AGRICULTURAL ENGINEERING (ENGENHARIA AGRÍCOLA)

Revista Brasileira de Ciências Agrárias
ISSN (on line) 1981-0997
v.17, n.1, e1143, 2022
Recife, PE, UFRPE. www.agraria.pro.br
DOI: 10.5039/agraria.v17i1a1143 - Protocol 1143
Subm. 15/06/2021 • App. 13/02/2022 • Pub. 28/03/2022

Aerodynamic properties of two quinoa (*Chenopodium quinoa* Willd.) cultivars

Jordana Moura Caetano[1]*, Ivano Alessandro Devilla[2], Pâmella de Carvalho Melo[2], Ana Cláudia Oliveira Sérvulo[1], Rafael Batista Ferreira[2]

[1] Universidade de Brasília, Faculdade de Agronomia e Veterinária, Brasília, DF, Brasil. E-mail: jordana.caetano@unb.br; anaclaudiaoservulo@hotmail.com
[2] Universidade Estadual de Goiás, Anápolis, GO, Brasil. E-mail: devilla@ueg.br; pamellamelo91@hotmail.com; rafael_g3bf@hotmail.com

ABSTRACT: The aerodynamic properties of seeds and grains are fundamental knowledge for the dimensioning of the machinery used in the processing, storage, harvest and post-harvest operations. The objective of this study was to determinate aerodynamic properties of two quinoa cultivars grains within different moisture contents. The cultivars BRS Piabiru and Real determined their physical properties (dimensions and density), terminal velocity, drag coefficient and Reynolds number, for seven moisture content (12.1, 12.8, 13.9, 15.3, 16.6, 18.0 and 19.5%d.b.). Cultivar Real have greater dimensions and lower densities than BRS Piabiru for the moisture content range studied. From the lowest to highest moisture content, terminal velocity varied from 2.70 to 3.26 m s^{-1} and from 2.57 to 3.13 m s^{-1} for cultivars BRS Piabiru and Real, respectively, while drag coefficient varied from 1.91 to 1.42 and from 2.77 to 2.44. Reynolds number is positive related to the moisture content for both cultivars. It is concluded that the moisture content and the physical characteristics of the cultivars have a significant effect on the aerodynamic properties of quinoa grains.

Key words: aerodynamic transport; drag coefficient; grain processing; Reynolds number; terminal velocity

Propriedades aerodinâmicas dos grãos de quinoa (*Chenopodium quinoa* Willd.)

RESUMO: O conhecimento das propriedades aerodinâmicas de produtos agrícolas é importante para o dimensionamento do maquinário utilizado no beneficiamento, armazenamento e operações de colheita e pós-colheita. O objetivo deste estudo foi determinar as propriedades aerodinâmicas dos grãos de quinoa. Para tal, determinaram-se as propriedades físicas (dimensões e massa específica), velocidade terminal, coeficiente de arrasto e o número de Reynolds das cultivares BRS Piabiru e Real, para sete teores de água (12,1; 12,8; 13,9; 15,3; 16,6; 18,0 e 19,5%b.s.). A cultivar Real possui dimensões maiores e massa específica menor que a BRS Piabiru para a faixa de teor de água estudada. Os resultados mostraram que a velocidade terminal aumentou de 2,70 para 3,26 m s^{-1} e 2,57 para 3,13 m s^{-1} para as cultivares BRS Piabiru e Real, respectivamente, com a elevação do teor de água dos grãos, enquanto o coeficiente de arrasto diminuiu para as respectivas cultivares, de 1,91 para 1,42 e 2,77 para 2,44. O aumento da umidade dos grãos também provocou aumento no número de Reynolds em ambas cultivares. Conclui-se que o teor de água e as características físicas das cultivares têm efeito significativo nas propriedades aerodinâmicas dos grãos de quinoa.

Palavras-chave: transporte aerodinâmico; coeficiente de arrasto; beneficiamento de grãos; número de Reynolds; velocidade terminal

* Jordana Moura Caetano - E-mail: jordana.caetano@unb.br (Corresponding author)
Associate Editor: Edna Maria Bonfim Silva

Introduction

Quinoa (*Chenopodium quinoa* Willd.) is a pseudo cereal grown mainly in the Andean region and introduced in Brazil in 1990's. It belongs to the Amaranthaceae family, Chenopodioideae subfamily. Quinoa is a rich protein source, amino acids essential to the human diet and high lipids content and is considered nutritionally superior among several other cereals (Spehar et al., 2011; Basantes-Morales et al., 2019). The global demand for quinoa has increased over the years, especially because it is an alternative source of gluten free and low-cholesterol food (Spehar et al., 2011).

Since the sowing until the pre-processing and processing operations it is necessary equipment suited to the grain physical characteristics. The lack of them results in poor adjustments of equipment made for other species, and this leads to quantitative and qualitative losses throughout the process to the storage.

Engineering is critical to provide tools for grains and seeds processing, with sufficient operating capacity and efficiency, even with the variability of products sizes and shapes. Among other factors, this optimization is possible with updating information about products physic and aerodynamic properties, enabling the formulation and evolution of machinery projects and equipment used on these stages of the production process (Haq et al., 2016; Jafari et al., 2020).

The knowledge of grain aerodynamic properties, highlighting the terminal velocity and the drag coefficient, is useful to enhance operations related to handling and pre-processing (Haq et al., 2016; Jafari et al., 2020). Besides, it is important to project and dimensioning equipment and structures needed in the harvest and post-harvest. Most of these equipment uses air to transport, drying, classification and cleaning (Haq et al., 2016; Shahbazi, 2015; Shahbazi et al., 2015).

