; Zare et al. 2012).

The first step in developing an automatic separation system on a potato harvester is the discrimination between the potato tubers and clods. Developing an automated system for separating clods from potato tubers is more challenging, since potato tubers have a wide diversity in shape, size and colour. Partially and completely muddy potatoes add another problem in developing automated separator systems (Hosainpour et al. 2011). Removing the clods and stones before entering the container in essential since these valueless items may occupy a large space in the container. Allowing impurities such as stones and clods to enter the container causes mechanical damage to the sound tubers due to the abrasive nature of them as well as wasting energy during transport or storage and can also reduce the air circulation in the storage, therefore, preventing the proper temperature and humidity control (Schweers et al. 2007). The objective of this study is to assess some properties of potato tubers that are directly related to the automatic separation process of them from clods and stones.

MATERIAL AND METHODS

Two potato tuber varieties, Sante and Marfona, used in the current study were harvested in 2017 from an educational research farm in the 'Bahar' district, Hamedan (34°48'N, 48°31'E; 1850 m a.s.l.), Iran. The tubers were hand-harvested, chosen at random, to avoid damage and ensure freshness during the harvesting and transportation. The potato tubers were stored in optimal conditions (13°C, 85% relative humidity) during the measurement process, with a maximum storage time before the measurement being 7 days. Prior to starting the measurements, the tubers were kept at the environmental temperature for at least 5 h to equilibrate to ambient conditions. All the experiments were carried out with five replications for each treatment. The initial moisture content of the potato tubers was determined by using a standard hot air oven at 70°C for 24 h (AOAC International 2016). The physical and mechanical properties of the potato tubers were determined by the steps that follow.

Classification. First, the tubers for each variety were grouped into three classes based on the maximum dimension (length – L), so that the potato tubers with L in the range of 35 to 55 mm were labelled as class 1 (first seed type), tubers with L in the range of 55 to 75 mm were labelled as class 2 (second seed type) and tubers with $L > 75$ mm were labelled as edible tubers.

Determination of the geometrical and morphological properties. Three major perpendicular dimensions of the tubers, namely, the length, width and thickness were measured to an accuracy of 0.01 mm by digital callipers (Insize, China). The geometric mean diameter, the arithmetic mean diameter, the sphericity, the aspect ratio and the surface area were computed for the tubers (Mohsenin 1986; Goyal et al. 2007).

To avoid shading errors, an illumination surface was made and utilised to determine the projected areas, PA_L, PA_W, PA_T, along the three mutually perpendicular axes. The projected areas were measured with the image processing method. The images of the potato tubers were taken with a digital camera (Canon EOS 750D; Canon, Japan) located vertically 50 mm above the centre of each sample from the three main planes, respectively. Meanwhile, the conversion error of the unit between the pixel area and the cm^2 was determined to be less than 1% by demarcating a standard circle with a 100 mm diameter. Afterwards, the captured images were transmitted to the computer using EOS Utility software (Version 3.5.10) and processed by an image analysis program that was pre-programmed with MATLAB (Version R2016a). This method has been successfully used for other agricultural products by several researchers (Jahns et al. 2001; Khoshnam et al. 2007). The average projected area (known as the criteria projected area) was calculated following Tabatabaeefar (2002).

Determination of the static friction coefficient and the rolling resistance. In order to determine the coefficient of static friction and rolling resistance of the potato tubers, five material surfaces, namely wood, galvanized iron sheet, aluminium sheet, rubber and glass were applied. The static friction coefficient was measured using the tilted

https://doi.org/10.17221/24/2018-RAE

plate method described by many researchers (Al-Maiman, Ahmad 2002; Pliestic et al. 2008). The inclined plate was gradually raised and the angle of inclination at which the sample initiated its sliding was read off the magnetic protractor with a sensitivity of one degree (ACE 28865, USA).

To determine the rolling resistance, the potato tubers were placed on an inclined plate versus an adjustable air stream and two rotational conditions of the object, upward and downward to the tilted surface, were considered. The rolling resistance was calculated using Eq. 1 (Mohsenin 1986):

$$R' = W\sin\theta \frac{v_1^2 - v_2^2}{v_1^2 + v_2^2} \quad (1)$$

where: R' – the rolling resistance on the inclined surface (N); W – the width (mm); θ – the inclination angle of the tilt surface (°); v_1 – the air stream velocity for the sample rolling up the inclined surface (m·s^{-1}); v_2 – the air stream velocity for the sample rolling down the inclined surface (m·s^{-1})

