Physical and aerodynamic properties of rough rice and corn: effect of moisture content and grain type

Nursigit Bintoro*, Joko Nugroho Wahyu Karyadi, Arifin Dwi Saputro, Redika Ardi Kusuma, Muftia Chairin Nissa, Sastika Nidya Ashari

(Department of Agricultural and Biosystem Engineering, Gadjah Mada University, Yogyakarta, 55281, Indonesia)

Abstract: The physical and aerodynamic properties of grain are very necessary in the development of pneumatic grain handling. These properties are influenced by moisture content and grain type. This study aimed to investigate the effect of moisture content and grain type on the physical and aerodynamic properties of rough rice and corn. In this study, three types of rough rice and corn, each in three levels of moisture contents were investigated. A completely randomized design, factorial 3 × 3 was used in the research. It was found that the physical properties consisting of major diameter (a), intermediate diameter (b), minor diameter (c), grain volume (V_p), grain weight (m_p), particle density (γ_p) and frontal area (A_p), and the aerodynamic properties consisting of terminal velocity (V_t), drag coefficient (C_d), drag force (F_d), and buoyant force (F_b) for both rough rice and corn were significantly affected by moisture content and grain type (p<0.05). It was also found that none of the evaluated equations could predict measured V_t accurately within the range of moisture content studied. Therefore, the use of theoretical equations to predict V_t should be done carefully.

Keywords: rough rice, corn, moisture content, physical properties, aerodynamic properties

Citation: Bintoro, N., J. N. W. Karyadi, A. D. Saputro, R. A. Kusuma, M. C. Nissa, and S. N. Ashari. 2024. Physical and aerodynamic properties of rough rice and corn: effect of moisture content and grain type. Agricultural Engineering International: CIGR Journal, 26(4):179-193.

1 Introduction

Engineering properties of agricultural grains including physical and aerodynamic properties are important in many engineering interests. These two properties are especially needed in process design and construction of machines for handling grain pneumatically. Similar opinions are also expressed by Chandio et al. (2022), Kalantari et al. (2022), and Alizadeh et al. (2023). Therefore, for a better understanding in the pneumatic process development, it is important to study the physical and aerodynamic properties of the grains.

Rough rice is one of the most important crops and serves as the staple food for most of the world's population (Rahman and Zhang, 2022; Zahra et al., 2022). Rough rice is also the main crop cultivated in Indonesia and based on its production potential, rice is classified into three varieties, namely superior, hybrid, and local varieties. Inpari-19, Mapan-05, and Mentik wangi respectively represent superior, hybrid and local varieties. These three rice varieties are very common cultivated in Indonesia. According to the grain shape classification proposed by Cruz (2002), Mentik wangi is classified as medium grain, while Inpari-19 and Mapan-05 are slender grains. Although Impari-19 and Mapan-05 have the same grain shape, however they have very different grains weight. The weight of 1000 grains at a moisture content of 14%

Received date: 2024-01-22 **Accepted date:** 2024-10-07

***Corresponding author: Nursigit Bintoro, Ph.D.** Department of Agricultural and Biosystem Engineering, Gadjah Mada University, Bulaksumur, Yogyakarta, Indonesia, 55281. E-mail: nursigit@ugm.ac.id.

(w.b.) for Inpari-19 and Mapan-05 are 26.746 and 31.280 grams, respectively, and the corresponding value for Mentik wangi is 28.677 grams (Ashari et al., 2019). Because these three varieties have different characteristics, it can be expected to exhibit different physical and aerodynamic properties.

Corn is known as an important agricultural grain in many countries (Feng et al., 2019; Erenstein et al., 2022). It is usually used as the staple food, feed, and raw material in many industries. In Indonesia, corn is the second important grain after rice. There are several common types of corn namely flint, dent, pop, flour, sweet, and waxy corns (Dickerson, 2003). The three often encountered corns are dent corn, flint corn, and popcorn and these three types of corn have very different appearance. In general, dent corn and flint corn have almost same size, however dent corn has a dent at the kernel surface, while flint corn is smooth. Popcorn has the smallest size as compared to dent and flint corn, and the surface is smooth like flint corn. The weight of 1000 grains at moisture content of 14% (w.b.) for dent corn, flint corn, and popcorn are 284.04; 247.72; and 144.47 grams, respectively (Nissa et al., 2019). Variety is also one of the important factors that have a major influence on the grain properties. Several researchers have reported the significant effect of variety on the physical and aerodynamic properties in various research works, such as Rajabipour et al. (2006) for wheat grains and Akbarnia and Rashvand (2019) for olive fruits.

In the postharvest stage, rough rice and corn are handled from wet to dry conditions before consumption. During the harvesting period, the grain is still wet with a high moisture content, whereas during the drying process the moisture content will gradually decrease and eventually reach a dry state. This means that postharvest handling of rough rice and corn will deal with these grains from wet to dry conditions. Usually, moisture content of rough rice and corn is around 25% and 14% (w.b.) in the wet and dry conditions, respectively. It has been reported in many research works that moisture content has strong influence on the properties of the grain. The important effect of moisture content on the physical and aerodynamic properties have been reported for sunflower seeds and its kernels (Khodabakhshian et al., 2012) and green gram (Dash et al., 2022). As afore mentioned, that type and moisture content of grain influence the physical and aerodynamic properties, so in-depth research is needed to evaluate the effect of these two factors on the physical and aerodynamic properties of the grain. Further, it is important to seek if there is any relationship between physical and aerodynamic properties with the grain moisture content. Besides that, as there are several proposed mathematical equations to predict terminal velocity, it is necessary to evaluate their accuracy in predicting the real value of terminal velocity obtained from the experiments. This research will be carried out by using indigenous rough rice and corn, which are commonly encountered in the tropical region of Indonesia except the popcorn, in three levels of moisture contents, which have never been done by previous researchers. The objectives of this study were to investigate the effect of moisture content and grain type on the physical and aerodynamic properties of rough rice and corn.

2 Materials and methods

In this study, the aerodynamic properties of the grains were expressed as terminal velocity (V_t), drag coefficient (C_d), drag force (F_d), and buoyant force (F_b). The expressions for V_t, C_d, F_d, and F_b are shown as Equations 1 to 4, respectively (Mohsenin, 1986). While the expression for frontal area (A_p) is shown in Equation 5 (Shahbazi et al., 2014; Shahbazi et al., 2015). In this research, the value of V_t would be measured directly from the experiment and this measured V_t was then used to calculate C_d and F_d.

$$V_t = \sqrt{\frac{2.m_p.g\,(\gamma_p-\gamma_a)}{A_p.\gamma_a.\gamma_p.C_d}} \quad (1)$$

$$C_d = \frac{2.m_p.g\,(\gamma_p-\gamma_a)}{\gamma_a.\gamma_p.{V_t}^2.A_p} \quad (2)$$

$$F_d = C_d.A_p.\frac{\gamma_a.V_t^2}{2} \quad (3)$$

$$F_b = \gamma_a.V_p.g \quad (4)$$

$$A_p = \frac{1}{4}\,\pi.a.b \tag{5}$$

Where a, b, and c are major, intermediate, and minor diameters of the grain, respectively (cm); m_p is the weight of single grain (g); V_p is the volume of single grain (cm^3); γ_p is the particle density of the grain (gr cm^{-3}); g is the gravitational force (980 cm s^{-2}); and γ_a is the air density (0.001184 g cm^{-3}).

