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Study of engineering properties of vegetable seeds for design of seed dryer

THINGUJAM BIDYALAKSHMI DEVI [1] and INDRA MANI[2]

ICAR-Indian Agricultural Research Institute, New Delhi 110 012

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ABSTRACT

A study was carried out to find the effect of moisture content on various engineering properties of carrot, onion and tomato seeds. The range of moisture studied was between 8±1 to 20±1% w.b for all the crop seeds. The bulk density for carrot, onion and tomato increased from 0.32±0.01 g/cm^3 to 0.43±0.04 g/cm^3, 0.45±0.01 g/cm^3 to 0.47 ±0.003 g/cm^{3}and 0.28±0.01 g/cm^3 to 0.30±0.01 g/cm^3, respectively when the moisture content decreased from 20±1 to 8±1% wet basis. Sphericity of carrot, onion and tomato decreased by 6.7%, 1.4% and 6% with the increase in moisture content by 60.68%, 58.6% and 60.48% for respectively. The true density and porosity increased for onion and tomato whereas the same decreased for carrot with the decrease in moisture content. All the other engineering properties such as test weight (1000 seed weight), surface area, arithmetic mean diameter, geometric mean diameter and angle of repose increased with the increase in moisture content. The coefficient of friction of all the crops decreased at four different surfaces e.g. wood, mild steel, aluminium and galvanized iron with the increase in moisture content. The regression equations for all the response variables were significant at $P<0.05$ with coefficient of determination, R^2 (>0.90).

Key words: Coefficient of friction, Porosity, Terminal velocity, Vegetable seeds

Vegetables are well known for its nutraceutical properties as they supplement rare minerals, vitamins and other micronutrients. They play a vital role in providing not only food security but also nutritional security. India ranks second in the production of fruits and vegetables next to China (APEDA 2017). Onion, tomato, carrot are most commonly grown vegetables in the country and are indispensable ingredients of most Indian cuisine. Seed is the basic and primary input for crop production. It has been observed in multi-location coordinated trials under National Seed Project that about 20-30% average increase in productivity could be achieved with the use of quality seed. Use of quality seeds also affect the influence of other inputs like irrigation, fertilizer and pesticides (Rashid and Singh 2000). Producing good quality seeds and maintaining its quality till the time of sowing is a great challenge to different stakeholders. Unlike in grains, extreme care is necessary for seeds during post-harvest phase to maintain its quality. The most important factors influencing seed quality maintenance are moisture content, temperature and relative humidity during post-harvest period (Dickie *et al.* 1990).

The knowledge of engineering properties of biological materials including physical, mechanical, aerodynamics, thermal and optical properties is necessary for the design and development of processing equipment. In fact, designing the seed processing equipment without considering engineering properties of biomaterials may yield poor results (Davies and El Okene 2009).

Any mechanical damage to grain and seed in threshing and handling operations causes reduction in germination power and viability of seeds. Physical properties such as size and shape, mass, volume, thousand grain weights, porosity, bulk and true densities are necessary for the design of various separating, drying, storage, and handling equipments for bulk materials (Tabatabaeefar and Rajabipour 2005, Altuntas *et al.* 2005). Thousand seed weight is required to determine theoretical estimation of seed volume (Liny *et al.* 2013). Designing of drying and aeration system for seeds requires the knowledge of bulk density, true density and porosity of the materials as it affects the resistance of airflow of the stored products (Liny *et al.* 2013). Low porosity in grain bed provide greater resistance to water vapour or air escape during drying and aeration process, that leads to higher power to drive the aeration fans. The aerodynamic property of the products, i.e. terminal velocity is important and required for designing of pneumatic conveying systems, cleaning and separation equipment (Sahay and Singh 2004). The engineering properties of biological materials are greatly influenced by the moisture content.

Therefore, this study was carried out to find the influence of moisture content on engineering properties of onion, carrot and tomato seeds useful for the design of seed dryer for selected vegetable crops.

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[1] Ph D Scholar (e mail: bidyala@gmail.com), [2] Head (e mail: maniindra99@gmail.com), Division of Agricultural Engineering.

