Physical and aerodynamic properties of date palm pollen grains

Mohamed M. IBRAHIM [1, 2], Mohamed GHONIMY [3, 1], Eid ABD EL RAHMAN [1]

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Abstract: The present study was designed to determine the effect of four moisture content levels (4, 5, 6, and 7 %) on the physical and aerodynamic properties of date palm pollen grain (DPP). The physical properties of DPP included pollen length (L), width (w), thickness (T), projected area (A_p), geometric mean diameter (d_g), mass (m), sphericity (S), and bulk density (ρ_p). It was observed that the moisture content did not significantly influence the physical properties of the DPP. The aerodynamic properties of DPP included the terminal velocity (V_t), drag coefficient (D_c), drag force (Df), and Reynolds number (Re). The pollen Reynolds number (Re) is significant at different pollen grain moisture content, and regression models were developed in the form of polynomial and exponential relationships. Also, the 3rd order polynomial relationship was found between Re and D_c. The results showed that the average values of V_t, D_c, Df, and Re were about 0.6 m s^{-1}, (0.38 to 0.45), 1.09E-11 N, and (0.29 to 0.42), respectively. The results of this study will be helpful in the performance of date palm pollination machines.

Key words: aerodynamic, date palm, pollen grain, properties, terminal velocity

Fizikalne in aerodinamične lastnosti pelodnih zrn dateljeve palme

Izvleček: Namen raziskave je bil določiti učinek štirih vsebnosti vode (4, 5, 6, in 7 %) na fizikalne in aerodinamične lastnosti pelodnih zrn dateljeve palme (DPP). Fizikalne lastnosti so obsegale dolžino peloda (L), širino (w), debelino (T), projekcijsko površino (A_p), poprečni geometrični premer (d_g), maso (m), sferičnost (S), in gostoto (ρ_p). Ugotovljeno je bilo, da vsebnost vode ni značilno vplivala na fizikalne lastnosti peloda. Aerodinamične lastnosti peloda so obsegale končno hitrost (V_t), koeficient upora (D_c), moč upora (Df) in Reynoldovo število (Re). Reynoldovo število peloda (Re) je bilo značilno različno pri različnih vsebnostih vode, razvit je bil regresijski model na osnovi polinomnih in ekspotencialnih razmerij. Med Re in D_c je bilo ugotovljeno polinomno razmerje tretjega reda. Rezultati so pokazali, da so bile poprečne vrednosti parametrov V_t, D_c, Df, in Re okrog 0,6 m s^{-1}, (0,38 do 0,45), 1,09E-11 N in (0,29 do 0,42). Rezultati raziskave bodo pripomogli k boljšemu delovanju opraševalnih naprav.

Ključne besede: aerodinamika, dateljeva palma, pelodna zrna, lastnosti, končna hitrost

1   Department of Agricultural Engineering, Faculty of Agriculture, Cairo University, Giza, Egypt
2   Corresponding author, e–mail: mohamed.ibrahim@agr.cu.edu.eg
3   Department of Plant Production and Protection, College of Agriculture and Veterinary Medicine, Qassim University, Buraydah, Saudi Arabia

1 INTRODUCTION

Date palm is the source of a wide range of products and services, including many necessities of life. The primary product of the date palm is fruit, which is rich in protein, vitamins, and mineral salts. The total date palm production in Egypt is about 1.64 million tons annually (FAOSTAT, 2019). Date palm pollination has been identified as a major factor for successful date production since quality and fruit yield depend on the correct application of pollen grains. It has conclusively been shown that the benefits of the pollination process lie in obtaining large-sized, high-quality fruits, avoiding the presence of small fruits (Salomón-Torres et al., 2017).

In Egypt, farmers select male palm trees and exchange palm pollen between farms even over long distances from the country (Bekheet and El-Sharabasy, 2015) Notably, the production of pollen from male palms differs significantly according to changing geographic regions. Generally, any male palm variety's pollen can be used to pollinate any female variety. Either, to establish a perfect pollination and achieve the highest yield with good fruit quality, it was advantageous to mix pollen grains with different carriers, essential minerals and ascorbic acid. It also improves the effectiveness of pollination (Radwan et al., 2022). However, as most male palms are seedlings, there are significant variances in the pollen quality of these plants (Salomón-Torres et al., 2021). In addition, pollen's physical and aerodynamic properties are one of the most important properties that affect pollination. The characteristics of pollen can affect its transmission from date palm pollinating machines to female flowers. Alharbi and Mousa (2021) studied some physical properties of palm pollen in the Qassim region, Saudi Arabia; they reported that date palm pollen grains come in a wide variety of shapes, sizes, and surface marking characteristics. The palm pollen sizes range from 3.3 to 704 μm. The pollen shape found in this study was spherical. The aerodynamic properties are the most important in describing the movement of grains in the air. For designers and operators of agricultural machinery, knowledge of the aerodynamic properties of the grain (floating velocity, final velocity, aerodynamic coefficient of resistance) is important and essential (Polyák and Csizmazia, 2010). These properties are terminal velocity, drag force, drag coefficient, and Reynolds number (Khoshtaghaza and Mehdizadeh, 2006). Terminal velocity is the steady air velocity value at which an object or a material is suspended in the vertical air stream. In other words, the maximum or terminal speed–attained in free fall before air resistance will keep it from falling faster (Mohsenin, 2020). The morphology of pollen grains may also affect the aerodynamic–properties. The relationship between terminal velocity and moisture content of pistachio nut was studied by Unal et al. (2008), 14.2 % increasing percentage in the terminal velocity was found depending on the change in moisture content from 5.83 to 30.73 % (*wb*). Morever, Matouk et al. (2008) mentioned that coffee cherries ('Catual') drag coefficient decreased from 0.05 to 0.03 as moisture content increased from 10.7 to 53.9 % (*d.b*). According to Eşref, and Nazmi (2016), as the moisture content of yellow lentil seeds increased the terminal velocity increased linearly from 1.5 to 2.09 m s^{-1} due to the increasing seed mass per unit frontal that faces the air stream. Abubakar et al. (2019) fabricated a measuring device to determine the terminal velocity of paddy rice, sorghum, and bean grains. Terminal velocities results in that study were 6.95 ± 0.37, 4.71 ± 0.24, and 10.98 ± 0.27 m s^{-1} for paddy rice, sorghum, and beans, respectively. In addition, the device efficiency was found to be 70.06 %. Thus, the main objective of this article is to determine the physical and aerodynamic properties of date palm pollen grain because these properties significantly impact the performance of date palm pollination machines.

2 MATERIALS AND METHODS

2.1 DATE PALM POLLEN GRAINS (DPP) PREPARATION

DPP collected from three resources of a local market in Siwa Oasis, Matrouh Governorate, Egypt, free of foreign matters, immature, and broken grains were selected for this study. The date palm pollen variety used in this research is not specified because commercial companies selling pollen have collected from more than one source and mixed them to improve the properties of the resulting crop.