There are also several mathematical equations that can be used to calculate terminal velocity theoretically. Gorial and O'challagan (1990) proposed an equation to compute V_t theoretically (Equation 6). The values of shape factor (Z), sphericity (S_p), equivalent diameter (D_e), and geometric mean diameter (D_g) were calculated using Equations 7, 8, 9, and 10, respectively. Equation 11 was another theoretical equation that was intended to calculate V_t theoretically. This equation assumed that the particle shape was a spherical with the particle diameter was D_p, the range of the Reynold's number (Re) was 10^3 – 2×10^5 with the average value of C_d was 0.44. In this study D_p was replaced by equivalent diameter or D_e. While Equation 12 was the same as the Equation 11, but the value of C_d was taken to be 0.50, which was the maximum value of C_d for the above range of Re values, according to the C_d chart provided by Mohsenin (1986). The prediction values of V_t by using Equations 6, 11, and 12 would be compared to the measured terminal velocity obtained from the experiment.

$$V_t = \sqrt{\frac{4.g.De.\gamma_t.\left(\frac{6.Z}{\pi}\right)}{3.\gamma_a.0.44}} \tag{6}$$

$$Z = \frac{\pi}{6}\cdot S_p.\left(\frac{D_e}{D_g}\right)^{\frac{1}{3}} \tag{7}$$

$$S_p = \left(\frac{a.b.c}{a}\right)^{\frac{1}{3}} \tag{8}$$

$$De = \left[\left(\frac{m_p}{\gamma_p}\right)\left(\frac{6}{\pi}\right)\right]^{1/3} \tag{9}$$

$$D_g = (a.b.c)^{1/3} \tag{10}$$

$$V_t = \sqrt{\frac{4.g.Dp.(\gamma_p-\gamma_a)}{3.\gamma_a.0.44}} \tag{11}$$

$$V_t = \sqrt{\frac{4.g.Dp.(\gamma_p-\gamma_a)}{3.\gamma_a.0.50}} \tag{12}$$

Ghamari et al. (2011) proposed experimental equations for predicting V_t of chickpea and rice. Equation 13 originally developed for predicting V_t of chickpea. However, as the visual appearance of chickpea is not much different from corn, therefore it was tried to be used to predict V_t of corn, while Equation 14 was used to predict V_t of rough rice in this study.

$$V_t = 4.98\,\left(\gamma_p.D_g.S_p\right)^{0.5} \tag{13}$$

$$V_t = 3.497\,\left(\frac{\gamma_p.m_p}{a}\right)^{0.5} \tag{14}$$

2.1 Materials

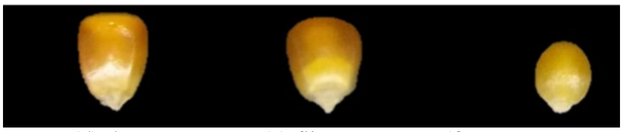
Two kinds of agricultural grains, namely rough rice and corn were used as the samples in the experiment. Each grain consisted of three different types in three different moisture contents. These grain samples were bought directly from the farmers at Yogyakarta, Indonesia, except for popcorn was bought through the online shop. The three types of rough rice grain were Inpari-19, Mentik wangi, and Mapan-05. While corn consisted of dent corn, flint corn, and popcorn. Some drying and wetting processes were carried out to obtain the desired moisture contents. The three moisture contents evaluated in this study were 14%, 20%, and 25% (w.b.) which represented dry, medium, and wet grains that were commonly encountered in the postharvest handling practices.

In this study, for the purpose of measuring terminal velocity an apparatus was constructed (Figure 2a). This apparatus consisted of (1). Adjustable centrifugal blower (Aldo Electric Blower 4", 1 phase, 220V, 2.5A), (2). PVC pipe with a length of 720 mm and diameter of 90 mm, (3). Wire screen with the size of 2 × 2 mm, (4). Conical plastic pipe with a length of 70 mm and upper diameter of 150 mm, and (5). Hot wire anemometer (Lutron, AM-4204). While Figure 2b illustrated the principle of forces acting on the falling object in the air. Theoretically, when F_g=F_b + F_d the grain would remain suspended in the air stream where the terminal velocity was attained.

2.2 Methods

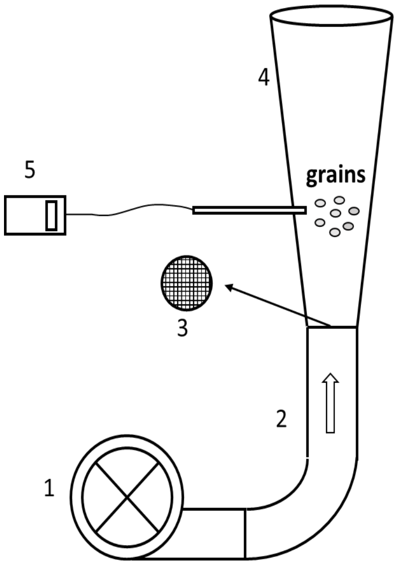
Rough rice and corn grain samples were selected and sorted, only healthy and unblemished grains were used in the study. Dimensions of the grains were determined using image-J from the photographs of the kernel in ten replications. Particle density of the grain was determined by using pycnometer and toluene was used as the liquid in the measurement in three replications. The weight of single grain was determined from the result of weighing 1000 grains using digital balance (Camry 100 g) with the accuracy of 0.01 gram in three replications. Then the volume of single grain kernel could be calculated from the value of particle density and weight of the grain.

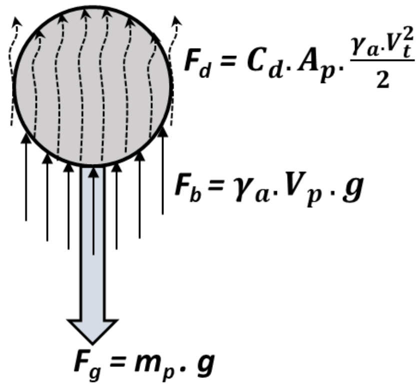
(a) Inpari-19 rice (b) Mentik wangi rice (c) Mapan-05 rice



(d) dent corn (e) flint corn (f) popcorn

Figure 1 Visual appearance of rough rice and corn used in the experiment





(a) Terminal velocity (b) The principle of forces acting on the falling object in the air

Figure 2 Apparatus used to measure

Terminal velocity of the grain was directly determined based on suspension velocity method using a self-constructed apparatus. About 5 grams of grain samples were poured into the apparatus and would be held on the wire screen, then the blower was turn on. By adjusting the speed of the blower, the grains would be lifted, the velocity of the flowing air when the grain suspended constantly in the cone plastic pipe would be the terminal velocity of the grain. This air speed then measured using hot wire anemometer as the terminal velocity of the grain. This measurement was carried out in three replications.

As the visual appearances between rough rice and corn were clearly different, statistical analysis was not conducted to compare between rough rice and corn, but it was carried out to compare among types/varieties of the same grain. Accordingly, this study used completely randomized design, factorial 3 × 3, and the means comparison was evaluated using Duncan's Multiple Range Test (DMRT). Regression analysis was done to evaluate the relationship between physical and aerodynamic properties with the moisture content.

3 Results and discussion

3.1 Physical properties

The physical properties of the grains consisting of a, b, c, A_p, m_p, V_p, and γ_p are presented in Tables 1 and 2 for rough rice and corn, respectively. It could be observed that except the particle density of corn, all physical properties of the grains increased with moisture content. The similar phenomenon was also reported by several researchers for different materials and physical properties. Taheri-Garavand et al. (2012) for hemp seeds and Gharekhani et al. (2013) for two varieties of rough rice. Increasing moisture content would increase the values of a, b, c, and m_p, as the results the physical properties of the grain related with these parameters would increase too, therefore the values of V_p, A_p, and γ_p were also increased. Singh et al. (2010) also reported that A_p and γ_p increased with moisture content for barnyard milled grain. As aforementioned, that the only γ_p of the corn decreased with the increase in moisture content. This means that in this situation the increase in grain volume was greater than the increase in weight with increasing water content. The similar results were also reported by Taheri-Garavand et al. (2012) for hemp seed and Ozturk and Esen (2013) for dent corn and popcorn. Statistical analysis confirmed that for both rough rice and corn, type and moisture content significantly affected the values of a, b, c, A_p, m_p, V_p, and γ_p (p<0.05). However, the interaction of type and moisture content only affected some of those parameters that were b, A_p and γ_p for rough rice and b, A_p, m_p, and V_p for corn (p<0.05). These findings indicated that moisture content and grain type were important factors that significantly affected the physical properties of the grain, therefore must be considered when determining the physical properties of the grain. The significant effect of moisture content and grain type on the physical properties of grain were also reported by Biabani and Sajadi (2018) for chickpea and Darfour et al. (2022) for corn.