MATERIALS AND METHODS

Sample preparation

Onion, carrot and tomato seeds were cleaned manually to remove all foreign materials including immature and broken seeds. The initial moisture content of all seeds was determined by standard oven drying method (ISTA 2016). Desired moisture contents of the samples were prepared by adding distilled water as determined (Sacilik *et al.* 2003):

$$Q = \frac{W_i\left(M_f - M_i\right)}{\left(100 - M_f\right)}$$

where, W_i, is the initial mass of sample in kg; M_i, is the initial moisture content of sample in % db; M_f, is the final moisture content of sample in % db.

The moistened samples were kept in tightly sealed High Density Polyethylene (HDPE) bags. The moisture was allowed to distribute uniformly throughout the sample by keeping it in refrigerator at 5°C. Before the start of experiment, samples were taken out and kept at room temperature for about 2 hr to equilibrate. All the engineering properties were studied at four moisture levels within the range of 20±1% to 8±1% wet basis. The upper and lower limits of moisture content were selected based on the moisture content during harvesting and for safe storage. The following engineering properties were studied.

Bulk density: The seeds were filled into a box of standard size (5×5×5 cm) up to the top level from a constant height, the top level was strike off and weighed (Mohsenin 1986). The excess seeds were removed to bring the top surface perfectly level and even. The seeds in the box were weighed by using an electronic balance. The bulk density was calculated as follows.

$$\textit{Bulk}\ \text{density}, \rho_b\left(\text{kg/m}^3\right) = \frac{\text{weight of seeds (kg)}}{\text{Volume of seeds (m}^3\text{)}}$$

True density: The true density (kg/m^3) was determined using liquid displacement method (Shepherd and Bhardwaj 1986). Toluene was used to prevent the absorption during measurement as it has low surface tension compare to water (Ogut 1998). The volume of displaced toluene (C_7H_8) was recorded by immersing 5 grams of seeds in 50 ml of toluene in a graduated measuring cylinder (Tavakkoli *et al.* 2009). The ratio of weight of seeds to the volume of displaced toluene gave the true density.

$$\text{True Density, } \rho_t\left(\text{kg/m}^3\right) = \frac{M_S}{V_S}$$

where, M_s, mass of solid particle; V_s, volume of toluene displaced.

Porosity: Porosity (ε) was measured as the percentage of void space in the bulk grain.

$$\varepsilon = \frac{\left(\rho_t - \rho_b\right)}{\rho_t} \times 100$$

where, ρ_t, True density; ρ_b, Bulk density.

Arithmetic mean diameter, geometric mean diameter and sphericity: 100 seeds each of onion, carrot and tomato were randomly selected to measure the axial dimensions. A digital verniercaliper (±0.01 mm) was used to measure the dimensions, viz. minor diameter (thickness, T), intermediate diameter (width, W) and major diameter (length, L). The arithmetic mean diameter (D_a) and geometric mean diameter (D_g) in mm were determined from the average of axial dimensions using the formula as given by Joshi *et al.* (1993).

$$D_a = \frac{L + W + T}{3}$$

$$D_g = (LWT)^{1/3}$$

Sphericity (ϕ) was calculated as the ratio of geometric mean diameter of the object to the major diameter (Mohsenin 1980).

$$\phi = \frac{(LWT)^{1/3}}{L}$$

Surface area: Surface area (A) was determined according to the methods reported by Mohsenin (1986).

$$A = \pi D_g^2$$

where, Dg is the geometric mean of the length, width, and thickness.

Test weight: The test weight of each samples was determined by counting thousand seeds from each sample and measuring its weight in an electronic balance accurate to 0.01g.

Coefficient of friction: The static coefficient of friction was determined on four structural surfaces (wood, mild steel, aluminium and galvanized iron) using inclined plane method as described by Varnamkhasti *et al.* (2008). The coefficient of friction was calculated using the following relationship.

$$\mu = \tan\alpha$$

where, μ is the coefficient of friction and α is the angle of tilt in degrees.