It is known that the moisture content alters the grain terminal velocity, and this relation is direct and positive, as seen in the crambe (Cardoso Neto et al., 2020) and grain sorghum (Rodrigues et al., 2019). But very little information about this is available for quinoa. Badr & Eissa (2018) determined the terminal velocity in quinoa grains to one single moisture content value (11.6%), and the authors found high variability in the sphericity, geometric diameter, and surface area.

Due to limited information about quinoa physic and aerodynamic characterization, this paper's objective was to determine terminal velocity, drag coefficient and Reynolds number for grains of two quinoa cultivars in a moisture content range.

Materials and Methods

The experiment was developed in Vegetal Products' Drying and Storage Laboratory, of the State University of Goiás (Anápolis, GO, Brazil). There were used grains of quinoa (*Chenopodium quinoa* Willd.), cultivars BRS Piabiru and Real, obtained from Dom Bosco's Farm (Embrapa Cerrados, Planaltina, GO, Brazil) and local market, respectively. After obtaining the grains and before this experiment, the product was kept in plastic bags in 5 ± 1 °C for a period of seven days to maintain the grains properties until the beginning this experiment. The BRS Piabiru samples were cleaned manually using sieve to remove foreign matter, then homogenized. The Real samples didn't need cleaning.

Dry mass was determined before adding the moisture content proposed to the samples (Vilche et al., 2003). The quantity of water added to the samples using a manual spray and calculated based on the initial moisture content. The samples returned to the plastic bags and were kept in a B.O.D. chamber under 4 ± 1 °C for eight days to achieve moisture equilibrium, according to Caetano et al. (2018). The moisture contents established for this study were: 12.1, 12.8, 13.9, 15.3, 16.6, 18.0 and 19.5%d.b. These values usually occur for quinoa in operations involving harvest and storage.

To determine the grains moisture content were adopted the drying method, in a hot air oven at 105 °C for 24 hours. This procedure was performed in triplicate, according to the rules of Seed Analysis (Brasil, 2009).

The bulk density (ρp, kg m^{-3}) was determined by the ratio between one grain mass and its volume. The grain volume was calculated as proposed by Mohsenin (1986) as the product of grain's surface area and thickess. The grain's lenght, width and thickness were measured for it using a digital pachymeter with 0.01 mm resolution. The samples for each moisture content value were composed by 25 grains chosen randomly, with four replications. Before taken the dimensions measurements, the grains were weighed using digital scale with 0.001 g precision. The unitary grain mass was obtained indirectly by dividing the weight for the number of grains.

The projected area was calculated using the Equation 1 (Teixeira et al., 2003).

$$Ap = \pi \cdot a \cdot b \tag{1}$$

where: Ap is the particle projected area, normal to its movement in relation to the fluid (mm²), a is the grain length (mm), and b is the grain width (mm).

The geometric diameter was calculated based on the grain dimensions using the Equation 2 (Mohsenin, 1986).

$$Dg = \left(a \cdot b \cdot c\right)^{\frac{1}{3}} \tag{2}$$

where: Dg is the average grain geometric diameter (m), a is the grain length (m), b is the grain width (m), and c is the grain thickness (m).

The terminal velocity was determined experimentally using air column (Figure 1), made with a centrifugal fan connected to a 0.15 m diameter transparent acrylic tube 2.0 m long, equipped with air flux homogenizing grid. The grains were placed on the top a second subsequent grid. The fan was driven by a 0.735 kW three-phase motor and the air flux flow was controlled by a frequency inverter.

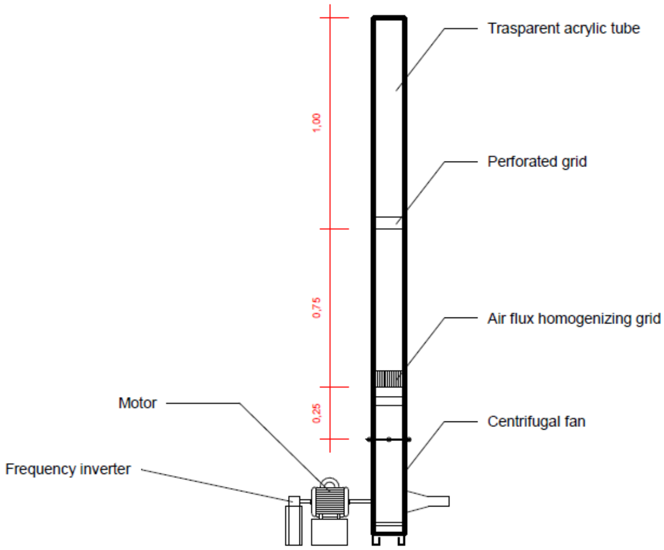

Figure 1. Layout of the equipment used to determine experimentally terminal velocity of quinoa grains.

For terminal velocity determination, a 2.0 grams sample, collected randomly, was placed on the center of the grid. The air flux was gradually increased until the product started to float. When the lowest rotational movement of the grains was achieved, the air velocity was measured centered in the top of the column using a digital anemometer.