Traditionally, pollen grains for some varieties are mixed and then used for pollination. Moisture content is one of the most important factors affecting the quality of the pollination process. The moisture content of the pollen grains was determined using the oven method at 103 ± 2 °C until reaching a constant mass (AOAC, 2000) and as described in many investigational studies. Results of minimum and maximum moisture content values of DPP were 3.6 and 8.2 % respectively. Considering the significance of moisture content in pollination process. Four levels of moisture content (4 %, 5%, 6 %, and 7 % *db.*) were used to determine the aerodynamic properties of the DPP. So far, each moisture content level was prepared using a pollen sample taken and placed in the oven at a temperature of 50 ºC, then the sample mass was measured, and moisture content was calculated every 15

minutes' interval, in order to find out the time required to remove moisture to reach the different required moisture contents (4 %, 5 %, 6 %, and 7 % *dry basis*). After that, each sample was placed inside a desiccator in order to acclimatize it to the ambient environment (Coşkun et al., 2005). Conversely, the levels of chosen moisture content cover the range often seen in stored DPP and was checked before each experiment.

2.2 PHYSICAL PROPERTIES OF DATE PALM POLLEN GRAIN

2.2.1 Date palm pollen grain mass (*m*)

The mass (*m*) of the date palm pollen grain was calculated by dividing the 1 g of pollen mass by the number of pollen per one gram. Using the hemocytometer method, it is possible to count the number of pollens in a specific volume of water (suspensions solution: water + pollen) (Mahmoud-Aly et al., 2018). A hemocytometer method consists of microscope (QUANTA FEG250, Japan) and a thick glass microscope slide (dimension 3×3 mm). The slide is divided into nine squares (dimension 1 × 1 mm), as shown in (Fig. 1). The volume covered by one square is calculated by multiplying the area of one square (1 mm x 1 mm = 1 mm^2) by the depth of the square (0.1 mm). Hence, the final volume of each square is 0.0001 ml. The 2.5 g of pollen grains were added to 500 ml of distilled water and mixed for 5 min using magnetic stiller, so the dilution factor is 200 ml of water 1 g^{-1} of pollen (500 ml of water 2.5 g^{-1} of pollen). The sample from suspension solution was loaded into slide by using a micropipette. Then the hemocytometer slide was placed under the microscope, so it could determine the pollens

number. The average pollen per small square was calculated (448 pollen). The number of pollen grains per one gram was calculated from equation (1).

$$N_{pg} = \frac{P_{ss} \times Du}{vss} \tag{1}$$

Where; N_{pg} is the number of pollen grains per one gram, P_{ss} is the average number of pollens per small square (448 pollen), *Du* is the dilution factor (equal to 200 ml g^{-1}), and *vss* is the volume of suspension upper small square (equal to 0.0001 ml).

2.2.2 Date palm pollen grain dimensions and projected area

The DPP dimensions were measured at different moisture content levels (4, 5, 6, and 7 %) using scanning electron microscopy (SEM, JSM-5200, Jeol Japan). Twenty date palm pollen were randomly selected from each moisture content level to determine grain dimensions and projected area (*Ap*). Three major dimensions of the pollen grain, namely length (*L*, μm), width (*w*, μm), and thickness (*T*, μm) were measured according to the biggest and smallest surface of the pollen grain (Obi and Offorha, 2015). The pollen samples were placed on a copper holder and coated with a fine gold layer using a fine coat (JFC-1100 E, Ion sputtering device, JEOL, Japan) before the observation to avoid electrostatic charging during observation. Then, the sample was observed under a high vacuum with acceleration voltage (25 kV) and at 500, 2000, and 5000-fold magnifications. The projected area of the pollen was determined by using the Image J program.
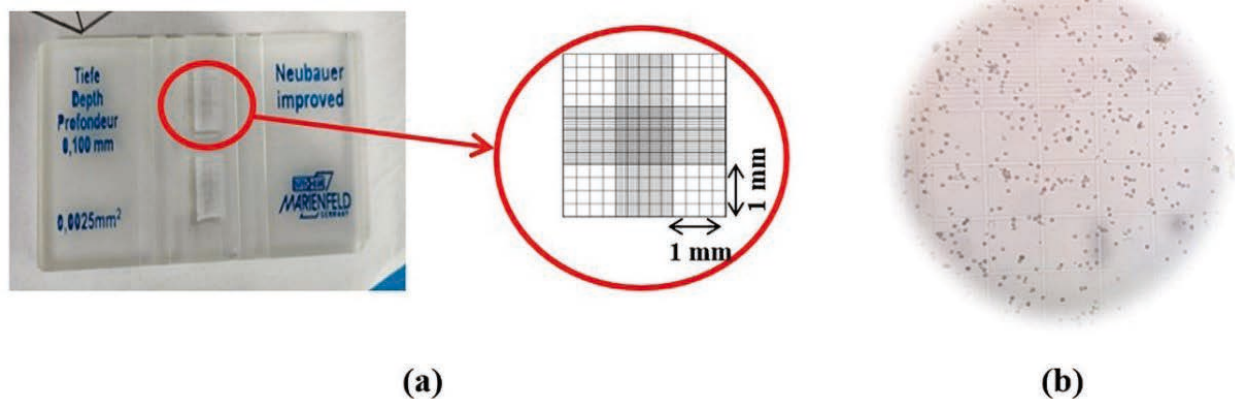

Figure 1: Pollen number determination using hemocytometer methods: (a) hemocytometer slide, and (b) pollen under microscope

2.2.3 The bulk density (ρ_p)

The bulk density (ρ_p) defined as the mass per unit volume of a particle, was determined for date palm pollen grain at different moisture content levels according to Abdelhady et al. (2023).

2.2.4 The geometric mean diameter (d_g)

The geometric mean diameter (d_g, μm) was calculated from equation (2) according to Mohsenin (2020)

$$d_g = (L.w.T)^{1/3} \qquad (2)$$

Where; L is the pollen grain length (μm), w is the pollen grain width (μm), and T is the pollen grain thickness (μm).

2.2.5 Sphericity (S)

The sphericity expresses the shape character of the pollen relative to that of a sphere of the same volume. Assuming that the diameter of the circumscribed sphere is equal to the longest intercept L of the ellipsoid and that the volume of the pollen grain is equal to the volume of a triaxle ellipsoid with intercepts L, w, and T. Also, the degree of sphericity (S) was calculated from equation (3), according to Mohsenin (2020).

$$S = \frac{d_g}{L} \qquad (3)$$

2.3 AERODYNAMIC PROPERTIES OF DATE PALM POLLEN GRAIN

2.3.1 Terminal velocity (V_t)

To evaluate the performance of pollination operations and options involving the presence of air flow, it is necessary to determine the terminal velocity of the date palm pollen grain. It will be used in studying the pollen grain in the airflow. When the pollen grain is immersed into an ascendant air flow, the pollen is subjected to the action of two kinds of forces: gravitational force and resisting drag force as shown in Fig. (2).