Angle of repose: The angle of repose was measured by emptying method using bottomless cylinder (300 mm diameter and 500 mm height). The cylinder was placed at the center of a raised circular plate and was filled with the seeds. The cylinder was raised slowly until it formed a cone on the circular plate (Taser *et al.* 2005, Kaleemullah and Gunasekar 2002).

Terminal velocity: Terminal velocity was measured using cylindrical air column (Joshi *et al.* 1993, Baryeh and Mangope 2002), which consisted of a vertical acrylic tube attached to a centrifugal blower. Wire meshes were placed at the bottom of the tube to get uniform air velocity throughout the entire cross section area. five grams of seed was dropped into the air stream from the top of the air column, in which air was blown to suspend the seed in the air stream. The air velocity was measured using a hot wire anemometer having a least count of 0.01 m/s when the seeds get suspended in air column.

Full factorial design was employed for the study. A one-way analysis of variance test (ANOVA) was carried out using the software SAS (version 9.3, IASRI) to examine the effect of moisture content on engineering properties of selected vegetable seeds i.e. carrot, onion and tomato with the proposed experimental design. The mean values and standard error for all the properties were evaluated using the MS Excel 2010.

RESULTS AND DISCUSSION

The effect of moisture content on bulk density, true density, terminal velocity, test weight, sphericity, surface area, geometric mean diameter, arithmetic mean diameter, porosity and angle of repose and coefficient of friction were evaluated in terms of their mean value and standard error (Table 1 and Table 3). The linear regression models were developed for each property by considering the highest coefficient of determination and least associated standard error (Table 2 and Table 4).

Bulk density

The bulk density of carrot, onion and tomato seed was observed as 0.32±0.01 g/cm^3, 0.45±0.01 g/cm^3, 0.289±0.01 g/cm^3 at 20±1% w.b. and 0.43±0.04 g/cm^3 respectively, 0.47±0.003 g/cm^3, 0.30±0.01 g/cm^3 at storage moisture content of 8±1 % w.b. respectively. The bulk density of all the selected crop seeds increased as the moisture content decreased (Table 1). The decreasing trend may be due to the fact that increase in mass due to moisture gain was lower than the accompanying volumetric expansion of the seeds (Pradhan *et al.* 2008). Similar decreasing trend in bulk density was reported by Altuntaş and Demirtola (2007) for legumes seeds, Garnayak *et al.* (2008) for Jatropha seed, Singh *et al.* (2010) for millet and Ilori *et al.* (2016) for amaranthus. The regression models were found significant at $P< 0.05$ for all the seeds. The coefficient of determination (R^2) for carrot, onion and tomato seeds was 0.96, 0.931 and R^2=0.931 respectively (Table 2).

True density

True density of carrot, onion and tomato seeds were observed as 1.23±0.12 g/cm^3, 1.14±0.05 g/cm^3, and 1.03±0.06 g/cm^3 at 20±1% w.b respectively and 1.07±0.05 g/cm^3, 1.15±0.06 g/cm^3 and 1.14±0.04 g/cm^3 at 8±1% w.b, respectively. True density of carrot seed decreased

Table 1 Engineering properties of carrot, onion and tomato seeds at different moisture levels