The drag coefficient was calculated using Equation 3, obtained by Mohsenin (1986) equation for terminal velocity.

$$C = \frac{2 \cdot m \cdot g \cdot (\rho p - \rho f)}{TV^2 \cdot \rho p \cdot \rho f \cdot Ap} \quad (3)$$

where: C is the drag coefficient (dimensionless), m is the grain mass (kg), g is the gravity acceleration (9.81 m s^{-2}), ρp is the grain density (kg m^{-3}), ρf is the air density (1.293 kg m^{-3}), TV is the terminal velocity (m s^{-1}), and Ap is the grain projected area, normal to its movement in relation to the fluid (m^2).

The Reynolds number was calculated using Equation 4, which includes the terminal velocity (Mohsenin, 1986).

$$Re = \frac{\rho f \cdot TV \cdot Dg}{\mu} \quad (4)$$

where: Re is the Reynolds number (dimensionless), ρf is the air density (1.293 kg m^{-3}), TV is the terminal velocity (m s^{-1}), Dg is the grain average geometric diameter (m), and μ is the air viscosity ($1.816 \cdot 10^{-5}$ N s m^{-2}, by 20°C).

The factorial arrangement 7 x 2 (moisture contents and cultivars) was conducted as random design and with four replicates. The comparison of mean values of the factors was carried out at 1% probability level. Terminal velocity, drag coefficient, Reynolds number versus moisture content of the quinoa cultivars were fitted to linear and polynomial models. Physical properties of the cultivars for each moisture content were compared with T test (α = 0.01).

For the further analysis of quail-quantitative treatments was considered regression models that showed significance ($p < 0.01$). The models were evaluated according to statistical criterion R^2, RMS (root mean square error) and "d" Wilmott to verify adequacy of fit. The best model with the highest R^2, RMS < 0.01 and "d" > 0.85 was selected to predict the terminal velocity, drag coefficient and Reynolds number of quinoa grains as a function of the moisture content. Data were analyzed by R-Statistic.

Results and Discussion

In general, Real samples had unitary grain mass 61% greater than BRS Piabiru samples. The mean projected area, geometric diameter and density are presented in Table 1. These physical properties differ ($p < 0.01$) among cultivars for all moisture contents established. Real cultivar has larger grains (85% in average - data not shown), but less dense (about 87.1% of $\rho_{BRSPiabiru}$). Also, this cultivar has greater projected area (29.9%) and geometric diameter (18.6%) than BRS Piabiru, while the BRS Piabiru density was 14.8% higher than Real.

The moisture added to grains influenced density at different rates for each cultivar, being more than ten times accented for Real (38.02 kg m^{-3} for each 1%d.b.) compared to BRS Piabiru (3.22 kg m^{-3} for each 1%d.b.). This behavior is particular to each species, cultivar and level of processing, and these characteristics interfere in the way that changes in grain dimensions occur as a function of the increase in moisture content. Consequently, the density of the grains doesn't show the same rate of change. For example, Cardoso Neto et al. (2020) showed relation between moisture content and density for crambe seeds with pericarp and no clear relation for crambe seeds without pericarp. Vilche et al. (2003) found

Table 1. Projected area (Ap), geometric diameter (Dg) and density (ρp) of quinoa grains, cultivars BRS Piabiru and Real, in a range of moisture content (W%d.b.) (standard deviation in parentheses).

W%d.b.	Ap (mm^2)	Dg (mm)	ρp (kg m^{-3})
Cultivar BRS Piabiru*			
12.1	3.28 (0.28)	1.63 (0.06)	1,332.75 (174.64)
12.8	3.30 (0.27)	1.64 (0.06)	1,328.99 (147.34)
13.9	3.42 (0.29)	1.67 (0.07)	1,260.96 (155.82)
15.3	3.41 (0.30)	1.67 (0.06)	1,340.42 (195.47)
16.6	3.37 (0.30)	1.66 (0.07)	1,358.79 (196.44)
18.0	3.47 (0.25)	1.69 (0.05)	1,337.11 (140.02)
19.5	3.41 (0.25)	1.68 (0.05)	1,376.73 (133.55)
Cultivar Real*			
12.1	4.65 (0.44)	1.99 (0.10)	1,038.92 (166.82)
12.8	4.92 (0.39)	2.05 (0.08)	1,076.21 (117.58)
13.9	4.81 (0.38)	2.03 (0.08)	1,137.99 (142.93)
15.3	5.04 (0.37)	2.08 (0.08)	1,131.30 (135.69)
16.6	4.99 (0.38)	2.08 (0.07)	1,150.07 (117.64)
18.0	4.70 (0.34)	2.02 (0.08)	1,286.90 (158.14)
19.5	4.67 (0.34)	2.02 (0.07)	1,311.00 (147.14)

*All parameters were significative between cultivars for all moisture contents. ($p < 0.01$).

densities between 1,065 and 1,111 kg m^{-3} for quinoa (cultivar not mentioned) for this same moisture content range.

The correlation indicates some distinctions between cultivars (Table 2). Moisture content promotes increasing the dimensions of BRS Piabiru grains. For Real grains, only density responds to moisture content. This leads that smaller quinoa grains are more likely to change their dimensions with moisture variations than the larger ones.

There is no sufficient data to assume one single parameter that answer directly to this different response in physical properties among quinoa cultivars due to moisture content raise. Possibly it can be explained by the particularities of each cultivar in seed morphology, however, no scientific works were found that investigated this hypothesis.