When these vector magnitudes are balanced (Fig. 2), the pollen grain begins a movement at a constant speed so-called terminal velocity that is depending on pollen mass (m), acceleration due to gravity (g), pollen

grain density (ρ_p), air flow density (ρ_a), drag coefficient (D_c), and pollen grain projected area (A_p).

The experimental DPP terminal velocity (V_t) was measured at different moisture content levels using a device illustrated in Fig. (3). It consists of a centrifugal fan connected with an electric motor (Dayton- 1/70 HP). The air velocity was controlled by a digital control switch/regulator inverter connected to the blower motor; it is allowed to change the speed of the motor (Obaia and Ibrahim, 2015). The next unit was a cylindrical tube, it is divided to three parts. The first part is a PVC pipe with a length of 200 mm and a diameter of 50 mm, connected at its upper end to a grid to homogenize airflow. The second part is a PVC pipe with a length of 700 mm and a diameter of 50 mm connected at its upper end to a perforated screen to carry pollen on it. This tube has two holes in the middle with a diameter of 5 mm to connect the sensors to measure the speed of the air stream. The third part of the tube is a transparent glass tube (acrylic) with a length of 900 mm and a diameter of 50 mm to watch the pollen grains being carried by the air stream. The terminal velocity of the studied DPP could be obtained by measuring the air velocity required to suspend the particles
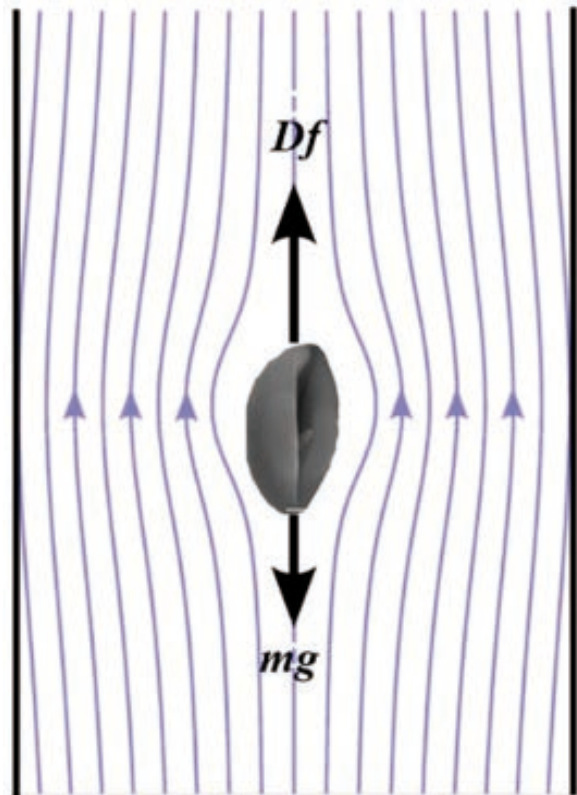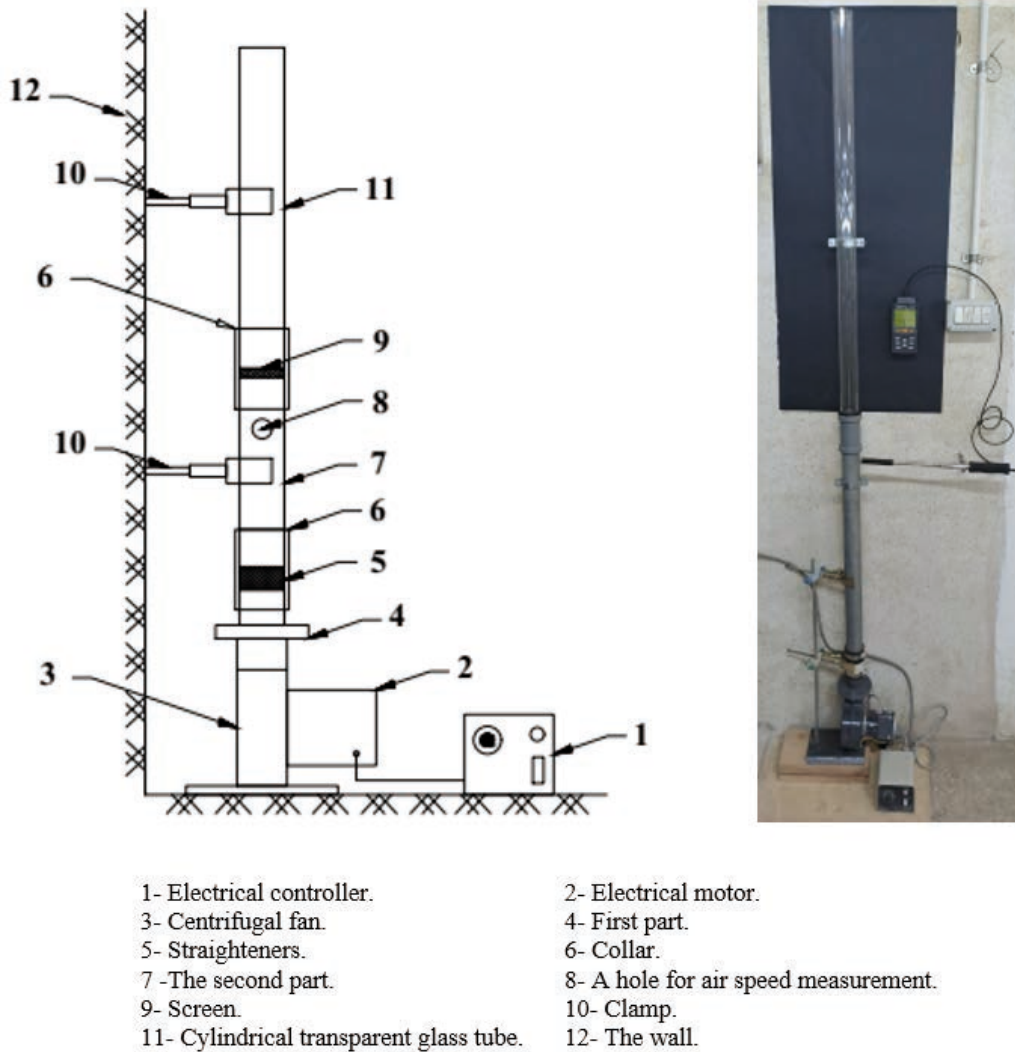

Figure 2: Pollen weight and drag force acting on the date palm pollen grain

1- Electrical controller.
3- Centrifugal fan.
5- Straighteners.
7 -The second part.
9- Screen.
11- Cylindrical transparent glass tube.