Moisture content (% wb)	Bulk density (g/cm^3)	True density (g/cm^3)	Terminal velocity (m/s)	Test weight (g)	Sphericity	Surface area (mm^2)	GMD (mm)	AMD (mm)	Porosity (%)	AOR (^{0})
Carrot seed										
8.15	0.43 ± 0.04	1.07 ± 0.05	1.81 ± 0.24	2.04 ± 0.22	0.45 ± 0.03	7.10 ± 0.22	1.50 ± 0.21	1.87 ± 0.24	60.32 ± 1.52	33.79 ± 0.51
12.01	0.38 ± 0.02	1.12 ± 0.06	2.12 ± 0.12	2.16 ± 0.10	0.44 ± 0.01	7.15 ± 0.20	1.50 ± 0.03	1.91 ± 0.07	66.55 ± 1.86	34.32 ± 0.17
16.37	0.35 ± 0.02	1.14 ± 0.06	2.40 ± 0.12	2.58 ± 0.10	0.43 ± 0.01	7.86 ± 0.20	1.57 ± 0.03	1.93 ± 0.07	69.60 ± 1.63	34.94 ± 0.17
20.73	0.32 ± 0.01	1.23 ± 0.12	2.52 ± 0.09	3.01 ± 0.21	0.42 ± 0.01	8.34 ± 0.24	1.62 ± 0.03	2.01 ± 0.08	73.82 ± 1.68	36.03 ± 0.50
Onion seed										
8.65	0.47 ± 0.003	1.15 ± 0.06	1.92 ± 0.40	3.61 ± 0.23	0.70 ± 0.02	13.39 ± 0.28	2.06 ± 0.08	2.17 ± 0.04	59.95 ± 1.70	31.21 ± 0.18
12.32	0.46 ± 0.003	1.15 ± 0.05	2.01 ± 0.09	3.81 ± 0.10	0.70 ± 0.01	14.25 ± 0.47	2.13 ± 0.08	2.24 ± 0.03	59.11 ± 2.01	33.27 ± 0.26
16.82	0.46 ± 0.003	1.15 ± 0.05	2.35 ± 0.20	3.93 ± 0.06	0.69 ± 0.01	14.78 ± 0.37	2.16 ± 0.04	2.26 ± 0.05	55.15 ± 0.97	34.31 ± 0.48
20.88	0.45 ± 0.01	1.14 ± 0.05	2.63 ± 0.08	4.20 ± 0.19	0.69 ± 0.01	15.47 ± 0.36	2.21 ± 0.09	2.32 ± 0.05	49.76 ± 1.74	35.41 ± 0.28
Tomato seed										
8.15	0.30 ± 0.01	1.14 ± 0.04	1.96 ± 0.05	3.09 ± 0.17	0.50 ± 0.01	7.59 ± 0.56	1.55 ± 0.06	1.96 ± 0.06	73.58 ± 1.11	38.05 ± 0.15
12.70	0.29 ± 0.01	1.12 ± 0.06	2.04 ± 0.03	3.14 ± 0.17	0.50 ± 0.01	8.96 ± 0.29	1.69 ± 0.03	2.08 ± 0.07	73.40 ± 0.97	38.52 ± 0.28
16.53	0.29 ± 0.002	1.07 ± 0.04	2.05 ± 0.03	3.17 ± 0.12	0.49 ± 0.01	9.58 ± 0.20	1.75 ± 0.02	2.15 ± 0.03	72.34 ± 1.35	38.70 ± 0.40
20.57	0.28 ± 0.01	1.03 ± 0.06	2.10 ± 0.03	3.20 ± 0.12	0.47 ± 0.01	10.10 ± 0.35	1.79 ± 0.03	2.20 ± 0.10	71.90 ± 1.35	38.91 ± 0.15

Values are mean ± SE. GMD, Geometric mean diameter; AMD, Arithmetic mean diameter; AOR, Angle of repose

Table 2 Regression model as a function of moisture content for different engineering properties of selected vegetable crop seeds

Property	Carrot seed			Onion seed			Tomato seed		
	Regression equation	R^2	P	Regression equation	R^2	P	Regression equation	R^2	P
Bulk density	-0.008x+0.483	0.960	0.020	-0.0014x+0.480	0.931	0.035	-0.00085x+0.3080	0.931	0.035
True density	0.0116x+0.974	0.960	0.040	-0.0007x+1.157	0.997	0.001	-0.00907x+1.221	0.935	0.033
Terminal velocity	0.05716x+1.393	0.959	0.021	0.06052x+1.339	0.970	0.015	0.010215x+1.889	0.957	0.022
Test weight	0.07902x+1.32	0.962	0.019	0.0459x+3.211	0.977	0.012	0.008395+3.027	0.995	0.003
Sphericity	-0.00256x+0.470	0.962	0.018	-.000145x+0.717	0.938	0.031	-0.00244x+0.527	0.911	0.046
Surface area	0.1058x+6.099	0.934	0.033	0.1638x+12.066	0.984	0.008	0.199943x+6.160	0.957	0.022
G. mean dia	0.01088x+1.392	0.924	0.039	0.012x+1.963	0.973	0.014	0.018997x+1.420	0.948	0.026
A. mean dia	0.011x+1.772	0.942	0.030	0.0114x+2.082	0.950	0.030	0.018953x+1.822	0.977	0.012
Porosity	1.03x+52.83	0.970	0.014	-.84388x+68.367	0.931	0.035	-0.14679x+74.933	0.918	0.042
Angle of repose	0.17477x+32.271	0.976	0.012	0.32897x+28.73	0.957	0.022	0.067697x+37.564	0.961	0.020

