Determining physical and aerodynamic properties of garlic to design and develop of a pneumatic garlic clove metering system

Mohammad Reza Bakhtiari[1*], Desa Ahmad[2]

(1. *Academic Researcher, Department of Agricultural Engineering Research, Agricultural and Natural Resource Research Center of Hamedan Province, Hamedan, Iran;*

2. *Department of Biological and Agricultural Engineering, Faculty of Engineering, Universiti Putra Malaysia (UPM), Serdang, Selangor, Malaysia*)

Abstract: This study was conducted to investigate some moisture-dependent physical and aerodynamic properties of garlic cloves (Allium Sativum L.). A completely randomized design (CRD) with five replications was chosen for the experimental layout. The data were analyzed by SAS program version 9.1 and means comparison were done by Duncan's multiple range test (DMRT). Regression analysis was used to determine the relationship between physical and aerodynamic properties, and their moisture contents. The average length, width, thickness, geometric and arithmetic mean diameter of garlic cloves were 32.0, 21.8, 20.9, 24.4 and 24.9 mm, respectively.The average of the surface area, projected area, one thousand kernel mass, volume and bulk density of garlic cloves increased from 1718.3 to 2029.1 mm2, 546.6 to 644.3 mm^2, 6783.0 to 8159.3 g, 5916.5 to 7356.0 mm^3 and 476.3 to 567.4 kg/m^3, respectively, with increasing moisture content from 35.8% to 60.5% w.b. Studies showed that as moisture content increased, the true density decreased from 1146.4 to 1109.3 kg/m3. Within the same moisture range, the terminal velocity of garlic cloves increased linearly from 15.6 to 16.7 m/s. Finally, a vacuum seed metering system (a unit of pneumatic planter) for planting garlic cloves was designed and developed based on physical and aerodynamic properties of garlic cloves.

Keywords:garlic clove, physical and aerodynamic properties, design and develop, seed metering system

Citation: Bakhtiari, M. R., and D. Ahmad. 2015. Determining physical and aerodynamic properties of garlic to design and develop of a pneumatic garlic clove metering system.AgricEngInt: CIGR Journal, 17(1): 59-67.

1 Introduction

Garlic (*Allium Sativum* L.), belongs to the Liliaceae family, widely used as food spice in many parts of the world. For many centuries various species of garlic have been used as vegetables and spices, and also as traditional medicines for the curing of various types of diseases. Recently, a lot of researches have going-on by many plant physiologists and chemists to ascertain the possibilities of medical applications of garlic plant because of its strong flavors, culinary and medicinal properties (Hacıseferoğulları et al., 2005).

Received date: 2014-11-05 **Accepted date:** 2015-01-16

***Corresponding author:Mohammad Reza Bakhtiari,** Academic Researcher, Department of Agricultural Engineering Research, Agricultural and Natural Resource Research Center of Hamedan Province, Hamedan, Iran. Email: ym_bakhtiyari@yahoo.com.

Garlic is planted by propagated vegetative with garlic cloves because it does not have any seeds. Yield, yield components and quality of garlic are affected by planting methods, cloves rates and sizes. The major problem associated with planting garlic, is the high cost in payment for employment of manpower to plant by hand. The capacity of man power is very low about 0.05 ha/man/day, and the cost for manpower planting is 11.9% of total cost of production (Yenpayub et al., 2005).

Masoumi et al. (2006)compared some physical properties of two common types of Iranian garlic cloves (white and pink). Results of their study showed that at different moisture range from 34.9% to 56.7% w.b., the bulk density, true density and porosity of cloves were significantly affected by moisture content ($p < 0.01$). They concluded that the type of garlic had a highly significant effect on the true density and porosity (P

<0.01), as well as significant effect on the bulk density (P < 0.05). They also established the relationship between volume and dimensions of cloves using regression analysis.

In a study an innovatively designed tractor-mounted, triple unit ground-wheel driven, row crop precision mechanical planter capable of planting three rows of garlic (*Allium sativum* L.) cloves on raised bed was designed, fabricated and tested by Bakhtiari and Loghavi (2009). The results showed that the new machine is capable of planting 220000 cloves/ha at the seeding depth and spacing of 12.3 and 22.7 cm, respectively. Also, miss index, multiple index and seed damage obtained were 12.23%, 2.43% and 1.41%, respectively.