2- Electrical motor.
4- First part.
6- Collar.
8- A hole for air speed measurement.
10- Clamp.
12- The wall.

Figure 3: Experimental set-up used for measuring the terminal velocity

in the vertical air stream. The air velocity was measured by using the hot wire air velocity meter connected with a velocity probe (TENMARS TM-4001-the air velocity: 0.01 - 25 m s⁻¹).

tational acceleration (9.81 m s⁻²), ρ_p is the particle bulk density (kg m⁻³), ρ_a is the air bulk density which equals to 1.206 kg m⁻³ at room temperature, A_p is projected area of date palm pollen grain (m²), and V_t is the pollen grain terminal velocity (m s⁻¹).

2.3.2 The drag coefficient (D_c)

The drag coefficient (D_c) of date palm pollen grains was calculated from equation (4) according to Mohsenin (2020).

$$D_c = \frac{2m.g.(\rho_p - \rho_a)}{\rho_p.\rho_a.A_p.V_t^2} \qquad (4)$$

Where D_c is the drag coefficient (dimensionless), m is the date palm pollen grain mass (kg), g is the gravi-

2.3.3 The drag force (Df)

When air flow occurs around the date palm pollen grain, the action of the forces involved can be illustrated by Fig. (4).

The pressure on the upper side of the pollen grain is less than the pressure P in the undisturbed air stream and that on the lower side is greater than the pressure P in the undisturbed air stream. The results in a decrease of pressure, -P, on the upper side indicated by arrows drawn
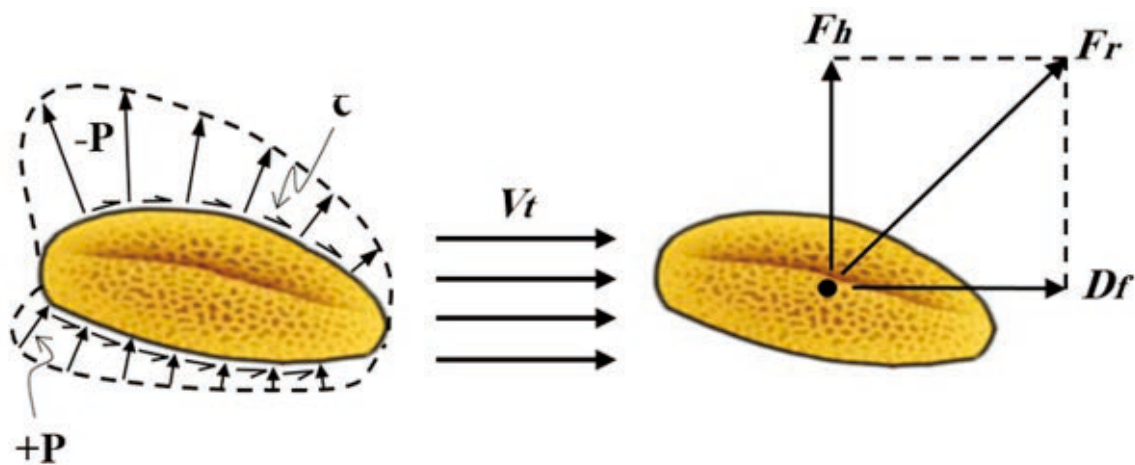
Figure 4: Air flow rate and force analysis acting the pollen grain

away from the surface, and an increase of pressure, +P, shown by arrows drawn toward the object. In addition, these forces normal to the surface of the pollen, and there are shear stresses, τ, acting tangential to the surface in the direction of airflow and resulting from frictional effects. The resultant force Fr, may be resolved into components of drag force (Df) and lift force (Fh). The equations for calculating Df and Fh have been derived by dimensional analysis assuming the smooth pollen grain having a projected area (Ap), moving through air flow density (ρ_a), drag coefficient (D_c), and air velocity (V_t). Therefore, the Df will be as the following equation,

$$Df = f(\rho_a, V_t, Ap, Dc) \qquad (5)$$

To derive the drag force using the Kirchhoff and Gogh-Mann dimensional analysis method, the following steps are followed:

1. Determine the number of properties involved in the relation, n = 5

Table 1: Symbols and dimensions of the properties affecting the drag force of date palm pollen grain

Property	Symbol	Dimension $M^\mu L^\lambda T^\tau$		
		μ	λ	τ
Drag force	Df	1	1	-2
Air density	ρ_a	1	-3	0
Air velocity	V_t	0	1	-1
Projected area	Ap	0	2	0
Drag coefficient	D_c	0	0	0

2. Write the dimensions of all the properties involved in the relationship are shown in table (1).

3. Choose three base quantities, in this case it is (ρ_a, V_t, Ap), which must satisfy the following condition:

$$\Delta = \begin{vmatrix} \mu_1 & \lambda_1 & \tau_1 \\ \mu_2 & \lambda_2 & \tau_2 \\ \mu_3 & \lambda_3 & \tau_3 \end{vmatrix} = \begin{vmatrix} 1 & -3 & 0 \\ 0 & 1 & -1 \\ 0 & 2 & 0 \end{vmatrix} \neq 0$$

4. Determine the number of criteria (k)
K = n-3 = 5-3 = 2

5. The relation (5) can be writen as follows:

$$\frac{Df}{\rho_a{}^{\mu_1} \ V_t{}^{\lambda_1} \ A_p{}^{\tau_1}} = f(1, \ 1, 1, \frac{Dc}{\rho_a{}^{\mu_2} \ V_t{}^{\lambda_2} \ A_p{}^{\tau_2}}) \quad (6)$$

6. On the basis of π theory, it can be writen:

$$\pi_1 = \frac{Df}{\rho_a{}^{\mu_1} \ V_t{}^{\lambda_1} \ A_p{}^{\tau_1}} \quad , \quad \pi_2 = \frac{Dc}{\rho_a{}^{\mu_2} \ V_t{}^{\lambda_2} \ A_p{}^{\tau_2}} \quad (7)$$

7. Estimating the values of μ, λ and τ for each criterion using dimensional analysis and solving equations algebraically and by substituting in the original exponential functional relationship, we get that:

$$Df = \frac{D_c \cdot A_p \cdot \rho_a \cdot V_t{}^2}{2} \qquad (8)$$

Where Df is the drag force (N), A_p is the date palm pollen grain projected area (m²), ρ_a is the air density which is equal to 1.206 kg m⁻³ at room temperature(Gupta, 2013), and V_t is the pollen grain terminal velocity (m s⁻¹).