Table 1 Physical properties of rough rice samples along with the DMRT results

Rough rice	a (cm)	b (cm)	c (cm)	A_p (cm^2)	V_p (cm^3)	m_p (g)	γ_p (g cm^{-3})
Inpari-19 14%	0.983±0.037^{a}	0.282±0.011^{a}	0.212±0.009^{a}	0.215±0.006^{a}	0.018±0.001^{a}	0.027±0.001^{a}	1.486±0.014^{a}
Inpari-19 20%	0.999±0.040^{ab}	0.282±0.011^{a}	0.223±0.008^{bc}	0.220±0.005^{abc}	0.019±0.001^{b}	0.028±0.001^{b}	1.514±0.026^{ab}
Inpari-19 25%	1.023±0.050^{b}	0.277±0.014^{ab}	0.232±0.006^{d}	0.219±0.013^{ab}	0.019±0.001^{ab}	0.029±0.001^{c}	1.584±0.011^{de}
Mentik wangi 14%	0.871±0.035^{c}	0.327±0.012^{c}	0.220±0.009^{b}	0.219±0.010^{ab}	0.019±0.000^{bc}	0.029±0.001^{c}	1.512±0.011^{ab}
Mentik wangi 20%	0.891±0.025^{cd}	0.338±0.011^{d}	0.236±0.008^{de}	0.238±0.008^{bcd}	0.020±0.001^{cd}	0.031±0.001^{d}	1.566±0.013^{cd}
Mentik wangi 25%	0.923±0.039^{d}	0.338±0.013^{d}	0.243±0.112^{e}	0.240±0.015^{cd}	0.020±0.001^{e}	0.033±0.001^{e}	1.607±0.016^{e}
Mapan-05 14%	0.998±0.041^{ab}	0.270±0.007^{b}	0.211±0.010^{a}	0.209±0.011^{a}	0.022±0.001^{e}	0.031±0.000^{d}	1.436±0.030^{f}
Mapan-05 20%	1.070±0.025^{e}	0.287±0.009^{a}	0.230±0.007^{cd}	0.245±0.014^{d}	0.022±0.001^{e}	0.033±0.001^{e}	1.540±0.026^{bc}
Mapan-05 25%	1.107±0.060^{f}	0.285±0.009^{a}	0.243±0.009^{e}	0.256±0.011^{d}	0.023±0.001^{f}	0.036±0.001^{f}	1.581±0.008^{de}

Note: a=major diameter, b=intermediate diameter, c=minor diameter, A_p=frontal area, V_p=grain volume, m_p=grain weight, γ_p=particle density. The values in the same column followed by the same letter were not significant different (α=5%).

Table 2 Physical properties of corn samples along with the DMRT results

Corn	a (cm)	b (cm)	c (cm)	A_p (cm^2)	V_p (cm^3)	m_p (g)	γ_p (g cm^{-3})
Dent corn 14%	1.161±0.084^{ab}	0.811±0.058^{a}	0.438±0.020^{ab}	0.754±0.048^{ab}	0.284±0.003^{a}	0.284±0.003^{a}	1.533±0.021^{ab}
Dent corn 20%	1.176±0.062^{b}	0.825±0.051^{ab}	0.443±0.036^{ab}	0.768±0.011^{b}	0.311±0.001^{b}	0.311±0.001^{b}	1.503±0.013^{c}
Dent corn 25%	1.303±0.065^{c}	0.944±0.050^{d}	0.478±0.039^{c}	0.970±0.021^{c}	0.318±0.001^{c}	0.318±0.001^{c}	1.465±0.012^{d}
Flint corn 14%	1.027±0.041^{d}	0.866±0.052^{bc}	0.443±0.030^{ab}	0.672±0.042^{d}	0.248±0.001^{d}	0.248±0.001^{d}	1.512±0.011^{bc}
Flint corn 20%	1.054±0.038^{d}	0.829±0.031^{ab}	0.487±0.024^{c}	0.718±0.023^{ad}	0.264±0.002^{e}	0.264±0.002^{e}	1.468±0.019^{d}
Flint corn 25%	1.119±0.049^{a}	0.895±0.051^{c}	0.489±0.038^{c}	0.785±0.012^{b}	0.275±0.002^{f}	0.275±0.002^{f}	1.463±0.019^{d}
Popcorn 14%	0.822±0.017^{e}	0.609±0.030^{e}	0.417±0.025^{a}	0.390±0.012^{e}	0.145±0.001^{g}	0.145±0.001^{g}	1.555±0.009^{a}
Popcorn 20%	0.896±0.022^{f}	0.677±0.027^{f}	0.414±0.025^{a}	0.476±0.010^{f}	0.152±0.001^{h}	0.152±0.002^{h}	1.519±0.007^{bc}
Popcorn 25%	0.966±0.027^{g}	0.723±0.046^{g}	0.466±0.052^{bc}	0.546±0.036^{g}	0.164±0.002^{i}	0.164±0.002^{i}	1.511±0.006^{bc}

Note: a=major diameter, b=intermediate diameter, c=minor diameter, A_p=frontal area, V_p=grain volume, m_p=grain weight, γ_p=particle density. The values in the same column followed by the same letter were not significant different (α=5%).

For both rough rice and corn, mostly the mean values of the physical properties differed among the type and moisture contents. Indicating that each grain type had its unique character depending on its moisture content even under the same grain name. For rough rice, the maximum values of the physical property parameters were found for Mapan-05 at 25% moisture content, except for the value of *b*. However, the minimum values were spread and were not owned by one particular type of rough rice (Table 1). While, for corn the minimum values of the physical property parameters were found for popcorn at 14% moisture content, except for the value of γ_p, and almost all maximum values were found for dent corn at 25% moisture content, except the values of *c* and γ_p (Table 2).

Table 3 Relationship between physical properties (y) and moisture content (x)

Grain	Variety	V_p	m_p	γ_p	A_p
Rough rice	Inpari-19	y = 6E-05x + 0.0172 R² = 0.9538	y = 0.0002x + 0.0232 R² = 0.984	y = 0.0087x + 1.3571 R² = 0.9158	y = -0,0001x² + 0,0051x + 0,1676 R² = 1
	Mentik wangi	y = 0.0001x + 0.0173 R² = 0.9671	y = 0.0004x + 0.0237 R² = 0.9919	y = -0.0045x + 1.5695 R² = 0.868	y = 0.0019x + 0.1949 R² = 0.8636
	Mapan-05	y = 1E-05x² - 0,0005x + 0,0259 R² = 1	y = 0.0004x + 0.0258 R² = 0.9987	y = 0.0133x + 1.2567 R² = 0.9633	y = 0.0043x + 0.1514 R² = 0.9329
Corn	Dent corn	y = 0.0029x + 0.1456 R² = 0.9782	y = 0.0032x + 0.2423 R² = 0.9314	y = -0.0061x + 1.6212 R² = 0.9868	y = 0.019x + 0.4568 R² = 0.7532
	Flint corn	y = 0.0022x + 0.1342 R² = 0.9805	y = 0.0025x + 0.2139 R² = 0.9952	y = -0.0045x + 1.5695 R² = 0.868	y = 0.0103x + 0.5229 R² = 0.975
	Popcorn	y = 0.0014x + 0.0723 R² = 0.9886	y = 0.0018x + 0.1184 R² = 0.9647	y = -0.0041x + 1.6097 R² = 0.9168	y = 0.0142x + 0.1917 R² = 1.0

Note: V_p=grain volume, m_p=grain weight, γ_p=particle density, A_p=frontal area.