A 10-row mechanical garlic planter was connected with a 5-hp power tiller for the experimental study of the mechanics of this project having taken into account the statistical investigation for the equilibrium of the power tiller with 10-row garlic planter, evaluating all the applied forces and position of the centre of mass. As the weight of garlic was reducing step by step during the operation, the equilibrium of all the applied forces was polished for consideration of the dynamics in the operation. To analyze the handle by changing and varying the handle length a computer program was written for it (Benjaphragairat et al., 2010).

The most important part of a pneumatic planter is the vacuum seed metering system (Murray et al., 2006; Bakhtiari, 2012). Therefore, with respect to the statement above and due to lack of basic engineering properties for design and development of new methods and planters for sowing garlic cloves, in this study the physical and aerodynamic properties of garlic cloves were measured, then the most suitable seed metering system for planting garlic cloves was designed and developed.

2 Material and methods

2.1 Determination of physical and aerodynamic properties of garlic clove

Ten kilograms of garlic cloves were randomly obtained from the bulk samples on March 17, 2010 from local farmers in Iran and were cleaned manually and removed of all foreign matter such as dust, dirt, stones, chaff and damage cloves. The initial moisture contents of garlic cloves were determined by using the standard hot air oven method at 130 ± 1^{o}C for 50 minutes by following the ASAE S352.2 standard method (ASABE, 1988). To obtain desired moisture content levels, samples were kept individually in polyethylene bags of 100 μm thickness and later kept at 5^{o}C in a refrigerator for two weeks to enable the moisture to distribute uniformly throughout the samples.

Before the experiments were conducted, the required quantity of the samples were placed in the laboratory for 2 hours and allowed to equilibrate to ambient conditions. For each moisture content (35.8%, 47.4% and 60.5% w.b.), the physical (the principle dimensions, geometric and arithmetic mean diameters, aspect ratio, sphericity, surface and projected areas, real volume, true and bulk densities, and porosity) and aerodynamic properties (the terminal velocity and drag coefficient) of garlic cloves were measured. A completely randomized design (CRD) with five replications was chosen for the experimental layout. The data were analyzed by SAS program version 9.1 and means separation test were done by Duncan’s multiple range test (DMRT). Regression analysis was used to determine the relationship between physical and aerodynamic properties and their moisture contents.

2.1.1Physical properties

2.1.1.1 Principle dimension

The principal dimensions (*L*: length, *W*: width and *T*: thickness) of fifty garlic cloves per replication in each moisture treatment were determined using a vernier digital caliper with an accuracy of 0.02 mm.

2.1.1.2 The geometric mean diameter

The geometric mean diameter (D_g) of the garlic cloves was calculated using Equation 1(Rich & Teixeira, 2005; Garnayak et al., 2008):

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

2.1.1.3 The arithmetic mean diameter

The arithmetic mean diameter (D_a) of the cloves was calculated using Equation 2(Rich & Teixeira, 2005; Garnayak et al., 2008; Bakhtiari & Loghavi, 2009;Solomon & Zewdu, 2009):

$$D_a = \frac{L+W+T}{3} \tag{2}$$

2.1.1.4 The aspect ratio

The aspect ratio (R_a) of cloves was calculated using Equation 3(Kabas et al., 2007; Ixtaina et al., 2008):

$$R_a = \frac{W}{L} \tag{3}$$

2.1.1.5 The sphericity

The sphericity (φ) of the cloves was calculated using Equation 4(Abalone et al., 2004):

$$\varphi = \frac{D_g}{L} = \frac{(LWT)^{1/3}}{L} \tag{4}$$

2.1.1.6 The surface area

The surface area (A_s) of the cloves was calculated with a sphere of the same geometric mean diameter, using Equation 5(Sacilik et al., 2003; Özgüven & Vursavuş, 2005; Kabas et al., 2007; Isik, 2008; Ixtaina et al., 2008; Bakhtiari et al., 2011):

$$A_s = \pi \times D_g^2 \tag{5}$$

2.1.1.7 The projected area

The projected area (A_p) of a cloves was measured using a scanner (Epson Expression 1680, Model G780B; Seiko Epson, Nagano, Japan) connected to a computer. For this purpose, three images were acquired and the images were analyzed using a Sigma Scan Pro 5 program (Karayel et al., 2004).