R^2, Coefficient of determination; $P<0.05$, significant at 5% level of significance; $P<0.01$, significant at 1% level of significance.

significantly from 1.23±0.12 to 1.07±0.05 g/cm^3 as the moisture content decreased from to 20.73% to 8.15% wet basis. Regression analysis showed linear relationship and found significant ($P< 0.05$) with coefficient of determination 0.96 (Table 1 and 2). But the true density of onion and tomato was found to decrease by 6.15% and 9.65% when the moisture content increased by 58.6% and 60.48% respectively (Table 1). The coefficient of determination for onion and tomato was 0.997 and 0.935 respectively (Table 2). The increase in true density may be attributed to the relative higher mass due to moisture absorption than the volume which is supported by Aghajani *et al.* (2012) for barley, Ilori *et al.* (2016) for amaranthus and Pandiselvam *et al.* (2014) for onion. Whereas decrease in true density might be attributed to increase in cell structure, higher volume expansion compared to increase in mass (Firouzi and Alizadeh 2012). Similar trend was observed in green wheat (Mahasneh *et al.* 2007) and hemp seed (Sacilik *et al.* 2003).

Table 3 Variation of coefficient of friction at different moisture levels for different material surfaces

Moisture content (%wb)	Wood	Mild steel	Aluminium	Galvanized iron
Carrot				
8.15	0.50±0.01	0.45±0.03	0.40±0.01	0.47±0.03
12.01	0.57±0.04	0.54±0.02	0.53±0.01	0.54±0.01
16.37	0.65±0.02	0.57±0.01	0.61±0.02	0.58±0.02
20.73	0.66±0.01	0.61±0.01	0.63±0.01	0.60±0.01
Onion				
8.65	0.45±0.01	0.41±0.03	0.40±0.02	0.40±0.02
12.32	0.47±0.02	0.43±0.01	0.45±0.01	0.45±0.01
16.82	0.52±0.02	0.49±0.02	0.47±0.01	0.47±0.02
20.88	0.53±0.01	0.50±0.01	0.50±0.01	0.50±0.01
Tomato				
8.15	0.51±0.02	0.47±0.01	0.52±0.02	0.50±0.01
12.70	0.52±0.01	0.55±0.01	0.58±0.01	0.52±0.01
16.53	0.59±0.01	0.59±0.02	0.60±0.01	0.57±0.02
20.57	0.61±0.01	0.64±0.02	0.62±0.01	0.61±0.02

Values are mean±SE.

Terminal velocity

The terminal velocity of carrot, onion and tomato at harvesting moisture content (20±1% w.b) was found as 2.52±0.09 m/s, 2.63±0.08 m/s, 2.10±0.03 m/s, whereas terminal velocity at safe storage moisture level (8±1% w.b) was 1.81±0.24 m/s, 1.92±0.40 m/s and 1.96±0.05 m/s, respectively. It increased significantly by 53.17%, 27% and 6.7% with the increase in moisture content by 60.68%, 58.6% and 60.48%. The regression models were found significant ($P<0.05$) with coefficient of determination (R^2) 0.96, 0.97 and 0.96 respectively for carrot, onion and tomato. The increase trend may be attributed to increase in mass of an individual seed due to increase in moisture than the increase in projected frontal area resulting to provide more force to lift. Similar trend of increase in terminal velocity with increase in moisture content was observed in cumin seed (Singh and Goswami 1996) and hemp seed (Sacilik *et al.* 2003).