2.3.4 Reynolds number (*Re*)

Reynolds number (*Re*) is an essential aerodynamic attribute that represents the ratio of inertial effects to viscous effects on the particle, in similar words, it is the ratio between the product of the particle's velocity and length scale to viscosity of the medium/fluid in which the particle is moving in this case, air (Zare et al., 2013). In most recent methodology, the Reynolds number (*Re*) was calculated from equation (9) (Grega et al., 2013):

$$Re = \frac{\rho_a . V_t . d_g}{\mu} \tag{9}$$

where ρ_a is the air density, which is equal to 1.206 kg m^{-3} at room temperature, V_t is the pollen grain terminal velocity (m s^{-1}), d_g is the geometric mean diameter of the seed (m), and μ is air viscosity (1.816 × 10^{-5} N s m^{-2} at room temperature).

The tested values of moisture content (*MC*) were 4, 5, 6, and 7 % *dry basis*.

2.4 STATISTICAL PROCEDURE

Measured data with all variables were statistically analyzed by a software program (CoStat ver. 6.400, 2008), applying a complete randomized design via analysis of variance. The means of the treatments were obtained, and Student-Newman-Keuls differences were tested at a 5 % level of probability.

3 RESULTS AND DISCUSSION

3.1 PHYSICAL PROPERTIES OF DATE PALM POLLEN GRAIN

The average values of the date palm pollen grain length (*L*), width (*w*), thickness (*T*), geometric mean diameter (d_g), projected area (A_p), mass (*m*), sphericity (*S*) and bulk density (ρ_p) at four levels of moisture content 4, 5, 6, and 7 % are listed in Table (2) and Fig. (5). It is clear that the pollen grain dimensions *L, w, T, d_g, S, m,* and ρs were insignificant at different pollen grain moisture content. The pollen grain length (*L*) increased by 1.0 and 2.03 % when the moisture content increased from 4 to 5, and 6 %, respectively while the *L* decreased by 1.5 % when the moisture content increased from 6 to 7 %. Also, the *L* increased by 1.0 % when the *MC* increased from 5 % to 6 %. The same trend was found for *w*, and *T*. The geometric mean diameter (d_g) remained nearly con-
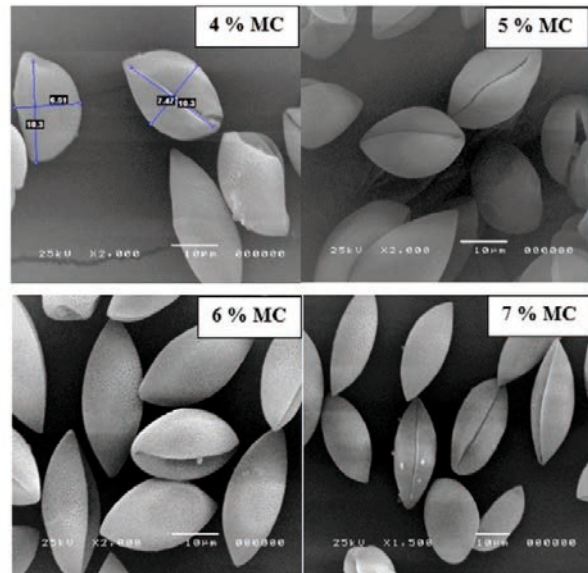

Figure 5: Scanning electron microscopy of date palm pollen grain at different levels of moisture content

stant (10.4 μm), with the *MC* increased from 4 to 7 %. The pollen mass (*m*), and sphericity (*S*) remained nearly constant at 1.1E-12 kg, and 0.52, respectively, with the *MC* increased from 4 to 7 %. The pollen grain projected area (*Ap*) increased by 1.4, 1.9, and 2.5 % when the moisture content increased from 4 to 5, 6, and 7 %, respectively. Also, the *Ap* increased by 0.5 and 1.1 % when the pollen grain moisture content increased from 5 % to 6 and 7 %, respectively. The bulk density (ρ_p) increased by 0.7, 1.4, and 2.6 % when the moisture content increased from 4 to 5, 6, and 7 %, respectively. Also, the ρ_p increased by 0.7 and 1.9 % when the pollen grain moisture content increased from 5 % to 6 and 7 %, respectively. The lack of increase in the dimensions and projected area of date pollen grain with the increase of moisture content is due to the hardness of the pollen cover and its lack of water absorption (Pope, 2010; Bunderson and Levetin, 2015).

3.2 AERODYNAMIC PROPERTIES OF DATE PALM POLLEN GRAIN

The average values of aerodynamic properties included terminal velocity (V_t), drag coefficient (D_C), drag force (*Df*), and Reynolds number (*Re*) of the date palm pollen grain (DPP) at different moisture content (4, 5, 6, and 7 %) are listed in Table (3). It's clear that the V_t, D_C, and *Df* were insignificant at different pollen grain moisture content. However, the pollen Reynolds number *Re* are significant at different pollen grain moisture content.

Table 2: Physical properties of date palm pollen grain at different moisture contents

MC,% dry basis	Pollen grain dimensions							
	L, μm	w, μm	T, μm	d_g, μm	S	m, kg	Ap, μm^2	ρ_p, kg m^{-3}
4	19.7 ± 8.6 a	8.6 ± 0.9 a	6.8 ± 2.6 a	10.4 ± 1.8 a	0.52 ± 0.1 a	1.1E-12 ± 6.2E-28 a	133.33 ± 58.0 a	692.9 ± 21.9 a
5	19.9 ± 4.1 a	8.8 ± 1.8 a	6.8 ± 1.7 a	10.4 ± 1.4 a	0.52 ± 0.1 a	1.1E-12 ± 6.2E-28 a	135.21 ± 41.9 a	697.6 ± 22.4 a
6	20.1 ± 4.2 a	8.8 ± 1.4 a	6.8 ± 1.4 a	10.5 ± 1.2 a	0.52 ± 0.1 a	1.1E-12 ± 6.2E-28 a	135.92 ±3 7.6 a	702.4 ±2 3.7 a
7	19.9 ± 4.3 a	8.9 ± 1.4 a	6.9 ± 1.4 a	10.4 ± 1.4 a	0.52 ± 0.1 a	1.1E-12 ± 6.2E-28 a	136.70 ± 38.1 a	711.2 ± 25.2 a
Significant	n.s	n.s	n.s	n.s	n.s	n.s	n.s	n.s

MC = Pollen moisture content, L = pollen length, w = pollen width, T = pollen thickness, d_g = pollen geometric mean diameter, S = pollen sphericity, m = pollen mass, Ap = pollen projected area, ρ_p = pollen bulk density
n.s. Not significant at the 0.05 and 0.01 probability levels

Table 3: Aerodynamic properties of date palm pollen grain at different moisture content