2.1.1.8 The real volume of each seed and true density

The real volume of each clove (V_s) and true density (ρ_t) of cloves (the ratio between the mass and the real volume of the cloves) were determined by the toluene displacement method using a pycnometer(Bakhtiari et al., 2011). All measurements were replicated five times.

2.1.1.9 The bulk density

The bulk density (ρ_b) of the cloves was determined using the standard test weight procedure reported by Özgüven and Vursavuş (2005)by filling a container of 30 cm height and 10 cm diameter with the garlic cloves from a height of 15 cm from the top surface of the container at a constant rate and then weighing the cloves (Equation 6).

$$\rho_b = \frac{M_s}{V_c} \tag{6}$$

2.1.1.10 The porosity

The porosity (ε) was calculated using the following relationship (Equation 7) (Bakhtiari, 2012):

$$\varepsilon = \left(\frac{\rho_t - \rho_b}{\rho_t}\right) \times 100 = \left(1 - \frac{\rho_b}{\rho_t}\right) \times 100 \tag{7}$$

2.1.2 Aerodynamic properties

2.1.2.1 Terminal velocity

In this study, for each moisture content, terminal velocity (v_t) of five garlic cloves were measured experimentally in the laboratory and each clove was tested three times and the average value was calculated. The suspension cloves air velocities were determined by a vertical cylinder of plexiglass which was used to observe cloves while suspended. The air flow rate was controlled by varying the speed of the fan motor. When the samples were suspended, air velocity was recorded as terminal velocity of cloves by an anemometer to a resolution of 0.1 m/s (Zewdu & Solomon, 2007).

2.1.2.2 Drag coefficient

The drag coefficient of the garlic cloves (C_d) were calculated using Equation 8 derived from Bakhtiari (2012):

$$C_d = \frac{2M_p g}{\rho_a A_p v_t^2} \tag{8}$$

3 Results and discussions

Means of the physical and aerodynamic properties of garlic cloves at different moisture contents are presented in Table 1. The best fit relationships between the physical and aerodynamic properties and the moisture content of garlic cloves are represented by the regression equations shown in Table 2.

Based on results of the physical and aerodynamic properties of garlic cloves a seed metering system for planting garlic cloves was designed and developed as follows:

3.1 Design and develop of a vacuum seed metering system for planting garlic cloves

3.1.1 Diameter of openings on the seed plate

Based on Barut and Özmerzi (2004) results, the shape of openings (holes) for the seed plate was recommended as a circular hole. To prevent the seed from entering the seed opening, angle of openings on the seed (metering) plate (2β) should be conical in shape (Figure 1) to be completely closed by a seed to avoid multiple seeds being picked up by the seed plate (Singh et al., 2005). Finding of Bakhtiari (2012) and Singh et al. (2005) showed the most suitable conical angle of the seed plate is 120°.

Table 1Means of the physical and aerodynamic properties of garlic clove at different moisture contents

Property	Unit	Moisture Content (% w.b.)[a]		
		35.8	47.4	60.5
Length, L	mm	30.93 b	31.96 b	33.08 a
Width, W	mm	20.79 b	21.64 b	22.83 a
Thickness, T	mm	19.89 b	21.08 a	21.73 a
Geometric mean diameter, D_q	mm	23.39 c	24.43 b	25.41 a
Arithmetic mean diameter, D_a	mm^2	23.87 c	24.89 b	25.88 a
Aspect ratio, R_a	decimal	0.67 a	0.68 a	0.69 a
Sphericity, φ	decimal	0.76 a	0.76 a	0.77 a
Surface area, A_s	mm^2	1718.29 c	1875.06 b	2029.13 a
Projected area, A_p	mm^2	546.60 c	595.75 b	644.32 a
1000 kernel mass of garlic cloves, M_{1000}	g	6783.00 b	7280.67 b	8159.33 a
Volume of one clove, V_s	mm^3	5916.50 c	6442.70 b	7356.00 a
True density, ρ_t	kg/m^3	1146.39 a	1130.02 b	1109.28 c
Bulk density,ρ_b	kg/m^3	476.28 b	537.91 a	567.39 a
Porosity, ε	decimal	58.45 a	52.39 b	48.85 b
Terminal velocity, v_t	m/s	15.60 b	16.37 a	16.67 a
Drag coefficient, C_d	decimal	0.77 a	0.77 a	0.86 a

[a] Means in the same rows followed by different letters are significantly different at 5% level by DMRT.