In addition to the present study, the importance of cultivar-specific characterization is noted by the results of other studies with quinoa. In Vilche et al. (2003) study both density and geometric diameter were strongly influenced by moisture content in quinoa grains. By the linear correlation of Pérez et al. (2017) data, to moisture contents under 12.4% it was noticed that the Colombian cGC variety (673.0 kg m^{-3}, Dg = 1.864 mm) had positive relations between density and moisture content, and the cTC variety (777.8 kg m^{-3}, Dg = 1.949 mm) had negative relations. Those authors concluded, for these cultivars, that grains dimensions may increase or decrease during the drying process.

For the moisture content range, terminal velocity of the BRS Piabiru grains was greater than Real grains ($p < 0.01$). The physical properties influenced by moisture content were also strongly correlated with terminal velocity (Ap and Dg for BRS Piabiru and density for Real).

The BRS Piabiru cultivar average terminal velocity was 3.00 m s^{-1} and the Real average terminal velocity was 2.87 m s^{-1}. Badr & Eissa (2018) found terminal velocities between 0.72 and 0.87 m s^{-1} (11.6%d.b. and 1,270 kg m^{-3}) for quinoa (cultivar not mentioned), much lower values than observed in this study. It is important to point that the product evaluated by Badr & Eissa (2018) showed a high variability of geometric diameter values (CV = 42.6%).

Table 2. Pearson linear correlation between physical and aerodynamic properties of quinoa grains, cultivars BRS Piabiru and Real: moisture content (W%d.b.), projected area (Ap), geometric diameter (Dg), density (ρp), terminal velocity (TV), drag coefficient (C) and Reynolds number (Re).

BRS Piabiru	W	Dg	Ap	ρp	TV	C	Re
W	1.00						
Dg	0.84	1.00					
Ap	0.74	0.98	1.00				
ρp	0.57	0.07	-0.05	1.00			
TV	0.98	0.85	0.76	0.56	1.00		
C	-0.94	-0.92	-0.84	-0.39	-0.98	1.00	
Re	0.98	0.89	0.81	0.50	1.00	-0.99	1.00
Real	**W**	**Dg**	**Ap**	**ρp**	**TV**	**C**	**Re**
W	1.00						
Dg	0.07	1.00					
Ap	-0.18	0.96	1.00				
ρp	0.96	-0.12	-0.34	1.00			
TV	0.98	0.19	-0.05	0.94	1.00		
C	-0.84	-0.44	-0.23	-0.76	-0.93	1.00	
Re	0.93	0.40	0.17	0.85	0.98	-0.97	1.00

The average density influenced on terminal velocity. Since the terminal velocity square value is related to grain density, it is assumed that greater densities results in greater terminal velocities. Similar results were obtained by Shahbazi (2014) for safflower seeds, where the 10.0%w.b. and 1,017.1 kg m^{-3} promoted terminal velocity equal to 7.5 m s^{-1}, while 25.0%w.b. and 1,081.5 kg m^{-3} promoted 8.4 m s^{-1}. Selvi et al. (2006) noted in linseed that increasing moisture content from 8.3 to 22.3%d.b. increased density by 1.02% and terminal velocity by 52%, from 2.5 to 3.8 m s^{-1}.

Similar to density, the terminal velocity of quinoa grains increased with the moisture content. Maximal terminal velocity (3.3 m s^{-1}) was achieved by BRS Piabiru with 19.5%d.b. and minimal terminal velocity (2.6 m s^{-1}) was achieved by Real with 12.1%d.b. This behavior was indirectly predicted by the observed density values.

The terminal velocities observed were lower than air flux velocities conventionally applied in the drying and aeration operations. According to Gratão et al. (2013), those velocities vary between 25 and 50 m s^{-1}. Nevertheless, there are more costs with energy for transportation of heavier grains or wetter grains, regardless of whether transport is by mechanical or pneumatic devices (Vilche et al., 2003). In this case, it is expected that operations with BRS Piabiru grains to cost more, since its terminal velocity in average was 4.65% higher than Real cultivar, for the moisture content range studied.

In general, with 61.2% increase between the lowest and the highest moisture content used in this study, the terminal velocity increased 19.7% for BRS Piabiru and 25.0% for Real. In corn seeds and crambe seeds, on this same moisture content range, the increase was 3.6% and 7.2%, respectively (Coskun et al., 2006).

Even though this influence of moisture content on terminal velocity is evident in several species, it is also evident how those values may vary. Obi (2016) evaluated the terminal velocity of three varieties of watermelon (Charleston grey, Kaolack, and Sugar baby) from which they varied from 5.27 to 6.67, 4.40 to 6.23, and 4.00 to 6.60 m s^{-1} with moisture contents ranged from 8.61 to 24.26, 10.30 to 26.11, and 7.78 to 23.23% w.b., respectively. Cetin (2007) reported variation in terminal velocity from 14.2 to 16.6 m s^{-1} for beans seeds cv. Barbunia with moisture contents between 18.3 and 32.4%d.b. In Coskun et al. (2006) study the variation was from 5.6 to 5.8 m s^{-1} for corn seeds with 11.5 and 19.7%d.b. Similar results were noted for buckwheat (*Fagopyrum esculentum* Moench) grains (Unal et al., 2017) and coffee cherry (Afonso Júnior et al., 2007).

The raise in terminal velocity, function of moisture content, may be also attributed to weigh gains per surface area that intercepts the air flow. According to Shahbazi et al. (2015), another possible explanation is that the drag coefficient is affected by the grain moisture content. This dependence justifies the need to define an air flux velocity range adjusted to a moisture content range to optimize the separation of straws from grains in harvest, for example. The harvester segregates grains and non-grain matter by using a pneumatic system, in which the aerodynamic forces from air flux influence the cleaning performance, reducing air velocity while increases cleaning loads (Liang et al., 2020). It is important to know that any operation involving the passage of air through a grain mass modifies its moisture content.