To create the air stream, a blower with an adjustable airflow rate (HP7160-BL; Hyundai, South Korea) was employed. Moreover, the velocity of the air stream was measured by a hot wire anemometer with a sensitivity of 0.1 m·s^{-1} (Lutron AM-4204; Lutron, Taiwan). For the horizontal plane, the rolling resistance (R) will be as follows (Eq. 2):

$$R = R'\cos\theta \quad (2)$$

Determination of the density and modulus of elasticity. Initially, the mass of each tuber was measured by a digital balance with a sensitivity of 0.01 g (Lutron GM-300p; Lutron, Taiwan). The volume of each potato sample was determined by using the water displacement and platform scale methods (Mohsenin 1986). The apparent density (ρ, g·cm^{-3}) and specific gravity (SG) of each potato were calculated in Equations 3 and 4 (Mohsenin 1986):

$$\rho = \frac{m}{V} \quad (3)$$

where: m – the mass of the tuber (g); V – the volume (cm^3)

$$\mathrm{SG} = \frac{m}{m_{\mathrm{dw}}} \quad (4)$$

where: m_{dw} – the mass of the water displaced (g)

Since the texture stiffness is positively and directly associated to the modulus of elasticity and this property plays an important role in almost all the harvest and postharvest processes (Van Zeebroeck et al. 2007), thus, the modulus of elasticity is considered as a criterion of stiffness for the separation of the tubers from the impurities. For measuring the elastic modulus of the tuber's texture, the specimen after peeling and halving was punctured in a universal testing machine (Zwick/ Roell Z0.5; Zwick Roell, Germany) with a 50 N load cell on the cross head that was equipped by a 10 mm probe. The force-deformation curve and texture properties of the sample at the rupture point were extracted using the testXpert 2 software (Version 3.3) at the loading speed of 50 mm·min^{-1}. The elastic modulus of the potato's texture was calculated by Boussinesq's problem using Eq. 5 (Mohsenin 1986):

$$E = \left(\frac{F}{D}\right) \times \left(\frac{1 - V^2}{2a}\right) \quad (5)$$

where: E – the modulus of elasticity (MPa); F – the force (N); D – the deformation (mm); a – the radius of the probe (mm)

The data were analysed by ANOVA with the SPSS software (Version 22). The differences were considered to be significant at $P \leq 0.01$. In order to examine the interaction effect between the variety and the class, a factorial experiment, in a randomised complete block design, was used.

RESULTS AND DISCUSSION

The average initial moisture content of the Marfona and Sante varieties was found to be about 83 and 75% (wet base), respectively. The physical and mechanical properties of the two potato varieties at the initial moisture content are presented in Table 1. As is shown in Table 1, in the first class, the three major dimensions (length, width, and thickness) and the mean diameters of the Marfona variety were lower than those of the Sante variety. Tabatabeefar (2002) reported that the Draga and Agria varieties had longer geometric mean diameters and larger masses than the Vital and Ajacks varieties of potatoes.

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Table 1. The physical and mechanical properties of the two potato varieties

Variety		C_1		C_2		C_3	
		mean	SD	mean	SD	mean	SD
Marfona	L (mm)	50.227	3.817	70.278	4.332	87.215	8.598
	W (mm)	45.606	3.51	61.61	4.366	69.274	6.576
	T (mm)	40.266	3.235	51.827	4.365	58.16	5.637
	D_g (mm)	45.142	2.921	60.734	3.914	70.462	5.538
	D_a (mm)	45.367	2.908	61.239	3.862	71.549	5.641
	R_a	0.911	0.071	0.877	0.047	0.798	0.075
	ϕ	0.901	0.048	0.865	0.035	0.811	0.052
	A_s (cm^2)	64.275	848.642	116.338	1,497.815	156.892	2,458.332
	PA_L (cm^2)	20.129	2.885	39.292	5.356	54.878	11.37
	PA_W (cm^2)	19.389	2.934	36.456	5.389	49.888	9.151
	PA_T (cm^2)	17.847	2.754	32.279	4.521	41.04	9.586
	CPA (cm^2)	19.122	2.804	36.009	4.95	48.602	9.9898
	ρ (g·cm^{-3})	1.061	0.006	1.072	0.012	1.074	0.008
	V (cm^3)	71.174	10.826	132.671	20.951	192.715	28.098
	SG	1.063	0.006	1.074	0.013	1.076	0.008
	E (MPa)	2	0.126	1.884	0.362	2.031	0.21
	m (g)	67.597	15.286	132	21.218	213.17	36.366
Sante	L (mm)	52.732	3.061	69.117	4.839	86.65	8.123
	W (mm)	48.226	4.099	62.341	5.388	71.869	5.315
	T (mm)	41.417	3.755	50.669	4.201	59.586	5.223
	D_g (mm)	47.178	3.068	60.176	4.272	71.758	4.689
	D_a (mm)	47.458	3.028	60.709	4.289	72.701	4.765
	R_a	0.914	0.058	0.902	0.049	0.835	0.086
	ϕ	0.895	0.036	0.871	0.031	0.831	0.052
	A_s (cm^2)	70.207	897.628	114.306	1,602.148	162.427	2,135.459
	PA_L (cm^2)	23.309	3.194	38.476	6.859	56.794	5.917
	PA_W (cm^2)	21.736	3.166	34.139	5.453	52.389	5.402
	PA_T (cm^2)	19.955	2.731	31.024	5.249	44.921	5.168
	CPA (cm^2)	21.667	2.922	34.546	5.695	51.368	5.248
	ρ (g·cm^{-3})	1.084	0.012	1.085	0.008	1.079	0.006
	V (cm^3)	71.326	15.904	131.713	30.467	201.062	22.468
	SG	1.086	0.012	1.087	0.008	1.08	0.006
	E (MPa)	1.813	0.387	2.109	0.291	2.024	0.285
	m (g)	75.22	14.3	147.08	29.896	220.94	36.177