Table 2Equations representing relationship between physical and aerodynamic properties and moisture content of garlic clove (M = 35.8-60.5% w.b.)

Source of Variation	R^2	Regression Equation	Equation Number
Seeds Length, L (mm)	0.9999 **	$L = 0.0870\ M + 27.8220$	9
Seeds Width, W (mm)	0.9963 *	$W = 0.0828\ M + 17.789$	10
Seeds Thickness, T (mm)	0.9594 ns	$T = 0.074\ M + 17.3570$	11
Geometric Mean Diameter, D_q (mm)	0.9973 *	$D_q = 0.0816\ M + 20.500$	12
Arithmetic Mean Diameter, D_a(mm)	0.9981 *	$D_a= 0.08130\ M + 20.9880$	13
Surface Area, A_s (mm^2)	0.9984 *	$A_s= 12.567\ M + 1272.2$	14
Projected Area, A_p (mm^2)	0.9985 *	$A_p = 3.9509\ M + 406.31$	15
One Thousand Kernel Mass, M_{1000}, (g)	0.9859 ns	$M_{1000} = 55.965\ M + 4726.9$	16
Volume of One Kernel, V_s (mm^3)	0.8907 ns	$V_s = 58.52317\ M + 3768.4502$	17
True Density, ρ_t (kg/m^3)	0.9989 *	$\rho_t = - 1.5042\ M + 1200.6$	18
Bulk Density, ρ_b (kg/m^3)	0.9453 ns	$\rho_b= 3.6578\ M + 351.98$	19
Porosity, decimal, ε	0.9660 ns	$\varepsilon = - 0.3861\ M + 71.725$	20
Terminal velocity, v_t	0.9218 **	$v_t= 0.0429\ M + 14.159$	21
Drag coefficient, C_d	0.7877 ns	$C_d = 0.0037\ M + 0.6196$	22

ns: Not significant; *: Significant at 5% level; **: Significant at 1% level

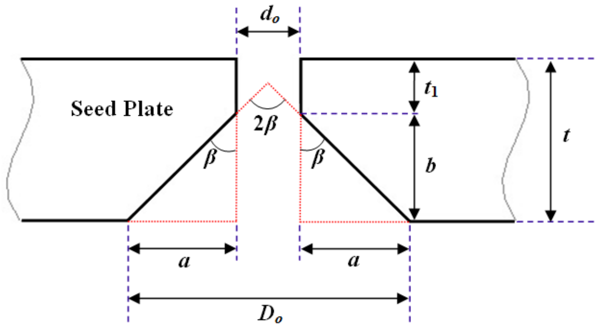

Figure 1Dimensions of openings (holes) on the seed plate (Source: Bakhtiari (2012))

Singh et al. (2005), in determining the diameter of opening on the seed (metering) plate for cotton seeds, considered the opening diameter based on the less than 50% size of the geometric mean diameter ($d_o \leq 50\%\ D_g$). Therefore it was extended on the other seeds and bulbs such as garlic cloves. In the present research, the diameter of openings on the seed plate (d_o) was also based on the less than 50% size of the geometric mean diameter of the garlic cloves. Due to this study, the maximum geometric mean diameter of garlic cloves was D_g= 25.41 mm (Table 1), Thus:

$d_o \leq 0.50 \times D_g$ and $d_o \leq 0.50 \times 25.41$ mm

then$d_o \leq 12.705$ mm (Figure 1 and Figure 2)

Based on Singh et al. (2005) and Bakhtiari (2012) for 2β = 90, 120 and 150^o:

$$D_g \cos 45 \leq d_o < D_g \quad 23$$

25.41 cos45 ≤ d_o< 25.41, then 17.96 ≤ d_o< 25.41

25.41 cos60 ≤ d_o< 25.41, then 12.70 ≤ d_o< 25.41

25.41 cos75 ≤ d_o< 25.41, then 6.57 ≤ d_o< 25.41

Therefore, the opening diameter of the seed plate (metering plate) must be considered between 6.57 to 25.41 mm in diameter for garlic cloves.