The regressions models showed similar behavior between cultivars for terminal velocity versus moisture content, but in different rates (Figure 2). For both cultivars the quadratic model fitted better to the data, with RMS = 0.03 m s^{-1} for both, and "d" equal to 0.98 and 0.97 for BRS Piabiru and Real respectively.

Afonso Júnior et al. (2007) had better adjustment with nonlinear model for terminal velocity versus moisture content for coffee grains and coffee cherry. Shahbazi et al. (2015) described same relationship with quadratic model for lentil seeds. In the study by Obi (2016) quadratic model was adjusted for the terminal velocity as a function of moisture content of watermelon seed (cv. Charleston grey). However, the linear model is better fitted for several species in this relation, as shown for quinoa seeds (Vilche et al., 2003), crambe seeds with and without pericarp (Cardoso Neto et al., 2020).

There was detected interaction between cultivars and moisture content for drag coefficient ($p < 0.01$). For all moisture content values, Real cultivar's drag coefficient

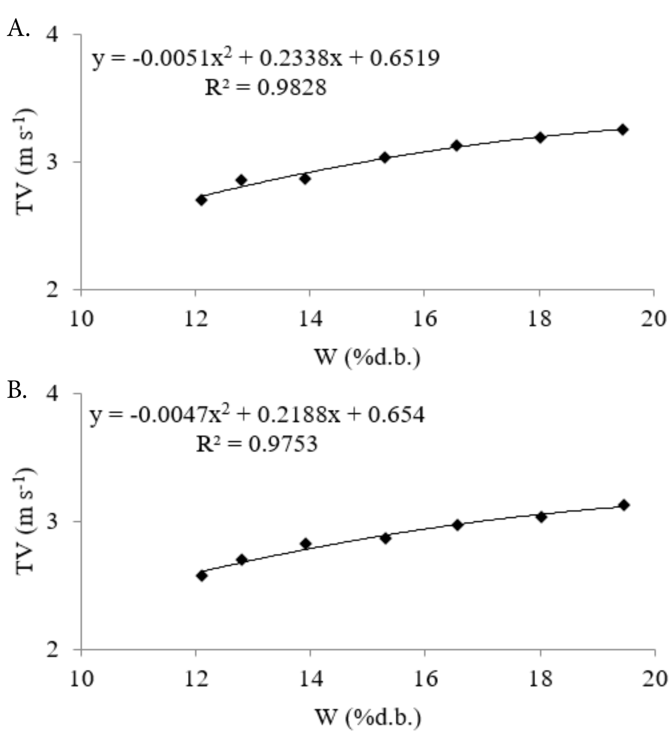

Figure 2. Terminal velocity (TV, m s^{-1}) of quinoa grains versus moisture content (W, %d.b.), regression equation and R^2 coefficient, cultivars BRS Piabiru (A) and Real (B).

(2.55) was greater than BRS Piabiru (1.60). This means that Real grains have 59.4% more aerodynamic resistance when compared with BRS Piabiru grains.

Moisture content influenced drag coefficient for both cultivars (Table 2). In a linear correlation between drag coefficient and physical properties, regardless cultivars, it was obtained 0.93 for Dg, 0.93 for Ap and -0.84 for density (data not shown). This means that larger grains will have higher aerodynamic resistance, while density will influence it inversely.

BRS Piabiru had drag coefficient strongly correlated to grains dimensions (Ap and Dg), and Real had drag coefficient more correlated to density. Although the Ap, TV and density are inputs to calculate the drag coefficient, this property may be more or less dependent on each parameter. It may suggest that in smaller grains its dimensions matter more for their aerodynamic resistance.

Mirzabe et al. (2021) investigated properties of arugula seeds (Eruca vesicaria L. or Eruca sativa Mill L.) with varying moisture contents (4.68, 9.60, 15.12 and 20.50%d.b.). The results presented also showed reduction in the drag coefficient (0.41, 0.39, 0.38 and 0.33) as a function of the increase in moisture contentes, but linear correlation between drag coefficient and geometric mean diameter (-0,93), projected area (-0,93) and bulk density (0,92), different from the behavior observed for quinoa grains. Masoumi et al. (2020) analyzed paddy grains (*Oryza sativa* L.), Hashemi and Gilaneh varieties, and observed negative linear correlation (-0.99) between physical properties (density and geometric mean diameter) and drag coefficiet for the moisture contente of 8.00, 10.50 and 13.00%w.b.

The quadratic model adjusted better ($p < 0.01$) for the drag coefficient versus moisture content for both cultivars, with RMS equal to 0.03 and 0.04, and "d" equal to 0.95 and 0.85 for BRS Piabiru and Real respectively. The Figure 3 shows the drag coefficient variation with moisture content for each cultivar.

Shahbazi et al. (2015) also better adjusted the drag coefficient versus moisture content with quadratic model for lentil seeds. For green and red lentil seeds the drag coefficient decreased from 0.69 to 0.40 and from 0.84 to 0.69, respectively, with the increasing moisture content from 10 to 25%w.b. Shahbazi et al. (2014) found negative linear relations in drag coefficient versus moisture content for *Cephalaria syriaca* L., triticale and wheat seeds.