MC (% dry basis)	V_t, m s^{-1}	D_c	Df, N	Re
4	0.59 ± 0.03 a	0.45 ± 0.16 a	1.09E-11 ± 7.1E-16 a	0.29 ± 0.014 b
5	0.60 ± 0.02 a	0.41 ± 0.13 a	1.09E-11 ± 3.1E-16 a	0.31 ± 0.015 b
6	0.60 ± 0.03 a	0.39 ± 0.12 a	1.09E-11 ± 5.1E-16 a	0.39 ± 0.011 a
7	0.60 ± 0.03 a	0.38 ± 0.10 a	1.09E-11 ± 7.2E-16 a	0.42 ± 0.039 a
Significant	n. s	n. s	n. s	*

MC = Moisture content, V_t = Terminal velocity, D_c = drag coefficient, Df = drag force, Re = Reynolds number
* Significant at the 0.05 probability level.
 n.s. Not significant at the 0.05 and 0.01 probability level

For terminal velocity (V_t), the average values of V_t were about 0.59 and 0.6 m s^{-1}. The terminal velocity (V_t) of pollen grains was thoroughly examined as it plays an important role in the performance of pollination machines. The frequency distribution of the measured values of V_t are shown in Figure (6). It is clear that the 25, 35, 30, and 30 % of the V_t measured values ranged from 0.59 to 0.6 m s^{-1} for 4, 5, 6, and 7 % (*dry basis*) of moisture content, respectively.

Also, from Table (3), the average values of drag coefficient (D_c) were 0.45 ± 0.16, 0.41 ± 0.13, 0.39 ± 0.12, and 0.38 ± 0.10 for 4, 5, 6, and 7 % (*dry basis*) of moisture content respectively. The results confirmed an inverse relationship between D_c and pollen moisture content, as the moisture content of pollen grains increased from 4 to 7 %. (dry basis) the drag coefficient decreased from 0.54 to 0.38. The pollen grain D_c decreased by 8.0, 13.3, and 15.5 % when the moisture content increased from 4 to 5, 6 and 7 % (*dry basis*) respectively. While, the D_c decreased by 4.9, and 7.3 % when the moisture content increased from 5 to 6 and 7 % (*dry basis*) respectively. In addition, the D_c decreased by 2.6 % when the moisture content increased from 6 to 7 % (*dry basis*). For drag force (Df), the Df remained nearly constant, 1.09E-11 N, with the MC increased from 4 to 7 % (*dry basis*). This means that the DPP mass is not affected by the increase

in moisture content (From Table 3), and therefore, it does not need an increase in the drag force.

The Reynolds number (Re) of date palm pollen grain increased by increasing moisture content. A direct relationship was observed for the Re as it increased from 0.29 to 0.42 as the moisture content increased from 4 to 7 % (*dry basis*) and Re increased by 6.9, 34.5, and 44.8 % when the moisture content increased from 4 to 5, 6, and 7 % (*dry basis*), respectively. While the Re increased by 25.8, and 35.5 % when the moisture content increased from 5 to 6 and 7 % (*dry basis*) respectively. In addition, the Re increased by 7.7 % when the moisture content increased from 6 to 7 % (*dry basis*). The maximum value of drag coefficient was found at moisture content level 4% (dry basis), while the highest value of V_t and Re were performed at 7 % (*dry basis*) moisture content level.

The relation between Reynolds number (Re) and drag coefficient (D_c) is shown in Fig. (7). It's clear that there is an inverse relationship between Re and D_c. The data of Re and D_c was analyzed to give the best fit relation of the 3rd order polynomial function:

$$D_c = a\,Re^3 + b\,Re^2 + c\,Re + d \qquad (10)$$

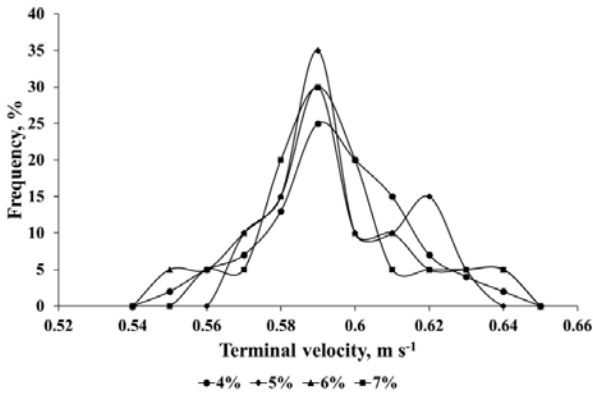The range of the Reynolds number (Re) into equation (10) were $0.42 \geq Re \geq 0.29$ while, the values of the

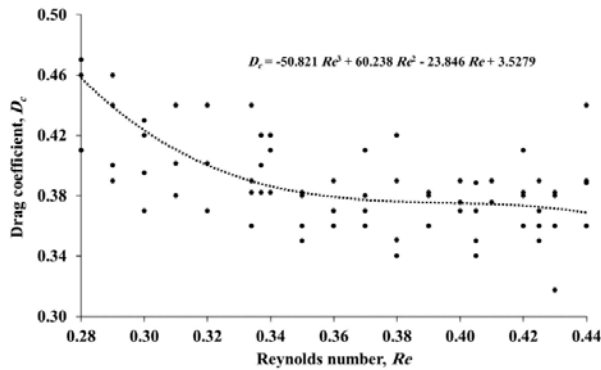**Figure 6**: The frequency distribution of the pollen grain terminal velocity

Figure 7: Drag coefficient (D_c) versus Reynolds number (Re) at four levels of moisture content

constants *a, b, c, and d* were (-) 50.821, 60.238, (-) 23.846, and 3.527 respectively.

3.3 REGRESSION MODELS

Data from the research of the date palm pollen grain's (DPP) aerodynamic characteristics at various *MC* levels were fitted and the best fit was chosen. The models created for the DPP's terminal velocity (V_t), drag coefficient (D_c), and Reynolds number (Re) as functions of

Table 4: Regression models of aerodynamic properties of date palm pollen grain

Regression models	R²
$V_t = -0.0025\ MC^2 + 0.0155\ MC + 0.5775$	0.93
$D_c = 0.0075\ MC^2 - 0.0605\ MC + 0.5025$	1.00
Df = Constant = 1.09E-11	
$Re = 0.249\ e^{\,0.134\ MC}$	0.95

MC are shown in Table 4. The R² varied between 0.93 and 1.00. The suitable models for predicting the aerodynamic characteristics of DPP as a function of moisture content were found to be polynomial regression models. As a function of moisture content, Pradhan et al. (2010) initiated a polynomial model for the terminal velocity of mung bean seeds, whereas linear models were created for the drag coefficient and Reynolds number. Additionally, Nalbandi et al. (2010) initiated a polynomial model for predicting Makhobeli seed terminal velocity as a function of moisture content. A linear relationship was reported by Khodabakhshian et al. (2012) between the V_t of Tef grain and its *MC*, while for the terminal velocity of coffee cherries and beans as a function of their moisture content and true density, a non-linear equation was derived by Matouk et al. (2008).