Table 3 presents the relationship between physical properties and moisture content of rough rice and corn studied in this experiment. Evaluating these mathematical relationships, it could be found that most of the physical property parameters of rough rice and corn were significantly expressed in linear regression equations. Similar results were also reported by Ozturk and Esen (2013) for three corn types of dent corn, popcorn, and sweetcorn and Gharekhani et al. (2013) for paddy and white rice. It was found that the only A_p for Inpari-19 and V_p for Mapan-05 of rough rice were found to have small values of R^2. Therefore, this parameter might not be suitable to be expressed as linear equation, but polynomial. Ganjloo et al. (2018) reported a polynomial increase of A_p with the moisture content for green peas. While Sangamithra et al. (2016) found a polynomial increase of V_p with the moisture content for maize kernel.

3.2 Aerodynamic properties

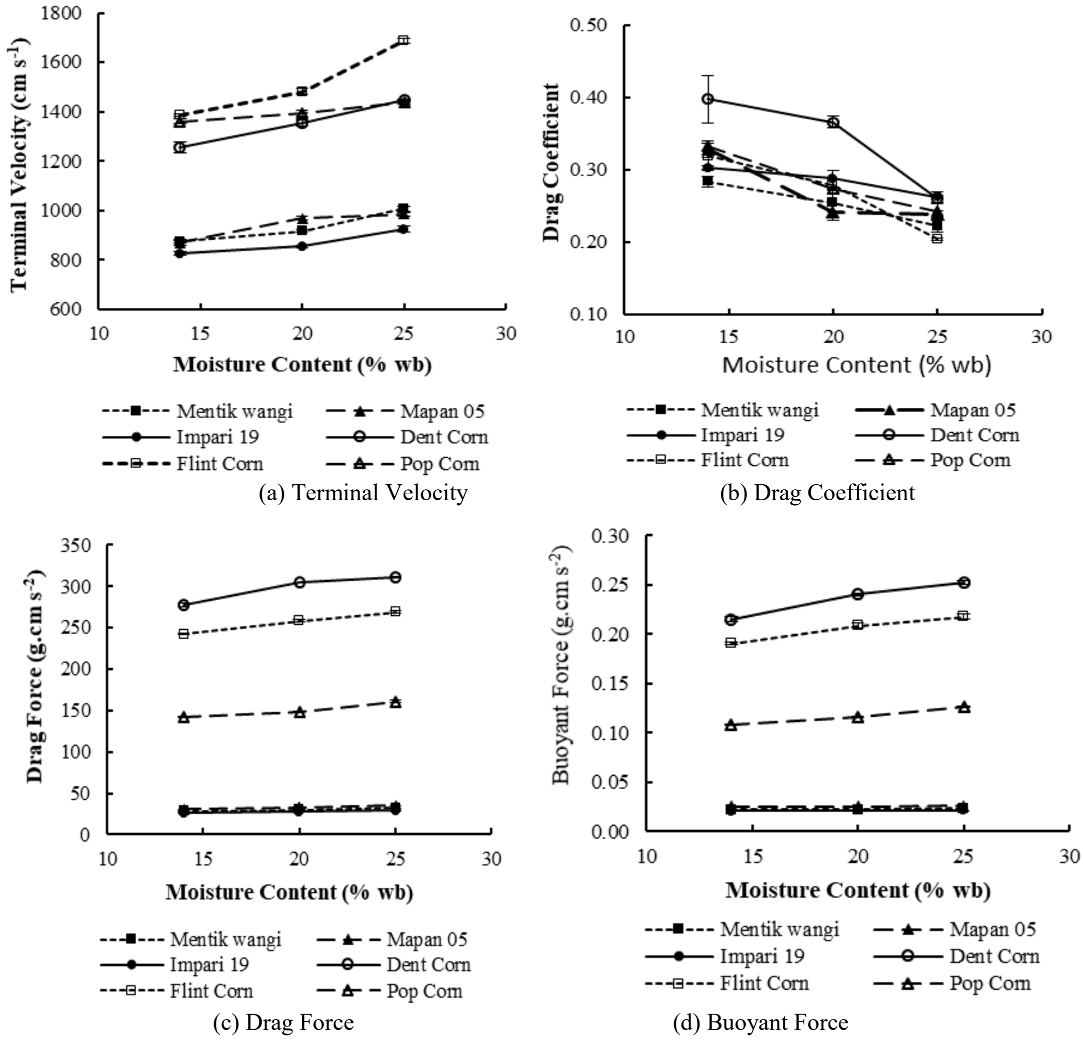
The effect of moisture content on the aerodynamic properties consisting of V_t, C_d, F_d, and F_b are presented in Figures 2. It could be observed that the values of V_t, F_d, and F_b consistently increased with moisture content, while C_d decreased with moisture content. Except for the values of C_d, corn had considerably higher values of the aerodynamic properties than rough rice within the range of moisture content studied. This was caused by the fact that corn had larger dimension than rough rice, consequently resulted in higher aerodynamic properties.

Terminal velocity of rough rice and corn consistently increased with moisture content (Figure 2a). As the moisture content of the grain increased, the dimensions and weight of the grain would increase too, causing an increase in the values of terminal velocity of the grain. The similar results were also reported by Shahbazi et al. (2015) for lentil seed and Jafari et al. (2020) for grains and straw of two wheat cultivars. Statistical analysis indicated that moisture content, grain type, and the interaction of these two factors significantly affected the values of V_t for both rough rice and corn (p<0.05). This suggested that in the determination or theoretical calculation of V_t, grain type and moisture content should be considered. Furthermore, it was necessary to make adjustments to the pneumatic machine in handling grain or corn when the type or moisture content of the grain changed. Basati et al. (2019) also found that moisture content, grain type, and the interaction of these two factors significantly affected V_t of lentil grain. While Jafari et al. (2020) found a significant effect of moisture content and grain type on V_t, but the interaction had no effect on V_t for wheat grain and straw. The results of mean comparison are presented in Tables 4 and 5 for rough rice and corn, respectively. It could be observed that the maximum value of V_t was found for Mentik wangi at 25% moisture content and flint corn at 25% for rough rice and corn, respectively. While the minimum value of V_t was found for Inpari-19 at 14% moisture content and dent corn at 14% for rough rice and corn, respectively.

These findings indicated that the maximum values of V_t occurred at the highest moisture content and the minimum values at the lowest moisture content, confirming the above statement that increasing moisture content would increase the values of V_t. The relationship between V_t and moisture content could be adequately expressed as linear regression equations (Table 6). This indicated that the rate of increment of V_t values toward moisture content was constant. This finding supported the results reported by Basati et al. (2019) for lentil grain and Masoumi et al. (2020) for paddy grain. However, Shahbazi (2015) reported that V_t increased non-linearly with moisture content for mungbean seeds. Although there was a discrepancy considering the pattern of the increment of V_t again moisture content, there was a common finding that the value of V_t increased as the moisture content of the grain increased. Inspecting the slopes or coefficient of the regression equations, it could be found that the largest slope was found for Mentik wangi and flint corn for rough rice and corn, respectively. The largest slope indicated that the values of V_t of these grains were the most susceptible to the change in the moisture content.