Quinoa's drag coefficient decreases white moisture content increasing. This is due to density and projected area are determinants in moisture content value. The results agreed with the ones presented by Afonso Júnior et al. (2007) to coffee cherry cv. Catuaí, which decreased with the moisture content variation from 10.7 to 53.9%w.b. Shahbazi (2014) also reported this behavior for safflower seeds. However, in the same paper written by Afonso Júnior et al. (2007) it was also presented positive variation in drag coefficients versus moisture content for coffee cherry cv. Conilon.

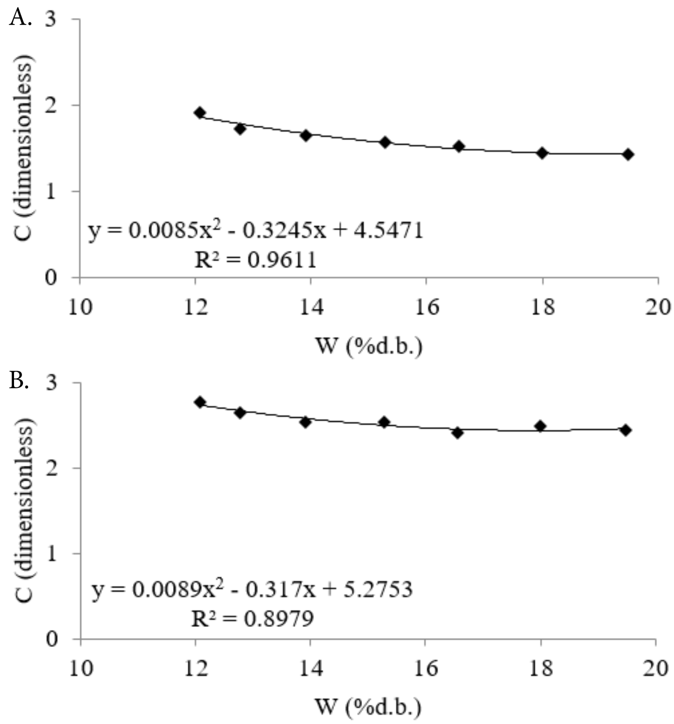

Figure 3. Drag coefficient (C, dimensionless) of quinoa grains versus moisture content (W, %d.b.), regression equation and R^2 coefficient, cultivars BRS Piabiru (A) and Real (B).

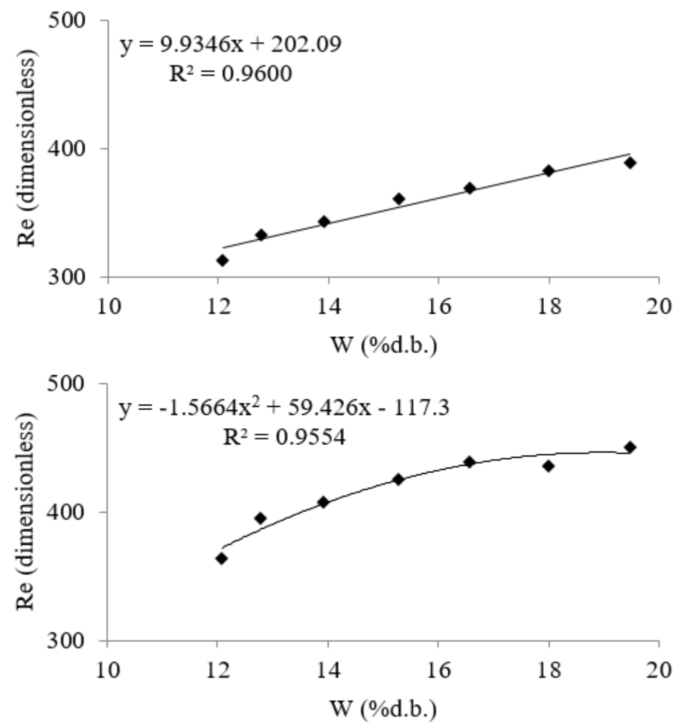

Figure 4. Reynolds number (Re, dimensionless) of quinoa grains versus moisture content (W, %d.b.), regression equation (R^2) cultivars BRS Piabiru (A) and Real (B).

Quinoa grains are more resistant to the air passage due to its size and shape when compared to sesame seeds (about two times greater) and soybean (20 times greater) (Gratão et al., 2013). In separation and cleaning operations the particles are separate when they are different and move to opposite directions due to differences in their respective drag forces. Non grain matters lighter than grains are moved through the air flux due to its drag force. On the other hand, the drag force is not very important in grains movement, as they are moved by gravity force and sieve's inertia. Thus, it is possible to regulate air flux properly to harvesters cleaning system from the particles drag force (Badretdinov et al., 2019).

Cultivars and moisture content influenced Reynolds number ($p < 0.01$), being statistically different especially between cultivars. BRS Piabiru average Reynolds number obtained was 355.5 and Real was 416.9. The variation observed is due to Real's geometric diameter is 18.6% greater than BRS Piabiru, and Reynolds number has direct relationship with this physical property.

Quinoa Reynolds number increases with moisture content. This was expected because the Reynolds number inputs respond in the same way. Shahbazi et al. (2015) reported values between 2,310.9 and 3,028.1 (31% variation) to green lentil seeds and between 1.215,0 and 1,535.1 (26% variation) to red lentil seeds in 10-25%w.b. range. Similar results were noted for watermelon seed (Obi, 2016).

For BRS Piabiru, the linear model better fitted the Reynolds number versus moisture content (RMS = 5.1) (Figure 4). For Real, the quadratic model better fitted this relation (RMS = 5.9).