For calculating D_o considering $b = t - t_1 = 1$ mm, for optimum diameter and angle of openings on the seed plate d_o = 20.0 mm and 2β = 150^o and from Equations 24 to 25:

$$a = b\tan\beta = (t - t_1)\tan\beta \quad 24$$

$$D_o = 2a + d_o = 2b \times \tan\beta + d_o \quad 25$$

$$D_o = 2(t - t_1) \times \tan\beta + d_o \quad 26$$

Now for calculating opening diameter of the seed plate, with b = 1 mm or $t - t_1$ = 1 mm, d_o = 20 mm and entrance section cone angle (opening angle of seed plate), 2β = 150^o, and Equation 26, $D_o \approx 27.5$ mm.

3.1.2 Number of openings on the seed plate

Whereas the rotational speed of the ground (transporting) wheel of seeding machine and seed plate were considered equal ($n_s = n_w$), then the circumference of ground wheel (C_w) for wheel diameter D_w = 25 in = 63.5 cm, from Equation 27 will be$C_w \approx 200$ cm.

$$C_w = \pi \times D_w \quad 27$$

If seed spacing within row (x_s) for garlic is 10 cm, thus from Equation 28 number of openings or cells on the seed plate with assuming N_r = 1, for garlic must be n = 20.

$$n = \frac{C_w}{x_s \times N_r} \quad 28$$

3.1.3 Diameter of the pitch circle of the seed plate

For determining the diameter of pitch circle of the seed plate (D_p), it can be given in terms of a circumference of pitch circle seed plate (Figure 2), as follows:

$$D_p = \frac{C_p}{\pi} = \frac{n \times (D_o + C_o)}{\pi} \quad 29$$

Substituting by n = 20, D_o = 27.5 mm (from Equation 29 for d_o = 20 mm, b = 1 mm and 2β = 150^o) and C_o = 22.5 mm, then $D_p \approx 320$ mm.

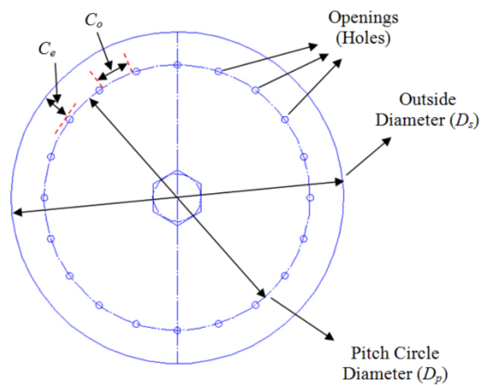

Figure 2 Schematic of seed plate and its components (Source: Bakhtiari (2012))

3.1.4 Outside diameter of the seed plate

For determining the outside diameter of the seed plate, D_s(Figure 2) from Equation 30,D_s≈380 mm.

$$D_s = D_p + D_o + 2C_e \quad 30$$

3.1.5 Vacuum of negative pressure

Based on this study (Table 1), the following properties have been obtained for garlic cloves:

Geometric mean diameter of garlic clove, D_g= 25.41 mm

Mass of one garlic clove, M_p = 8.16 g

Projected area of garlic clove, A_p = 644.32 mm^2

Thus, from Equation 31(Singh et al., 2005), P_o = 124.24 Pa.

$$P_o = F_D / A_p = M_p g / A_p \quad 31$$

or based on results of this study for garlic cloves considering from Table 1:

Terminal velocity of garlic cloves, v_t = 16.67 m/s

Drag coefficient, C_d = 0.86

Mass density of the air, ρ_a= 1.168 kg/m^3(for given arbitrary constant temperature T = 30^{o}C and based on Geankoplis (2003), Page 971, Table A 3-3) and from Equation 32, $P_o = 139.57$ Pa.