Based on the values of V_t obtained from the experiment, then the values of C_d were calculated by using Equation 2. Figure 2b presents the relationship between C_d and moisture contents for both rough rice and corn grains. In contrast with V_t, the values of C_d for both rough rice and corn consistently decreased with moisture content. Increasing moisture content would cause the weight and dimensions of the grain increased, causing the grain heavier and wider and consequently developed higher values of C_d in the air stream. This finding agreed with the result reported by Shahbazi et al. (2014) for makhobeli, triticale and wheat seeds; Mishra et al. (2019) for sponge gourd, garden pea, and radish seeds; Masoumi et al. (2020) for awn less paddy; and Jafari et al. (2020) for two cultivars of wheat grain and straw. Statistical analysis revealed that moisture content, grain type, and the interaction of these two factors significantly affected the values of Cd (p<0.05). Gupta et al. (2007) also reported that the interaction between cultivars and moisture content significantly affected C_d for three cultivars of sunflower seeds. Sharma et al. (2012) also found that moisture content, cultivars, and the interaction of these two factors significantly affected Cd values for unshelled and shelled sunflowers. Tables 4 and 5 present the values of C_d for rough rice and corn, respectively. It was observed that the maximum value of C_d was found for Mapan-05 at 14% moisture content and dent corn at 14% for rough rice and corn, respectively.

While the minimum value of C_d was found for Mentik wangi at 25% moisture content and flint corn at 25% for rough rice and corn, respectively. The maximum and minimum values of C_d were found for the smallest and the largest evaluated moisture content, respectively. These findings strengthening aforementioned statement that the values of C_d decreased with increasing moisture content. The relationships between C_d and moisture content could be expressed satisfactorily as the linear equations for both rough rice and corn (Table 6). The same as V_t, this indicated that the rate of increment of C_d with the moisture content was constant. This finding supported the results reported by Khodabakhshian et al. (2012) for sunflower seed and kernel, Shahbazi et al. (2014) for makhobeli, triticale and wheat seeds, and Masoumi et al. (2020) for awn less paddy grain.



(a) Terminal Velocity (b) Drag Coefficient
(c) Drag Force (d) Buoyant Force

Figure 2 Changes in aerodynamic property values with moisture content of rough rice and corn samples

The values of F_d were calculated using Equation 3 after the values of V_t and C_d were obtained. Figure 2c presents the relationship between F_d and moisture content for both rough rice and corn grains. It could be observed that the values of F_d consistently increased with moisture contents, the same phenomenon as for V_t values. Increasing moisture content would cause the grain heavier and wider, consequently increased the value of V_t and A_p, and finally increase the value of F_d. Dimitriadis et al. (2014) stated that F_d was related with surface area and reported the increment of F_d with the increase of A_p for lavender flower. Meanwhile, Kırmacı and Pakdemirli (2012) found that V_t of durum wheat spike increased accompanied by a decrease in C_d values, this phenomenon was the same as that observed in this study. Statistical analysis indicated that moisture content, grain type, and the interaction of these two factors significantly affected the values of F_d for both rough rice and corn (p<0.05).

While Tables 4 and 5 present the mean comparation of F_d for rough rice and corn, respectively. It was observed that the maximum and minimum values of F_d for rough rice were found for Mapan-05 at 25% moisture content and Inpari-19 at 14% moisture content, respectively. The same values for corn were found for dent corn at 25% moisture content and popcorn at 14% moisture content, respectively. Table 6 presents the relationships between F_d and moisture content for rough rice and corn studied in this research. As can be seen that F_d increased linearly with moisture content, the same phenomenon as that observed for V_t. The values of F_d for Mapan-05 and dent corn were the most susceptible to the change in moisture content for rough rice and corn, respectively, as indicated by the highest regression coefficient in those equations.

Table 4 Aerodynamic properties of rough rice along with the DMRT results

Rough rice	V_t (cm s^{-1})	C_d	F_d (g cm s^{-2})	F_b (g cm s^{-2})
Inpari-19 14%	825.555±6.939[a]	0.302±0.004[a]	26.190±0.591[a]	0.021±0.001[a]
Inpari-19 20%	854.444±5.092[b]	0.287±0.014[a]	27.365±0.690[b]	0.021±0.001[ab]
Inpari-19 25%	924.444±13.878[c]	0.262±0.009[b]	28.889±0.452[c]	0.021±0.001[ab]
Mentik wangi 14%	874.444±5.092[c]	0.283±0.008[a]	28.081±0.397[d]	0.022±0.000[bc]
Mentik wangi 20%	915.555±6.939[e]	0.254±0.015[bc]	29.854±0.274[e]	0.023±0.001[cd]
Mentik wangi 25%	1006.667±12.018[f]	0.222±0.011[e]	31.876±0.228[f]	0.024±0.001[d]
Mapan-05 14%	870.000±13.333[bc]	0.328±0.014[f]	30.629±0.084[g]	0.025±0.001[e]
Mapan-05 20%	968.889±8.389[d]	0.241±0.014[cd]	32.782±0.131[h]	0.025±0.001[e]
Mapan-05 25%	984.444±8.389[d]	0.238±0.007[cd]	34.819±0.109[i]	0.026±0.000[e]

Note: (1) V_t=terminal velocity, C_d=drag coefficient, F_d=drag force, F_b=buoyant force;(2) The values in the same column followed by the same letter were not significant different (α=5%).

Table 5 Aerodynamic properties of corn along with the DMRT results

Corn	V_t (cm s_{-1})	C_d	F_d (g cm s^{-2})	F_b (g cm s^{-2})
Dent corn 14%	1255.555±29.123[a]	0.397±0.040[a]	278.145±2.628[a]	0.215±0.003[a]
Dent corn 20%	1353.333±14.530[b]	0.366±0.010[b]	304.465±0.484[b]	0.240±0.002[b]
Dent corn 25%	1446.667±5.773[d]	0.259±0.006[de]	311.689±1.011[c]	0.252±0.002[c]
Flint corn 14%	1386.667±6.667[c]	0.318±0.022[c]	242.576±0.994[d]	0.190±0.002[d]
Flint corn 20%	1481.111±15.031[e]	0.278±0.012[d]	258.538±1.461[e]	0.209±0.003[e]
Flint corn 25%	1685.555±10.715[f]	0.204±0.002[f]	268.906±1.436[f]	0.218±0.003[f]
Popcorn 14%	1359.999±11.547[b]	0.331±0.006[c]	141.470±0.910[g]	0.108±0.001[g]
Popcorn 20%	1392.222±15.031[c]	0.273±0.003[d]	148.899±0.775[h]	0.116±0.001[h]
Popcorn 25%	1437.778±8.389[d]	0.241±0.014[e]	160.976±1.351[i]	0.126±0.001[i]

Note: V_t=terminal velocity, C_d=drag coefficient, F_d=drag force, F_b=buoyant force.

The values in the same column followed by the same letter were not significant different (α=5%).

Table 6 Relationship between aerodynamic properties (y) and moisture content (x)

Grain	Variety	V_t	C_d	F_d	F_b
Rough rice	Inpari-19	y = 8.8523x + 694.05 R^2 = 0.9193	y = -0.0036x + 0.3547 R^2 = 0.9584	y = 0.2437x + 22.688 R^2 = 0.9839	y = 7E-05x + 0.02 R^2 = 0.9538
	Mentik wangi	y = 11.85x + 699.18 R^2 = 0.9302	y = -0.0055x + 0.3617 R^2 = 0.9952	y = 0.3433x + 23.185 R^2 = 0.9919	y = 0.0001x + 0.02 R^2 = 0.9671
	Mapan-05	y = 10.604x + 732.56 R^2 = 0.8853	y = -0.0084x + 0.4347 R^2 = 0.8193	y = 0.3802x + 25.266 R^2 = 0.9987	y = 2E-05x^2 - 0,0006x + 0,03 R^2 = 1
Corn	Dent corn	y = 17.338x + 1010.9 R^2 = 0.9985	y = -0.0123x + 0.5822 R^2 = 0.8777	y = 3.0933x + 237.27 R^2 = 0.9314	y = 0.0034x + 0.1689 R^2 = 0.9782
	Flint corn	y = 26.795x + 990.81 R^2 = 0.933	y = -0.0103x + 0.4693 R^2 = 0.953	y = 2.4025x + 209.42 R^2 = 0.9952	y = 0.0025x + 0.1558 R^2 = 0.9805
	Popcorn	y = 7.0147x + 1258.7 R^2 = 0.9773	y = -0.0082x + 0.4436 R^2 = 0.9855	y = 1.7557x + 115.92 R^2 = 0.9647	y = 0.0017x + 0.0838 R^2 = 0.9886

Note: V_t=terminal velocity, C_d=drag coefficient, F_d=drag force, F_b=buoyant force.