Test weight

The test weight (1000 seed weight) for all the three crops increased significantly with the increase in moisture content. The test weight of carrot, onion and tomato seed decreased from 3.01±0.21 to 2.04±0.22 g, 4.20±0.19 to 3.61±0.23 g and 3.20±0.12 to 3.09±0.17 g with decrease in moisture content from 20.73 to 8.15% (w.b), 20.88 to 8.65 (w.b) and 20.57% to 8.15(w.b.) respectively. The regression models were found significant ($P<0.05$) for all the selected seeds with coefficient of determination (R^2) 0.959 for carrot, 0.970 for onion and 0.957 for tomato, respectively (Table 2). The increase in test weight was due to increase in moisture content. Similar results were reported by Pandiselvam *et al.* (2014) for onion, Firouzi and Alizadeh (2012) for cowpea,

Table 4 Regression model for coefficient of friction as a function of moisture content on different material surfaces

Material surface	Carrot			Onion			Tomato		
	Regression equation	R^2	P	Regression equation	R^2	P	Regression equation	R^2	P
Wood	0.01288x+0.41076	0.932	0.035	0.00664x+0.39442	0.953	0.024	0.00908x+0.424149	0.910	0.046
Mild steel	0.01215x+0.37023	0.934	0.034	0.00782x+0.34151	0.958	0.021	0.01329x+0.370935	0.979	0.010
Aluminium	0.01806x+0.28212	0.902	0.050	0.00811x+0.33496	0.972	0.014	0.00779x+0.469029	0.940	0.030
GI	0.01003x+0.4048	0.920	0.041	0.00753x+0.34333	0.951	0.025	0.00969x+0.408733	0.966	0.017

$R^{2,}$ Coefficient of determination; $P<0.05$, significant at 5% level of significance; $P<0.01$, significant at 1% level of significance.

Mollazade *et al.* (2009) for cumin, Altuntas *et al.* (2005) for fenugreek, Kumara *et al.* (2013) for makhana and Amin *et al.* (2004) for lentil.

Sphericity

The sphericity for carrot, onion and tomato seeds was observed as 0.42±0.01, 0.69±0.01, 0.47±0.01 respectively at moisture content of 20±1% w.b. and 0.45±0.03, 0.70±0.0.2 and 0.50±0.01 respectively at 8±1% wet basis. Sphericity decreased by 6.7%, 1.4% and 6% with the increase in moisture content by 60.68%, 58.6% and 60.48% for carrot, onion and tomato respectively. Regression analysis showed linear relationship and found significant ($P<0.05$) for all the selected crops seeds. The coefficient of determination (R^2) for carrot, onion and tomato was 0.96, 0.94 and 0.91 respectively. The results showed that the increase in length is relatively more than the width and thickness. Similar trends of decrease were reported by Nimkar and Chattopadhyay (2001) for green gram, Baryeh and Mangope (2002) for pigeon pea and Tavakoli *et al.* (2009) for soybean.

Surface area

The surface area for all the crop seeds increased significantly as the moisture content increased. The surface area of carrot, onion and tomato increased from 7.10±0.22 to 8.34±0.24 m^2, 13.39±0.28 to 15.47±0.36 m^2 and 7.59±0.56 to 10.10±0.35m^2 with increase in moisture content from 8.15 to 20.73% (w.b), 8.65 to 20.88% (w.b) and 8.15 to 20.57 % (w.b.), respectively (Table 1). Regression models were found significant ($P<0.05$) for all the selected crop seeds. The coefficient of determination (R^2) for carrot, onion and tomato was 0.93, 0.98 and 0.96, respectively (Table 2). The trend observed may be because of the fact that the size of the seed increases due to absorption of moisture. Similar trends of increase were reported by Sacilik *et al*. (2003) for hemp seed, Altuntas *et al.* (2005) for fenugreek, Tavakoli *et al.* (2009) for soybean.