$$P_o = \frac{F_D}{A_p} = \frac{0.5C_d \rho_a A_p v_t^2}{A_p} = 0.5C_d \rho_a v_t^2 \quad 32$$

By considering the highest amount for P_o = 139.57, D_g = 24.41 (Table 1) and from Equation 33(Sial & Persson, 1984), d_o will be between 0.2 kPa to 3.6 kPa:

$$P_m = P_o \left(\frac{D_g}{d_o} \right)^2 = P_o \times (D_g / d_o)^2 = 139.57 \times (25.41 / d_o)^2$$

Hence, the lowest and highest of required minimum pressure difference P_m, for holding one garlic cloves of 25.41 mm geometric mean diameter, mass of 7.41 g and d_o = 5.0 - 20.0 mm and would be 0.2 and 3.6 kPa, respectively.

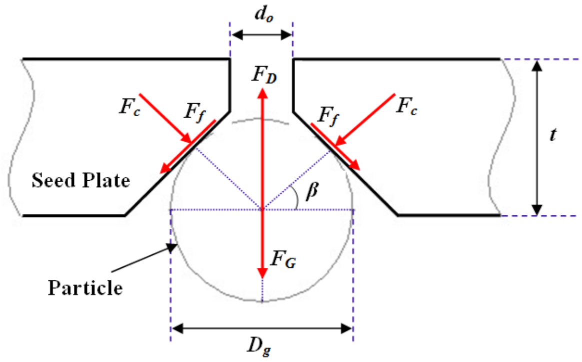

Figure 3 Forces acting on a seed held in a conical opening of a seed plate
(Source: Bakhtiari (2012))

In order to estimate the optimum vacuum pressure of the pneumatic seeding machine (precision vacuum seeder), the mathematical model was used that was developed by Karayel et al. (2004).

Based on this study, the following maximum amounts of the physical properties have been obtained for garlic cloves (Table 1):

One thousand kernels mass, M_{1000} = 8159.33 g;

Projected area of garlic cloves, A_p = 644.32 mm^2;

Sphericity of garlic cloves, φ = 77%;

Unit (true) density of garlic cloves, ρ_t = 1146.39 kg/m^3.

Therefore for garlic cloves:

1) Predicted vacuum pressure of the pneumatic seeding machine as a function of one thousand kernels mass (Equation 34):

$$P = 1.18 \times (M_{1000})^{0.20}, (R^2 = 0.92) \quad 34$$

Therefore for garlic clove P will be P = 7.15 kPa.

2) Predicted vacuum pressure of the pneumatic seeding machine as a function of projected area (Equation 35), P = 3.99 kPa. 33

$$P = 1.96 \times (A_p)^{0.11}, \quad (R^2 = 0.59) \quad 35$$

3) Predicted vacuum pressure of the pneumatic seeding machine as a function of sphericity (Equation 36), P = 3.51 kPa.

$$P = 0.04 \times (\varphi) + 0.43, (R^2 = 0.80) \quad 36$$

4) Predicted vacuum pressure of the pneumatic seeding machine as a function of true (kernel) density (Equation 37), P = 3.31 kPa.

$$P = 0.002 \times (\rho_t) + 1.02, \quad (R^2 = 0.57) \quad 37$$

The predicted vacuum pressure values by the models for garlic clove were: 3.31 3.51, 3.99, and 7.15 kPa.

Based on present results above (opening diameter of the seed plate, d_o = 5.0 - 20.0 mm; angle of openings on the seed plate, 2β = 90^o, 120^o and 150^o; number of openings or cells on the seed plate, n = 20; pitch circle diameter of the seed plate, D_p ≈ 320 mm; outside diameter of the seed plate, D_s ≈ 380 mm), a vacuum seed metering system to install on pneumatic seeding machine in order to planting garlic clove was designed and developed (Figure 4 to Figure 11).