The values of F_b were calculated using Equation 4, which practically only depended on the values of grain volume (V_p) because the values of air density and gravitational force were constant. Figure 2d presents the relationship between F_b and moisture content for both rough rice and corn grains. It could be observed that the values of F_b for both rough rice and corn consistently increased with moisture contents, the same phenomenon as for V_t and F_d. As moisture content increased, grain dimensions would increase too, causing V_p to increase and finally increased the value of F_b. Khorshidpour et al. (2020) found that F_b of sugar beet increased as the volume of the samples increased. Statistical analysis indicated that moisture content and grain type significantly affected the values of F_b for both rough rice and corn (p<0.05). However, the interaction of these two factors only significantly affected F_b for corn grain (p<0.05).

Tarighi et al. (2011) reported that F_b was significantly affected by cultivar for pomegranate. In contrast, Saracoglu et al. (2012) found that there was no significant effect of variety on the F_b values of two varieties of quince fruit. The mean comparation of F_b for rough rice and corn presented in the Tables 4 and 5. The maximum and minimum values of F_b for rough rice were found for Mapan-05 at 25% moisture content and Inpari-19 at 14% moisture content, respectively. The corresponding values for corn were found for dent corn at 25% moisture content and popcorn at 14% moisture content, respectively. These conditions were the same as the observed maximum and minimum values in F_d. The relationship between F_b and moisture content for rough rice and corn studied in this research are presented in Table 6. As can be seen that F_b increased linearly with moisture content, the same phenomenon as that observed for V_t and F_d. The values of F_b for Mentik wangi and dent corn were found to have the highest regression coefficient, indicated that these grain types were the most susceptible to the change in moisture content for rough rice and corn, respectively.

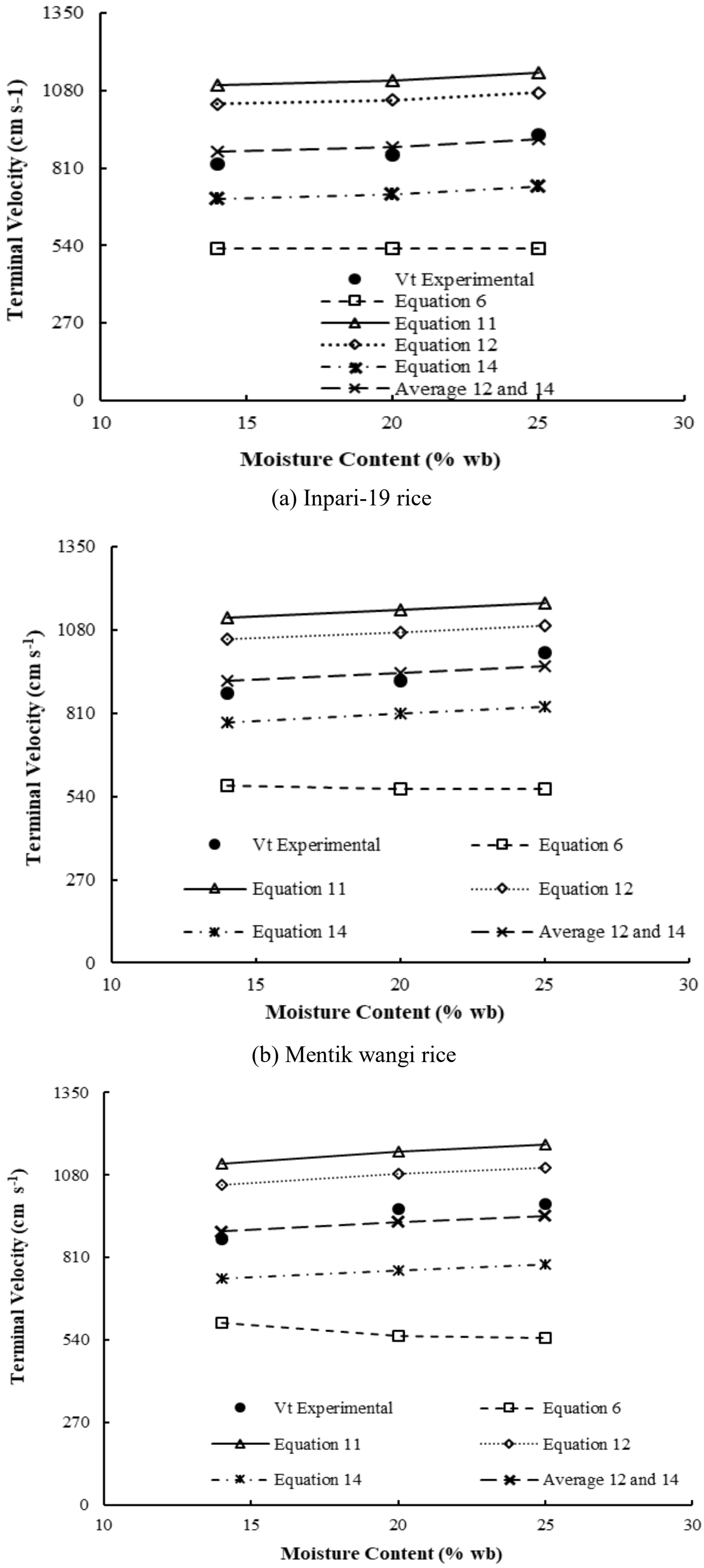
3.3 Comparison between predicted and measured V_t

In this study, V_t was directly measured in the experiment. However, this value could also be calculated using several proposed theoretical equations. Equations 6, 11, and 12 were used to predict the measured values of V_t for both rough rice and corn. While Equations 13 and 14 were used to predict V_t for corn and rough rice, respectively. Figure 3 presents the comparison between predicted and measured values of V_t for rough rice and corn. The accuracy of the equations was evaluated by calculating the Root Means Square Error (RMSE).

It could be seen that there was no single theoretical equation which could predict measured V_t accurately for both rough rice and corn in every moisture content. Gürsoy and Güzel (2010) found that the values of the experimental V_t were found to be less than the theoretical predicted V_t for wheat, barley, lentil, and chickpea. For rough rice, among the evaluated equations it was found that the average value of V_t calculated using Equations 12 and 14 was the most accurate for predicting V_t for the three types of the rough rice with an average RMSE value of 26,201. For corn, among the evaluated theoretical equations there was no single equation could predict V_t for all types of corn. Equation 13 was the most accurate for dent corn with the RMSE values of 23.672. While Equation 12 was the best for flint corn and popcorn with the RMSE values of 16.176 and 4.010 for flint corn and popcorn, respectively. Equations 11 and 12 assumed that the grain shape was a spherical, and the prediction results using these equations mostly deviated quite far from the experimental results. This finding revealed that the assumption of rough rice and corn to be a spherical was not true, because visually the shape of these grains relatively far from spherical.