Shahbazi et al. (2014) obtained better fit of Reynolds number versus moisture content using linear model for *Cephalaria syriaca* L., wheat, and triticale. Shahbazi (2015) also found linear model better fitted for beans seeds.

Reynolds number can be correlated with several parameters in storage and processing context. For both cultivars studied, the Reynolds number correlations with physical properties were similar to those noted for terminal velocity and drag coefficient. Fregolente et al. (2004) claim that Reynolds number can also be strongly correlated to effective radial thermal conductivity and to heat transfer coefficient, both important in non-isothermal processes by fixed bed grain drying.

Regarding this whole discussion, the regression models presented in this study are important to support the decision-making throughout the grain processing operations, considering that the harvest equipment are regulated based on grain moisture content at the harvest time.

Conclusions

The quinoa aerodynamic properties are influenced by both grain's moisture content and physical properties (density, projected area, and geometric diameter).

The terminal velocity varied from 2.70 to 3.26 m s^{-1} and from 2.57 to 3.13 m s^{-1} for cultivars BRS Piabiru and Real, respectively. The terminal velocity varies in a quadratic trend with moisture content increasing, in a positive correlation. The BRS Piabiru terminal velocity presented greater values due its greater density.

The drag coefficient varied from 1.91 to 1.42 and from 2.77 to 2.44 for cultivars BRS Piabiru and Real, respectively. The drag coefficient decreases with moisture content increasing in a quadratic trend. Real cultivar had greater drag coefficient. This property was influenced by terminal velocity and grains weight.

Reynold's number of cultivar BRS Piabiru were found varied from 312.93 to 389.26, while to cultivar Real varied from 364.08 to 450.76. The Reynolds number also presented positive correlation with moisture content, but in a linear trend.

Acknowledgements

The authors thank the Conselho Nacional de Desenvolvimento Científico e Tecnológico – CNPq for fellowships J. M. Caetano.

Compliance with Ethical Standards

Author contributions: Conceptualization: IVD; Data curation: JMC, PCM; Formal analysis: JMC, ACOS; Investigation: JMC, PCM; Methodology: IVD; Project administration: IVD, JMC; Resources: IVD; Supervision: IVD; Writing – original draft: JMC, IVD. PCM, ACOS, RBF; Writing – review & editing: JMC, IVD, PCM, ACOS, RBF.

Conflict of interest: There is no conflict of interest.

Financing source: The Conselho Nacional de Desenvolvimento Científico e Tecnológico

Literature Cited

Afonso Júnior, P.C.; Correa P.C.; Pinto, F.A.C.; Queiroz, D.M. Aerodynamic properties of coffee cherries and beans. Biosystems Engineering, v.98, n.1, p.39-46, 2007. https://doi.org/10.1016/j.biosystemseng.2007.03.010.

Badr, M.M.; Eissa, A.S. Some physical, mechanical and aerodynamic properties of quinoa seeds (*Chenopodium quinoa* Wild). Misr Journal of Agricultural Engineering, v.35, n.4, p.1365-1382, 2018. https://doi.org/10.21608/mjae.2018.95306.

Badretdinov, I.; Mudarisov, S.; Lukmanov, R.; Permyakov, V.; Ibragimov, R.; Nasyrov, R. Mathematical modeling and research of the work of the grain combine harvester cleaning system. Computers and Electronics in Agriculture, v.165, e104966, 2019. https://doi.org/10.1016/j.compag.2019.104966.

Basantes-Morales, E.R.; Alconada, M.M.; Pantoja, J.L. Quinoa (*Chenopodium quinoa* Willd) production in the Andean Region: challenges and potentials. Journal of Experimental Agriculture International, v.36, n.6, p.1-18, 2019. https://doi.org/10.9734/jeai/2019/v36i630251.

Brasil. Ministério da Agricultura e Reforma Agrária. Regras para análise de sementes. Brasília: MAPA, 2009. 395p.

Caetano, J.M.; Melo, P.C.; Devilla, I.A.; Gratão, P.T.S. Eficiência da técnica de reumedecimento de grãos utilizando ar frio e úmido. Global Science and Technology, v.11, n.1, p. 49-57, 2018. https://rv.ifgoiano.edu.br/periodicos/index.php/gst/issue/view/35. 13 May. 2021.

Cardoso Neto, S.R.; Resende, O.; Costa, L.M.; Oliveira, D.E.C.; Rodrigues, G.B.; Quequeto, W.D. Velocidade terminal dos frutos e sementes de crambe em função do teor de água. Research, Society and Development, v.9, n.3, e152932592, 2020. https://doi.org/10.33448/rsd-v9i3.2592.

Cetin, M. Physical properties of barbunia bean (*Phaseolus vulgaris* L. cv. 'Barbunia') seed. Journal of Food Engineering, v.80, n.1, p.353-358, 2007. https://doi.org/10.1016/j.jfoodeng.2006.06.004.

Coskun, M.B.; Yalçin, I.; Özarslan, C. Physical properties of sweet corn seed (*Zea mays saccharata* Sturt.). Journal of Food Engineering, v.74, n.4, p.523-528, 2006. https://doi.org/10.1016/j.jfoodeng.2005.03.039.

Fregolente, L.V.; Santos, A.A.; Jorge, L.M.M. Estimativa das propriedades térmicas efetivas de grãos em um secador de leito fixo. Ciência e Tecnologia de Alimentos, v. 24, n. 2, p. 270-276, 2004. https://doi.org/10.1590/S0101-20612004000200019.