L – length; W – width; T – thickness; D_g – geometric mean diameter; D_a – arithmetic mean diameter; R_a – aspect ratio; ϕ – sphericity; A_s – surface area; PA_L – projected area along the length; PA_W – projected area along the width; PA_T – projected area along the thickness; CPA – criteria projected area; ρ – density; V – volume; SG – specific gravity; E – the modulus of elasticity; m – mass of tuber; C1 – class 1; C2 – class 2; C3 – class 3; SD– standard deviation

In addition, in the third class, the sphericity and aspect ratio of the Sante variety were more than those of the Marfona variety. Tabatabeefar (2002) concluded that the sphericity for Ajacks, Draga and Vital varieties was the same. The effect of the tuber size (class) on physical properties of the tubers except for the density and modulus of elasticity was significant (Table 2).

https://doi.org/10.17221/24/2018-RAE

Table 2. The analysis of variance of the potato tuber's physical properties in the different varieties and classes

Indp.Var.	Source	*df*	MS	*F*-value
D_g	variety	1	32.596	1.403
	class	2	1,875.625	80.738**
	variety × class	2	8.114	0.349
	error	24	23.231	
	total	29		
D_a	variety	1	35.158	1.483
	class	2	1,975.055	83.29**
	variety × class	2	6.676	0.282
	error	24	23.713	
	total	29		
R_a	variety	1	0.001	0.242
	class	2	0.026	8.706**
	variety × class	2	0.006	1.933
	error	24	0.003	
	total	29		
ϕ	variety	1	0.001	0.57
	class	2	0.015	11.475**
	variety × class	2	0.006	4.603
	error	24	0.001	
	total	29		
A_s	variety	1	4,743,581.065	1.249
	class	2	2.588×10^8	68.155**
	variety × class	2	1,201,422.776	0.316
	error	24	3,796,571.115	
	total	29		
CPA	variety	1	128.725	5.508
	class	2	1,865.218	79.811**
	variety × class	2	15.915	0.681
	error	24	23.37	
	total	29		
ρ	variety	1	0.001	14.515**
	class	2	8.406×10^{-5}	0.97
	variety × class	2	0	2.368
	error	24	8.664×10^{-5}	
	total	29		
V	variety	1	47.396	0.094
	class	2	39,474.11	78.122**
	variety × class	2	64.568	0.128
	error	24	505.291	
	total	29		
SG	variety	1	0.001	14.515**
	class	2	8.436×10^{-5}	0.97
	variety × class	2	0	2.368
	error	24	8.695×10^{-5}	
	total	29		
E	variety	1	0.001	0.009
	class	2	0.039	0.466
	variety × class	2	0.107	1.262
	error	24	0.085	
	total	29		
m	variety	1	25.984	0.026
	class	2	66,623.705	65.825**
	variety × class	2	1,512.008	1.494
	error	24	1,012.129	
	total	29		

Table 2. To be continued

Indp. Var. – independent variable; *Dg* – geometric mean diameter; *Da* – arithmetic mean diameter; *Ra* – aspect ratio; ϕ – sphericity; *As* – surface area; CPA – criteria projected area; ρ – density; *V* – volume; SG – specific gravity; *E* – the modulus of elasticity; *m* – mass of the tuber; *df* – the degree of freedom; MS – mean of squares; **significant difference at $P \leq 0.01$

The mean values of the static coefficient of friction and the rolling resistance of the two potato tuber varieties and the five abrasion surfaces are given in Table 3. As seen in Table 3, the coefficient of static friction in the second and third classes on the wood surface was the highest for both varieties. According to the results, after the wood, the highest static coefficient of friction values was followed by the rubber, the glass and the aluminium sheet, respectively, and it was the lowest on the galvanized iron sheet. Dalvand (2011) found out which coefficient of sliding friction, whether on glass, galvanized iron and wood surfaces for the peeled potato tubers, was greater than the corresponding values for the unpeeled potatoes.