It was also observed that increasing the value of C_d from 0.44 in the Equation 11 to 0.50 in the Equation 12 would increase the accuracy of this equation. This indicated that C_d had very significant effect on the accuracy of the prediction equations. From Figures 3d-3f, it could be seen that Equation 13 gave a predictive value that was close to the experimental results. Equation 13 was actually developed for chickpea, but because the physical properties of chickpea were very similar to those of corn, this equation was able of approaching the results of the experiment compared to the other equations evaluated in this study. It was reported that chickpea had the values of a, b and c were 0.810 to

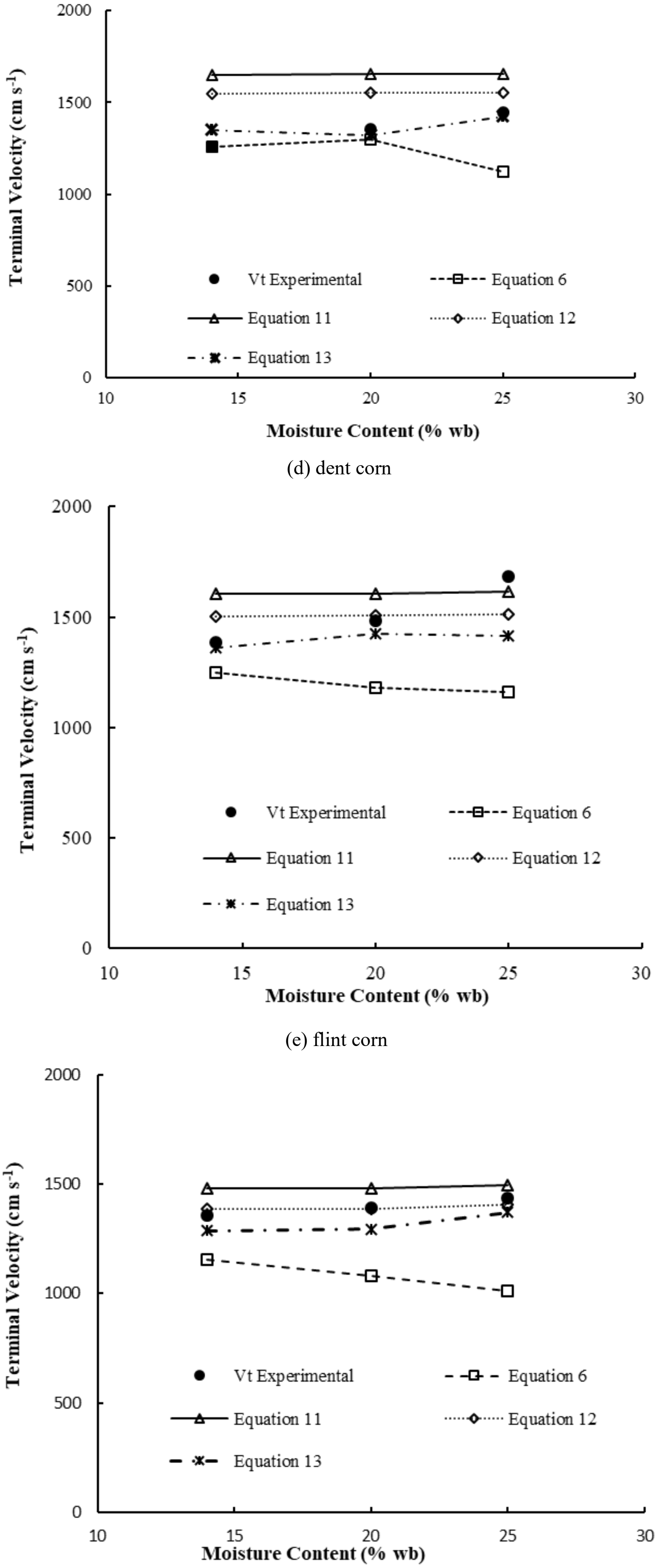
1.114 cm, 0.592 to 0.865 cm, and 0.556 to 0.806 cm, respectively (Shirsat, 2015); γ_p was 1.487 to 1.633 g cm^{-3} (Shirsat, 2015), and 1.379 to 1.408 g cm^{-3} (Ghamari et al., 2014); V_p was 0.131 to 0.548 cm^3 (Sastry et al., 2019); m_p was 0.129 to 0.391 (Ghamari et al., 2014); and A_p was 0.583 to 0.715 cm^2 (Işİk and Işİk, 2008). These values were very close to the physical properties of the corn samples used in this study (Table 2).



(a) Inpari-19 rice

(b) Mentik wangi rice

(c) Mapan-05 rice



(d) dent corn

(e) flint corn

(f) popcorn

Figure 3 Comparison between theoretically calculated and measured terminal velocities

4 Conclusions

It was found that the physical properties consisting of *a*, *b*, *c*, V_p, m_p, γ_p and A_p, for both rough rice and corn were significantly affected by moisture content and grain type. The interaction of these two factors significantly affected *b*, γ_p, and A_p for rough rice and *b*, A_p, m_p and V_p for corn (p<0.05). The aerodynamic properties represented by V_t, C_d, F_d, and F_b for both rough rice and corn were also significantly affected by moisture content and grain type. While the interaction was found to be significant in all aerodynamic properties, except on F_b of rough rice (p<0.05). Mostly the relationships between physical and aerodynamic properties of rough rice and corn with moisture content could be adequately expressed as linear regression equations. It was also found that none of the evaluated equations could predict measured V_t accurately within the range of moisture content studied.

Acknowledgments

The authors wish to thank the Department of Agricultural and Biosystem Engineering, Gadjah Mada University for providing laboratory facilities during the experiment.

Conflict of Interest

The Authors declare no conflict of interest.

References

Akbarnia, A., and M. Rashvand. 2019. An evaluation of the physical, dynamic and aerodynamic properties of olives. *Research in Agricultural Engineering*, 65(2): 48-55. 1

Alizadeh, B., T. Leblicq, and W. Saeys. 2023. Aerodynamic properties of harvested perennial ryegrass: Effects of particle mass, size and moisture content. *Biosystems Engineering*, 228: 67-79. 1

Ashari, S. N., N. Bintoro, J. N. W. Karyadi, and A. D. Saputro. 2019. Engineering analysis the effect of moisture content and paddy varieties on physical and mechanical properties of rough rice (*Oryza sativa*). Yogyakarta, Indonesia: Gadjah Mada University.

Basati, Z., E. A. Asli-Ardeh and V. Rasooli-Sharabiani. 2019. Effect of moisture content on terminal velocity of lentil grain. *Research in Agricultural Engineering*, 65: 7-12.

Biabani, A., and S. J. Sajadi. 2018. Effect of moisture content on biophysical characteristics of chickpea cultivars. *Legume Research*, 41(3): 432-435.

Chandio, F. A., Y. Li, Z. Ma, F. Ahmad, T. N. Syed, S. A. Shaikh, and M. H. Tunio. 2022. Influences of moisture content and compressive loading speed on the mechanical properties of maize grain orientations. *International Journal of Agricultural Biological Engineering*, 14(4): 41-49.

Cruz, N. M. D. 2022. Rice grain quality evaluation procedures. In *A Proposal for IRRI to Establish a Grain Quality and Nutrition Research Center*, ed. R. Graham, ch. 2, 7-15. Philippines: International Rice Research Institute.

Darfour, B., E. A. Ayeh, K. M. Odoi, and S. W. N. O. Mills. 2022. Physical characteristics of maize grain as influenced by varietal and moisture differences. *International Journal of Food Properties*, 25(1): 1351-1364.

Dash, B. S., S. K. Swain, D. Behera, K. Rayaguru, and M. Meshram. 2022. Effect of moisture content on engineering properties of green gram for designing of agricultural equipment. *Asian Journal of Dairy and Food Research*, 41(1): 47-55.