4 DISCUSSION

The present study evaluated and modeled the physical and aerodynamic properties of date palm pollen grain (DPP) as a function of moisture content. In summary, the physical properties of DPP included pollen length (*L*), width (*w*), thickness (*T*), projected area (A_p), geometric mean diameter (*dg*), mass (*m*), sphericity (*S*), and bulk density (ρ_p). It was observed that the physical properties of the DPP were not significantly influenced by the moisture content. The aerodynamic properties of DPP included the terminal velocity (V_t), drag coefficient (D_c), drag force (*Df*), and Reynolds number (*Re*). The results indicated that the terminal velocity increased slightly from 0.59 to 0.6 m s⁻¹ with an increase in moisture content from 4 to 7 % (*dry basis*). As it was noted by Nalbandi et al. (2010) the slight increase in the terminal velocity of the DPP with an increase in the moisture content may be attributed to the formation of the pollen grain cover is a solid layer that does not absorb water, so there is no increase in the pollen grain mass thus the critical speed of pollen is not affected. Furthermore, Sharma et al. (2012) reported an increase in the terminal velocity of mung bean from 4.86 to 5.29 m s⁻¹ as the moisture content increased from 7.28 to 17.77 % (*db*). Strong evidence was found according to Galedar et al. (2010) study, the terminal velocity (m s⁻¹) of sunflower, soybean, and canola seeds increased by 10.67 %, 2.16 %, and 4.31 %, as the moisture content of the seeds increased from 7.35 to 23.7, 9.52 to 24.64, and 7.11 to 25.72 % (wb), respectively, these results agree with the present study findings. Also results showed that the D_c od DPP decreased from 0.45 to 0.38 with the increase in moisture content from 4 to 7 % (*dry basis*). The results of this investigation concur with the bulk of other studies conducted by various research-

ers, which found an inverse relationship between the drag coefficient and the moisture content of seeds. The inverse connection could be explained by variations in the seeds' surface characteristics, actual densities, morphologies, and sizes as the moisture content increased. Also, it was mentioned by Nalbandi et al. (2010) that Makhobeli, triticale, and wheat seeds' drag coefficient decreased by increasing seeds' moisture content.; while Mohsenin (2020) reported that as the *MC* increased from 6.2 to 14.4 % (*dry basis*) for the cultivars NSFH-36, PSFH-118, GKSFH-2002, and SH-3322, respectively, the drag coefficient of four different cultivars of unshelled sunflower seeds decreased from 0.23 to 0.18, 0.31 to 0.20, 0.27 to 0.16, and 0.36 to 0.12. The current study's findings are consistent with those of Pradhan et al. (2010) for mung bean seed; the drag coefficient decreased as moisture content increased. The trend observed in the Reynolds number of DPP investigated in this study as the moisture content increased from 0.29 to 0.42 was approximately similar to that reported by Schwendemann et al. (2007) for saccate pollen grains. It was reported that the Reynolds number of saccate pollen grains increased from 2.3E-2 to 6.5E-2 with increased moisture content. The *Df* of DPP remained constant (1.09E-11 N) at different moisture content levels.

5   CONCLUSION

The physical and aerodynamic properties of date palm pollen grain (DPP) as a function of moisture content were evaluated. The physical properties of DPP included pollen grain dimensions (length *L*, width *w*, thickness *T*), projected area (A_p), geometric mean diameter (*dg*), mass (*m*), sphericity (*S*), and bulk density (ρ_p). The results indicated that, the pollen grain dimensions' *L, w, T,* and *dg* were insignificant at different pollen grain moisture content. Also**,** the pollen mass (*m*), and sphericity (*S*) remained nearly constant 1.1E-12 kg and 0.52, respectively, with the moisture content increased from 4 to 7 %. While, the pollen grain projected area (*Ap*) increased by 1.4, 1.9, and 2.5 % when the moisture content increased from 4 to 5, 6, and 7 % respectively. The pollen grain bulk density increased from 692.9 to 711.2 when the moisture content increased from 4 % to 7 %. The aerodynamic properties of DPP included the terminal velocity (V_t), drag coefficient (D_c), drag force (*Df*), and Reynolds number (*Re*). The results of aerodynamic properties indicated that the pollen grain V_t, *Df*, and *Df* were insignificant at different pollen grain moisture content. However, the pollen grain Reynolds number is significant at different pollen grain moisture content. There is an inverse relationship between the *Re* and D_c. The op-

timal models for predicting the aerodynamic properties of DPP as a function of moisture content were found to be polynomial regression models. Finally, the results of this study will be helpful in the performance of date palm pollination machines.

6   ACKNOWLEDGMENTS

7   REFERENCES

Abdelhady, A., Ibrahim, M., Mansour, H., El-Shafie, A., & Abd El Rahman, E. (2023). Physico-mechanical properties of sugarcane stalks. *Acta Technologica Agriculturae, 26*(3), 142–151. https://doi.org/10.2478/ata-2023-0019

Abubakar, A.J., Iya, S.A., Kabri, H.U., & Abdulrafeeu, M.A. (2019). Development of a terminal velocity measuring device for grains. *Nigeria Journal of Engineering Science and Technology Research*, *5*(1), 76-83.

Alharbi, A.B., & Mousa, H.M. (2021). Study of the expected impact of palm pollen on human respiratory tract allergy. *Pakistan Journal of Biological Sciences*, *24*, 326-334. https://doi.org/10.3923/pjbs.2021.326.334

AOAC (2000). *Official Methods of Analysis of the Association of Official Analytical Chemists*, 14th Ed. Washington D.C. USA.

Bekheet, S.A., & El-Sharabasy, S.F. (2015). Date palm status and perspective in Egypt. In *Date palm genetic resources and utilization* (pp. 75-123). Springer, Dordrecht. https://doi.org/10.1007/978-94-017-9694-1_3

Bunderson, L.D., & Levetin, E. (2015). Hygroscopic weight gain of pollen grains from *Juniperus* species. *International Journal of Biometeorology*, *59*(5), 533-540. https://doi.org/10.1007/s00484-014-0866-9

Coşkun, M.B., Yalçin, I., & Özarslan, C. (2005). Physical properties of sweet corn seed (*Zea mays saccharata* Sturt.). *Journal of Food Engineering, 74*(4), 523–528. https://doi.org/10.1016/j.jfoodeng.2005.03.039

Eşref, I.Ş.I.K., & Nazmi, İ.Z.L.İ. (2016). Effects of moisture content on some physical properties of the yellow lentil. *Journal of Agricultural Sciences*, *22*(2), 307-316. https://doi.org/10.1501/Tarimbil_0000001389

FAOSTAT. (2019). *FAO Statistical Yearbook*. Value of Agricultural Production

Galedarm M.N., Tabatabaeefar, A., Jafari, A., Sharifi, A., Mohtasebi, S.S., & Fadaei, H. (2010). Moisture dependent geometric and mechanical properties of wild pistachio (*Pistacia vera* L.) nut and kernel. *International Journal of Food Properties*, *13*(6), 1323- https://doi.org/1338.10.1080/10942910903062099

Grega, L., Anderson, S., Cheetham, M., Clemente, M., Colletti,

A., Moy, W., Talarico, D., Thatcher, S.L., & Osborn, J.M. (2013). Aerodynamic characteristics of saccate pollen grains. *International Journal of Plant Science, 174*(3), 499–510. https://doi.org/10.1086/668694

Gupta, Er. S.K. (2013). Engineering Thermodynamics. printed by Rajendra Ravindra Printers Pvt. Ltd., 7361, Ram Nagar, New Delhi.