Figure 4Vacuum garlic clove metering system (right view)

Figure 5Vacuum garlic clove metering system (up view)

Figure 6 Vacuum garlic clove metering system (left view)

Figure 7Vacuum garlic clove metering system (inside view)

Figure 8Vacuum garlic clove metering system (the seed container and seed plate)

Figure 9Vacuum garlic clove metering system (the cover and open arc-shaped seal)

Figure 10Vacuum garlic clove metering system (the cover)

Figure 11 Parts of the vacuum garlic clove metering system

4 Conclusions

In this study the average length, width, thickness, geometric and arithmetic mean diameter of garlic cloves were calculated as 32.0, 21.8, 20.9, 24.4 and 24.9mm, respectively. The results showed that the average of the surface area, projected area, one thousand kernel mass, volume and bulk density of garlic cloves increased from 1718.3 to 2029.1 mm^2, 546.6 to 644.3 mm^2, 6783.0 to 8159.3 g, 5916.5 to 7356.0 mm^3 and 476.3 to 567.4 kg/m^3, respectively, with increasing moisture content from 35.8% to 60.5% w.b. Studies showed that as moisture content increased, the true density decreased from 1146.4 to 1109.3 kg/m^3. Within the same moisture range, the terminal velocity of garlic cloves increased linearly from 15.6 to 16.7 m/s. Finally, in this study a vacuum seed metering system in order to install on the pneumatic garlic planter was designed and developed based on physical and aerodynamic properties of garlic cloves and some design parameters.

List of Symbols (Optional)

A_p	Projected area normal to direction of motion, m^2
a	Horizontal length of conical openings, mm
A_s	Surface area of clove, mm^2
b	Thickness (vertical length) of conical openings, mm
C_d	Drag coefficient, dimensionless
C_e	Clearance from edge of openings to outside edge of the seed plate, mm
C_o	Clearance between openings on seed plate, mm
C_p	Circumference of the pitch circle seed plate, mm
C_w	Circumference of drive (transporting) wheel, cm
D_a	Arithmetic mean diameter of clove, mm
D_g	Geometric mean diameter of clove, mm
d_o	Opening diameter of the seed plate
D_o	Diameter of conical opening edges (outside diameter of the seed opening) on the seed plate, mm
D_p	Diameter of pitch circle of the seed plate, mm
D_s	Outside diameter of the seed plate, mm
D_w	diameter of drive (transporting) wheel, cm
F_c	Contact force, N
F_D	Drag force, N
g	Gravitational acceleration of clove, m/s2
L	Length of clove, mm
M_{1000}	One thousand kernel mass, g
M_p	Mass of a single clove, kg
M_s	Total mass of the cloves in the container, kg
n	Number of openings (holes or cells) on the seed plate
N_r	Ratio between teeth of drive wheel sprockets and seed plate gears
n_s	Rotational speed of the seed plate, rpm
n_w	Rotational speed of ground wheel of the planter, rpm
P	Predicted vacuum pressure, kPa
p	Probably level
P_m	Required minimum pressure difference, Pa
P_o	Negative (vacuum) pressure, Pa
P_t	Pressure difference at terminal velocity, Pa
R_2	Coefficient of determination
R_a	Aspect ratio of clove, dimensionless
T	Thickness of clove, mm
t	Thickness of the seed plate, mm
t_1	Thickness of openings, mm
V_c	Volume of the container, m3
V_s	Volume of the clove, m3
v_t	Terminal velocity of cloves, m/s
W	Width of clove, mm
x_s	Theoretical space between seeds within the row, cm

Greek symbols

β	Entrance section cone angle, degree
ε	Porosity, %
ρ_a	Specific density of air, kg/m^3
ρ_b	Bulk density, kg/m^3
ρ_t	True density, kg/m^3
φ	Sphericity of the clove, dimensionless

References

Abalone, R., A. Cassinera, A. Gastón, and M. A. Lara. 2004. Some physical properties of amaranth seeds. *Biosystems Engineering*, *89*(1): 109-117.

ASABE. 1988. ASAE Standards S352.2. Moisture measurement. Ungrounded seed and seeds: St. Joseph, MI 49085-9659, USA.

Bakhtiari, M. R. 2012. *Design, development and evaluation of a kenaf pneumatic seeding machine.* PhD Thesis, Universiri Putra Malaysia, Kuala Lumpur, Malaysia. Retrieved from http://www.upm.edu.my.