It was concluded that the tuber size class and surface type as well as the interaction between them had a significant effect on the static coefficient of friction (Table 4). Moreover, the effect of the class and interaction between it and the surface type on the rolling resistance of the tuber was significant. In a similar research, Yurtlu et al. (2011) studied the frictional properties of four potato varieties, the Agria, Marabel, Marfona and Sante, on five surfaces: a galvanized sheet, a court fabric, stainless steel, rubber and an iron sheet. Their results showed that the abrasion surface and variety significantly affected both the static and dynamic coefficient of friction, as well as, among all the abrasion surfaces, the court fabric had the highest and

https://doi.org/10.17221/24/2018-RAE

Table 3. The means and standard deviations of the coefficient of static friction and rolling resistance for the different potato varieties and surfaces

Variety	Property	Surface type	C_1		C_2		C_3	
			mean	SD	mean	SD	mean	SD
Marfona	static coefficient of friction	galvanized iron sheet	0.33	0.03	0.32	0.01	0.32	0.01
		aluminium sheet	0.39	0.06	0.41	0.02	0.37	0.03
		wood	0.40	0.03	0.53	0.09	0.54	0.07
		rubber	0.43	0.04	0.51	0.09	0.53	0.05
		glass	0.42	0.03	0.45	0.02	0.44	0.03
	rolling resistance (N)	galvanized iron sheet	0.05	0.01	0.11	0.03	0.05	0.03
		aluminium sheet	0.04	0.01	0.08	0.01	0.03	0.02
		wood	0.03	0.03	0.07	0.04	0.05	0.03
		rubber	0.03	0.01	0.06	0.04	0.05	0.03
		glass	0.03	0.02	0.09	0.03	0.04	0.02
Sante	static coefficient of friction	galvanized iron sheet	0.34	0.05	0.31	0.04	0.31	0.01
		aluminium sheet	0.42	0.04	0.39	0.02	0.38	0.02
		wood	0.37	0.07	0.51	0.05	0.51	0.06
		rubber	0.35	0.07	0.51	0.08	0.48	0.14
		glass	0.35	0.03	0.42	0.04	0.41	0.04
	rolling resistance (N)	galvanized iron sheet	0.07	0.02	0.07	0.04	0.02	0.01
		aluminium sheet	0.06	0.01	0.07	0.02	0.03	0.02
		wood	0.05	0.02	0.04	0.03	0.07	0.05
		rubber	0.02	0.01	0.05	0.03	0.07	0.01
		glass	0.04	0.01	0.08	0.05	0.07	0.04

C1 – class 1; C2 – class 2; C3 – class 3; SD– standard deviation

Table 4. The analysis of variance of the potato tuber's frictional properties in the different varieties, classes, and surface types

Independent variable	Source	*df*	MS	*F*-value
Static coefficient of friction	variety	1	0.019	6.37
	class	2	0.044	15.1**
	surface type	4	0.119	40.955**
	variety × class	2	0.001	0.279
	variety × surface type	4	0.003	1.088
	class × surface type	8	0.019	6.355**
	variety × class × surface type	8	0.002	0.569
	error	120	0.003	
	total	149		
Rolling resistance	variety	1	3.121×10^{-5}	0.04
	class	2	0.013	16.51**
	surface type	4	0.002	1.906
	variety × class	2	0.003	3.911
	variety × surface type	4	0	0.608
	class × surface type	8	0.003	3.246**
	variety × class × surface type	8	0.001	0.702
	error	120	0.001	
	total	149		

df – degree of freedom; MS – Mean of Squares; **significant difference at $P \leq 0.01$

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the galvanized sheet had the lowest value of the static coefficients of friction, the latter one causes less risk of damage for the potato. Regarding the rolling resistance of the tubers, it can be found that commonly for two varieties in the first two classes, this property was the highest and lowest on the galvanized iron sheet and the rubber and the wood surface, respectively.

CONCLUSION

In this study some physical and mechanical properties of two potatoes varieties were determined for the mechanised separating of potato tubers from stones and clods. The study results showed that the class (tuber size), surface type, and interaction of them have a highly significantly effect on the frictional properties of the potato tubers. The coefficient of static friction for both potato varieties had the highest and lowest values on the wood and galvanized iron sheet surfaces, respectively. The effect of the variety on the geometric and arithmetic mean diameters, aspect ratio, sphericity, surface area, criteria projected area, volume, elastic modulus and mass of the tubers was not significant with a probability of 99%, but it was significant on the density and specific gravity. In general, the Marfona density for all three classes with values of 1.061, 1.072 and 1.074 $g\cdot cm^{-3}$, respectively was less than the Sante density with the corresponding values of 1.084, 1.085 and 1.079 $g\cdot cm^{-3}$, respectively. The surface type, tuber size, and interaction of them affected the frictional properties (the static coefficient of friction and rolling resistance) of the potatoes with a probability of 99%.

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