Kara, M., Bastaban, S., Öztürk, I., Kalkan, F., & Yildiz, C. (2012). Moisture-dependent frictional and aerodynamic properties of safflower seeds. *International Agrophysics, 26,* 203–205. https://doi.org/10.2478/v10247-029-3

Kashaninejad, M., Mortazavi, A., Safekordi, A., & Tabil, L.G. (2005). Some physical properties of pistachio (*Pistachio vera L.*) nut and its kernel. *Journal of Food Engineering. 72,* 30-38. https://doi.org/10.1016/j.jfoodeng.2004.11.016

Khodabakhshian, R., Emadi, B., AbbaspourFard, M.H., & Saiedirad, M.H. (2012). The effect of variety, size, andmoisture content of sunflower seed and its kernel on their terminal velocity, drag coefficient, and reynolds number. *International Journal of Food Properties, 15*(2), 262–273. https://doi.org/10.1080/10942912.2010.483613

Khoshtaghaza, M., & Mehdizadeh, R. (2006). Aerodynamic properties of wheat kernel and straw materials. *Agricultural Engineering International: the CIGR E journal.* Manuscript FP 05 007. Vol. VIII.

Mahmoud-Aly, M., Li, Y., Shanab, S.M.M., Amin, A.Y., & HanafyAhmed, A.H. (2018). Physiological characterization of a chlamydomonas reinhardtii vacuolar transporter chaperon1 mutant under phosphorus deprivation condition. *Bioscience Biotechnology. Research, 15,* 4532-4539.

Matouk, A.M., Abd El-latif, S.M., & Tharwat, A. (2008). Aerodynamic and mechanical properties of some oil crops. *Journal of Agricultural Science, Mansoura University, 33*(6), 4195–4211. https://doi.org/10.21608/JSSAE.2008.200033

Mohsenin, N.N. (2020). Physical Properties of Plant and Animal Materials: V: *Physical Characteristics and Mechanical Properties*. Routledge. https://doi.org/10.4324/9781003062325

Nalbandi, H., Seiiedlou, S., & Ghassemzadeh, H.R. (2010). Aerodynamic properties of turgenialatifolia seeds and wheat kernels. *International Agrophysics. 24,* 57–61.

Obaia, A.R., & Ibrahim, M.M. (2015). Physical and aerodynamic property of some agricultural crops. The 4th Annual Conference of Agricultural and Bio-Engineering "The role of agricultural and biological engineering to achieve agriculture strategy regionally and internationally" 6 – 7 September 2015 Agricultural Engineering Research Institute. Egypt. *Journal of Agricultural Research, 93*(5-B), 577–585.

Obi, O.F., & Offorha, L.C. (2015). Moisture-dependent physical properties of melon (*Citrullus colocynthis* L.) Seed and kernel relevant in bulk handling. *Cogent Food & Agriculture. 1,* 1-4. http://dx.doi.org/10.1080/23311932.2015.1020743.

Polyák, N.I., & Csizmazia, Z. (2010). Measuring the terminal velocity of particles with an elutriator using image analysis. *Image Analysis in Agriculture (CIGR Workshop*), Budapest. (pp. 50-56). ISBN 978-963-503-417-8.

Pope, F.D. (2010). Pollen grains are efficient cloud condensation nuclei. *Environmental Research Letters, 5*(4), 044015. http://dx.doi.org/10.1088/1748-9326/5/4/044015

Pradhan, R.C., Meda, V., Naik, S.N., & Tabil, L. (2010). Physical properties of canadian grown flaxseed in relation to its processing. *International Journal of Food Properties. 13*(4), 732–743. https://doi.org/10.1080/10942910902818137

Salomón-Torres, R., Ortiz-Uribe, N., Villa-Angulo, R., Villa-Angulo, C., Norzagaray-Plasencia, S., & Garcia-Verdugo, C. (2017). Effect of pollenizers on production and fruit characteristics of date palm (*Phoenix dactylifera* L.) cultivar Medjool in Mexico. *Turkish Journal of Agriculture and Forestry, 41*(5), 338-347. https://doi.org/10.3906/tar-1704-14

Salomón-Torres, R., Krueger, R., García-Vázquez, J.P., Villa-Angulo, R., Villa-Angulo, C., Ortiz-Uribe, N., & Samaniego-Sandoval, L. (2021). Date palm pollen: Features, production, extraction and pollination methods. *Agronomy, 11*(3), 504. https://doi.org/10.3390/agronomy11030504

Schwendemann, A.B., Wang, G., Mertz, M.L., McWilliams, R.T., Thatcher, S.L., & Osborn, J.M. (2007). Aerodynamics of saccate pollen and its implications for wind pollination. *American Journal of Botany, 94*(8), 1371-1381. https://doi.org/10.3732/ajb.94.8.1371

Sharma, R., Sogi, D.S., & Balasubramanian, S. (2012). Aerodynamic characteristics of unshelled and shelled sunflower seeds: Significance of moisture and cultivars. *International Journal of Food Properties, 15*(1), 1-10. https://doi.org/10.1080/10942911003687215

Soliman, S.S., Alebidi, A.I., Al-Saif, A.M., Al-Obeed, R.S., & Al-Bahelly, A.N. (2017). Impact of pollination by pollen-grain-water suspension spray on yield and fruit quality of segae date palm cultivar (*Phoenix dactylifera* L.). *Pakistan Journal of Botany, 49*(1), 119-123.

Unal, H., Isık, E., Izli, N., & Tekin, Y. (2008). Geometric and mechanical properties of mung bean (*Vigna radiata* L.) grain: Effect of moisture. *International Journal of Food Properties, 11*(3), 585-599. https://doi.org/10.1080/10942910701573024

Zare, D., Bakhshipour, A., & Chen, G. (2013). Physical properties of cumin and caraway seeds. *International Agrophysics, 27,* 491–494. https://doi.org/10.2478/intag-2013-0020