Arithmetic mean diameter and geometric mean diameter

Regression models showed the significant effect of moisture content on arithmetic mean diameter and geometric mean diameter for all the crop seeds ($P<0.05$) (Table 2). Arithmetic mean diameter of carrot, onion and tomato increased by 7%, 6.5% and 10.9%, whereas geometric mean diameter increased by 7.4%, 6.8% and 13.4% with the increase in moisture content by 60.68%, 58.6% and 60.48% respectively (Table 1). The coefficient of determination (R^2) for carrot, onion and tomato was 0.942, 0.950 and 0.977 for arithmetic mean diameter whereas that of geometric mean diameter was 0.924, 0.973 and 0.948, respectively. The increase in mean diameter may be due to absorption of moisture resulting in swelling of seeds. Similar results were reported by Pandiselvam *et al.* (2014) for onion seed, Mollazade *et al.* (2009) for cumin, Tavakoli *et al.* (2009) for soybean.

Porosity

Porosity for carrot decreased from 73.82 to 60.32%, whereas that of onion and tomato increased from 49.76 to 59.95% and 71.90 to 73.58% with the decrease in moisture content from 20±1% w.b to 8±1 % wet basis. The decreasing trend in porosity may be attributed to the higher decrease in true density than bulk density whereas for increasing trend it provides an idea that decrease in bulk density is more than true density. It also indicates that the volume, shape and size increases as the seed gains moisture which creates a more intimate contact with each other, thereby reducing the pore space. The decrease in trend was also observed in hemp (Sacilik *et al.* 2003) and fenugreek (Gupta and Das 1997). Increasing trend was observed in cumin (Mollazade *et al.* 2009) and soybean (Tavakoli *et al.* 2009).

Angle of repose

The angle of repose for all the selected crops seed increased with the increase in moisture content (Table 1). Angle of repose for onion, carrot and tomato increased by 6.22%, 11.86% and 2.21% when the moisture content increased by 60.68%, 58.6% and 60.48% respectively (Table 1). The coefficient of determination of carrot, onion and tomato obtained from the regression models was 0.976, 0.957 and 0.961 respectively (Table 2). This increasing trend of angle of repose with moisture content occurs due to the reason that surface layer of moisture surrounding the particle hold the aggregate of seeds together by the surface tension (Pradhan *et al.* 2008). Similiar trends were observed for neem nut (sacilik *et al.* 2003), millet (Konak *et al.* 2002), amaranthus (Ilori *et al.* 2016), cowpea (Firouzi and Alizadeh 2012).

Coefficient of friction

The developed regression models showed significant effect of moisture content on coefficient of friction for all the crop seeds. The mean coefficient of friction increased for all the material surfaces with the increase in moisture content (Table 3). The coefficient of determination (R^2) for carrot on wood, mild steel, aluminium and galvanized iron was 0.932, 0.934, 0.902, 0.920, whereas for onion it was 0.953, 0.958, 0.972, 0.951 and that of tomato was 0.910, 0.979, 0.940, 0.966 respectively (Table 4).

The increasing trend may be attributed to increase of adhesion force between seeds and the surface resulting in more sticking of the materials as the moisture increases. Similar trends were observed in red pepper (Üçer *et al.* 2010), millet grain (Adebowale *et al.* 2012), pigeonpea (Shepherd and Bhardwaj 1986) and soybean (Tavakoli *et al.* 2009).

The study was carried out to find the effect of moisture content on various engineering properties of carrot, onion and tomato seed for design of seed dryer. The range of moisture studied was between 8±1 to 20±1% wet basis. Bulk density increased for all the studied crop seeds with decrease in moisture content. The porosity of onion and tomato seed increased, whereas that of carrot decreased as the moisture content decreased. All the other engineering properties such as test weight (1000 seed mass), surface area, arithmetic mean diameter, geometric mean diameter and angle of repose decreased with the decrease in studied range of moisture content. The regression analysis revealed that all the developed linear regression models ($P<0.05$) can be used to predict the engineering properties of vegetable seeds with an accuracy of more than 0.90. The closeness of engineering properties and almost similar behaviour of all the selected crops revealed that a single seed dryer can be designed for drying of carrot, onion and tomato seed by selection of optimum design values from engineering properties.

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