Dickerson, G. W. 2003. "Specialty corns". Cooperative Extension Service College of Agriculture and Home Economics, New Mexico State University. Accessed on May 20, 2024. https://pubs.nmsu.edu/_h/H232.pdf.

Dimitriadis, C. I., J. L. Brighton, M. J. O'Dogherty, M. I. Kokkora, and A. I. Darras. 2014. Physical and aerodynamic properties of lavender in relation to harvest mechanization. *International Journal of Agronomy*, 2014(1): 276926.

Erenstein, O., M. Jaleta, K. Sonder, K. Mottaleb, and B. M. Prasanna. 2022. Global maize production, consumption and trade: trends and R&D implications. *Food Security*, 14(5): 1295-1319.

Feng, J., Z. Wu, D. Qi, Y. Jin, and W. Wu. 2019. Accurate measurements and establishment of a model of the mechanical properties of dried corn kernels. *International Agrophysics*, 33(3): 373-381.

Ganjloo, A., M. Bimakr, S. Zarringhalami, M. J. Safaryan, and M. Ghorbani. 2018. Moisture-dependent physical properties of green peas (*Pisum sativum* L). *International Food Research Journal*, 25(3): 1246-1252.

Ghamari, S., H. Rabbani, and J. Khazaei. 2011. Mathematical models for predicting the terminal velocity of chickpea, rice and lentil. *World Applied Science Journal*, 15(11): 1557-1561.

Ghamari, S., H. Goli, A. Khanahmadzadeh, and K.

Mohammadi. 2014. Effect of moisture content on terminal velocity of chickpea varieties. *International Journal of Agriculture and Forestry*, 4(3A): 8-11.

Gharekhani, M., M. Kashaninejad, A. D. Garmakhany, and A. Ranjbari. 2013. Physical and aerodynamic properties of paddy and white rice as a function of moisture content. *Quality Assurance and Safety of Crops & Foods*, 5(3): 187-197.

Gorial, B. Y., and J. R. O'challagan. 1990. Aerodynamic properties of grain/straw materials. *Journal of Agricultural Engineering Research*, 46: 275-290.

Gupta, R. K., G. Arora, and F. Sharma. 2007. Aerodynamic properties of sunflower seed (*Helianthus annuus* L.). *Journal of Food Engineering*, 79(3): 899-904.

Gürsoy, S., and E. Güzel. 2010. Determination of physical properties of some agricultural grains. *Research Journal of Applied Science, Engineering and Technology*, 2(5): 492-498.

IşIk, E., and H. IşIk. 2008. The effect of moisture of organic chickpea (*Cicer arientium* L) grain on the physical and mechanical properties. *International Journal of Agricultural Research*, 3(1): 40-51.

Jafari, M., G. R. Chegini, and J. Khazaei. 2020. 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*, 68(5): 831-840.

Kalantari, D., H. Jafari, M. Kaveh, M. Szymanek, A. Asghari, A. Marczuk, and E. Khalife. 2022. Development of a machine vision system for the determination of some of the physical properties of very irregular small biomaterials. *International Agrophysics*, 36: 27-35.

Khodabakhshian, R., B. Emadi, M. H. A. Fard, and M. H. Saiedirad. 2012. The effect of variety, size, and moisture content of sunflower seed and its kernel on their terminal velocity, drag coefficient, and Reynold's number. *International Journal of Food Properties*, 15(2): 262-273.

Khorshidpour, B., M. Honarvar, and H. A. Chenarbon. 2020. Assessment of several hydrodynamic properties of sugar beet (*Beta vulgaris* L.). *Food Science and Nutrition*, 8(10): 5641-5649.

Kırmacı, S., and M. Pakdemirli. 2012. Flow analysis and determination of drag forces for spikes of crops. *Mathematical and Computational Applications*, 17(1): 83-91.

Masoumi, M., A. Mahmoudi, M. R. Alizadeh, and S. Abdollahpour. 2020. Effect of awn on aerodynamic properties of paddy grains (*Oryza Sativa* L.). *Agriculture Engineering International: CIGR Journal*, 22(2): 208-216.

Mishra, A., J. P. Sinha, S. Kauka, and B. S. Tomar. 2019. Study of engineering properties of selected vegetable seeds. *Indian Journal of Agricultural Sciences*, 89(10): 1693–1697.

Mohsenin, N. N. 1986. *Physical Properties of Plant and Animal Materials*. 2nd Revised. New York: Gordon and Breach Science Publishers.

Nissa, M. C., N. Bintoro, J. N. W. Karyadi, and R. A. Kusuma. 2019. Mathematical analysis of the effect of grain type and moisture content on physical and mechanical properties of corn (*Zea mays* L.). Yogyakarta, Indonesia: Gadjah Mada University.

Ozturk, T., and B. Esen. 2013. Physical and mechanical properties of some hybrid corn varieties. *International Journal of Agricultural and Biological Engineering*, 6(1): 111-116.

Rahman, A. N. M. R. B., and J. Zhang. 2022. Trends in rice research: 2030 and beyond. *Food & Energy Security*, 12(2):e390.

Rajabipour, A., A. Tabatabaeefar, and M. Farahani. 2006. Effect of moisture on terminal velocity of wheat varieties. *International Journal of Agriculture and Biology*, 8(1): 10-13.

Sangamithra, A., J. S. John, R. S. Prema, K. Nandini, K. Kannan, S. Sasikala, and P. Suganya. 2016. Moisture dependent physical properties of maize kernels. *International Food Research Journal*, 23(1): 109-115.

Saracoglu, T., N. Ucer, and C. Ozarslan. 2012. Selected geometric characteristics, hydrodynamic properties, and impact parameters of quince fruit (*Cydonia vulgaris* Pers.). *International Journal of Food Properties*, 15(4): 758-769.

Sastry, V. S. S. R., H. D. Upadhyaya, and T. R. Srinivas. 2019. Variation for seed physical and hydration properties of chickpea (*Cicer arietinum* L.) mini core collection and their relevance to conservation and utilization. *Plant Genetic Resources*, 17(4): 331-324.

Shahbazi, F., S. Valizadeh, and A. Dowlatshah. 2014. Aerodynamic properties of makhobeli, triticale and wheat seeds. *International Agrophysics*, 28(3): 389-394.

Shahbazi, F. 2015. Evaluation and modelling of aerodynamic properties of mung bean seeds. *International Agrophysics*, 29(1): 121-126.

Shahbazi, F., S. Valizadeh, A. Dowlatshah, and E. Hassanzadeh. 2015. Aerodynamic properties of lentil seeds. *International Agrophysics*, 29(3): 391-396.

Sharma, R., D. S. Sogil, and S. Balasubramanian. 2012. Aerodynamic characteristics of unshelled and shelled sunflower seeds: significance of moisture and cultivars. *International Journal of Food Properties*, 15(1): 1-10.

Shirsat, B. S. 2015. Studies on some physical properties of chickpeas. *International Journal of Applied Research*, 1(7): 857-560.

Singh, K. P., N. H. Mishra, and S. Saha. 2010. Moisture-dependent properties of barnyard millet grain and kernel. *Journal of Food Engineering*, 96(4): 598-606.

Taheri-Garavand, A., A. Nassiri, and S. M. T. Gharibzahedi. 2012. Physical and mechanical properties of hemp seed. *International Agrophysics*, 26(2): 211-215.

Tarighi, J., S. Dadashi, M. A. Ghazvini, and A. Mahmoudi. 2011. Comparison of physical and hydrodynamic properties of two Iranian commercial pomegranates. *Agriculture Engineering International: CIGR Journal*, 13(3): 1-7.

Zahra, N., M. B. Hafeez, A. Nawaz, and M. Farooq. 2022. Rice production systems and grain quality. *Journal of Cereal Science*, 105: 103463.