Bakhtiari, M. R., D. Ahmad, J. Othman, and N. Ismail. 2011. Physical and mechanical properties of kenaf seed. *Applied Engineering in Agriculture, 27*(2): 263-268.

Bakhtiari, M. R., and M. Loghavi. 2009. Development and evaluation of an innovative garlic clove precision planter. *Journal of Agricultural Science and Technology (JAST), 11*(2): 125-136.

Barut, Z. B., and A. Özmerzi. 2004. Effect of different operating parameters on seed holding in the single seed metering unit of a pneumatic planter. *Turkish Journal of Agriculture and Forestry, 28*(6): 435-441.

Benjaphragairat, J., N. Ito, and H. Sakurai. 2010. Study of the mechanics of a 5 hp power tiller attached to a 10-row garlic planter. *Agricultural mechanization in Asia, Africa, and Latin America (AMA), 41*(1): 40-44.

Garnayak, D. K., R. C. Pradhan, S. N. Naik, and N. Bhatnagar. 2008. Moisture-dependent physical properties of jatropha seed (*Jatropha curcas* L.). *Industrial Crops and Products, 27*(1): 123-129.

Geankoplis, C. J. 2003. *Transport processes and separation process principles* (Fourth ed.): Pearson Education, New Jersey.

Hacıseferoğulları, H., M. Özcan, F. Demir, and S. Çalışır. 2005. Some nutritional and technological properties of garlic (*Allium sativum* L.). *Journal of food engineering, 68*(4): 463-469.

Isik, E. 2008. Effect of moisture content on some physical and mechanical properties of sira bean grains. *Transactions of the ASABE, 51*(2): 573-579.

Ixtaina, V. Y., S. M. Nolasco, and M. C. Tomás. 2008. Physical properties of chia (*Salvia hispanica* L.) seeds. *Industrial Crops and Products, 28*(3): 286-293.

Kabas, O., E. Yilmaz, A. Ozmerzi, and İ. Akinci. 2007. Some physical and nutritional properties of cowpea seed (*Vigna sinensis* L.). *Journal of Food Engineering, 79*(4): 1405-1409.

Karayel, D., Z. B. Barut, and A. Özmerzi. 2004. Mathematical modelling of vacuum pressure on a precision seeder. *Biosystems Engineering, 87*(4): 437-444.

Masoumi, A. A., A. Rajabipoor, L. G. Tabil, and A. A. Akram. 2006. Physical attributes of garlic (*Allium sativum* L.). *Journal of Agricultural Science and Technology (JAST), 8*(1): 15-23.

Murray, J. R., J. N. Tullberg, and B. B. Basnet. 2006. Planters and their components: types, attributes, functional requirements, classification and description (ACIAR Monograph No. 121). 135-137.

Özgüven, F., and K. Vursavuş. 2005. Some physical, mechanical and aerodynamic properties of pine (*Pinus pinea*) nuts. *Journal of Food Engineering, 68*(2): 191-196.

Rich, E. C., and A. A. Teixeira. 2005. Physical properties of mucuna (velvet) bean. *Applied Engineering in Agriculture 21*(3): 437-443.

Sacilik, K., R. Öztürk, and R. Keskin. 2003. Some physical properties of hemp seed. *Biosystems Engineering, 86*(2): 191-198.

Sial, F. S., and S. P. E. Persson. 1984. Vacuum nozzle design for seed metering. *Transactions of the ASAE, 27*(1): 688-696.

Singh, R. C., G. Singh, and D. C. Saraswat. 2005. Optimisation of design and operational parameters of a pneumatic seed metering device for planting cottonseeds. *Biosystems Engineering, 92*(4): 429-438.

Solomon, W. K., and A. D. Zewdu. 2009. Moisture-dependent physical properties of niger (*Guizotia abyssinica Cass*.) seed. *Industrial Crops and Products, 29*(1): 165-170.

Yenpayub, J., S. Kingthong, and J. Benjaphragairat. 2005. Design and development of a garlic planter in Thailand.

Zewdu, A. D., and W. K. Solomon. 2007. Moisture-dependent physical properties of tef seed. *Biosystems Engineering, 96*(1): 57-63.