Gratão, P.T.S.; Devilla, I.A.; Sérvulo, A.C.O.; Jesus, F.F.; Ferreira, D.A. Perda de pressão estática em uma coluna de grãos de quinoa. Revista Brasileira de Engenharia Agrícola e Ambiental, v.17, n.8, p. 848-854, 2013. https://doi.org/10.1590/S1415-43662013000800008.

Haq, R.; Wani, M.; Prasad, K. Engineering properties of high and low altitude rice varieties from Kashmir valley at different processing levels, Cogent Food & Agriculture, v.2, n.1, 1133371, 2016. https://doi.org/10.1080/23311932.2015.1133371.

Jafari, M.; Chegini, G.R.; Khazaei, J. Determination of physical properties, moisture absorption process and aerodynamic properties of grain and cluster straw of two wheat cultivars. Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis, v.68, n.5, p.831–840, 2020. https://doi.org/10.11118/actaun202068050831.

Liang, Z.; Xu, L.; Baerdemaeder, J.D.; Li, Y.; Saeys, W. Optimisation of a multi-duct cleaning device for rice combine harvesters utilising CFD and experiments. Biosystems Engineering, v.190, p.25-40. 2020. https://doi.org/10.1016/j.biosystemseng.2019.11.016.

Masoumi, M.; Mahmoudi, A.; Alizadeh, M.R.; Abdollahpour, S. Effect of awn on aerodynamic properties of paddy grains (*Oryza sativa* L.). Agricultural Engineering International, v.22, n.2, p.208-216, 2020. https://cigrjournal.org/index.php/Ejounral/article/view/5465/3349. 13 May. 2021.

Mirzabe, A.H.; Hajiahmad, A.; Asadollahzadeh, A.H. Moisture-dependent engineering properties of arugula seed relevant in mechanical processing and bulk handling. Journal of Food Process Engineering, v.44, n.6, e13704, 2021. https://doi.org/10.1111/jfpe.13704.

Mohsenin, N.N. Physical properties of plant and animal materials. New York: Gordon and Breach Publishers, 1986. 841p.

Obi, O.F. Evaluation and modeling of the aerodynamic characteristics of watermelon seed of different varieties. International Journal of Food Properties, v.19, n.10, p.2165-2174, 2016. https://doi.org/10.1080/10942912.2015.1113181.

Pérez, S.V.; Larrarte, S.C.; Escorcia, N.L.; Bustos, C.R.B. Aproximaciones experimentales al establecimiento de la cinética de secado para semillas de quinua. Semilleros Formación Investigativa, v.3, n.1, p.77-84, 2017. https://hdl.handle.net/20.500.11839/6440. 13 May. 2021.

Rodrigues, G.B.; Resende, O.; Oliveira, D.E.C. de; Sousa, K. A. Propriedades físicas das sementes de sorgo granífero. Revista Engenharia na Agricultura, v.27, n.6, p.490-497, 2019. https://doi.org/10.13083/reveng.v27i6.969.

Selvi, K.Ç.; Pinar, Y.; Yesiloglu, E. Some Physical Properties of Linseed. Biosystems Engineering, v.95, n.4, p.607-612, 2006. https://doi.org/10.1016/j.biosystemseng.2006.08.008.

Shahbazi, F. Evaluation and modeling of aerodynamic properties of mung bean seeds. International Agrophysics, v.29, n.1, p.121-126, 2015. https://doi.org/10.1515/intag-2015-0001.

Shahbazi, F. Evaluation and modeling some engineering properties of three safflower varieties. International Agrophysics, v.160, n.4, p.23-40, 2014. https://doi.org/10.1515/cerce-2015-0002.

Shahbazi, F.; Valizadeh, S.; Dowlatshah, A. Aerodynamic properties of Makhobeli, triticale and wheat seeds. International Agrophysics, v.28, n.3, p.389-394, 2014. https://doi.org/10.2478/intag-2014-0029.

Shahbazi, F.; Valizadeh, S.; Dowlatshah, A.; Hassanzadeh, E. Aerodynamic properties of lentil seeds. International Agrophysics, v.29, n.3, p.391-396, 2015. https://doi.org/10.1515/intag-2015-0045.

Spehar, C.R.; Rocha, J.E.S.; Santos, R.L.B. Desempenho agronômico e recomendações para cultivo de quinoa (BRS Syetetuba) no Cerrado. Pesquisa Agropecuária Tropical, v.41, n.1, p.145-147, 2011. https://doi.org/10.5216/pat.v41i1.9395.

Teixeira, M.M.; Martyn, P.J.; Hara, T.; Cunha, J.P.A.R. Propriedades físicas e aerodinâmicas aplicadas ao projeto de máquinas de limpeza para grãos de milho. Engenharia na Agricultura, v.11, n.52, p.1-4, 2003.

Unal, H.; Izli, G.; Izli, N.; Asik, B.B. Comparison of some physical and chemical characteristics of buckwheat (*Fagopyrum esculentum* Moench) grains, CyTA - Journal of Food, v.15, n.2, p.257-265, 2017. https://doi.org/10.1080/19476337.2016.1245678.

Vilche, C.; Gely, M.; Santalla, E. Physical properties of quinoa seeds. Biosystems Engineering, v.86, n.1, p.59–65, 2003. https://doi.org/10.1016/S1537-5110(03)00114-4.