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Physical and aerodynamic properties of paddy and white rice as a function of moisture content

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RESEARCH PAPER

Abstract

Knowledge of the physical properties of agricultural foods and products is important for designing the equipment for processing, transportation, sorting, separation and storing. The objective was to study the aerodynamic properties of paddy and white rice as a function of moisture content. Several physical properties (linear dimensions, geometric mean diameter, sphericity, thousand kernel weight, bulk and kernel densities, porosity) and aerodynamic properties (terminal velocity and drag coefficient) were investigated as a function of moisture content in the range from 5 to 37% (wet basis; w.b.) for paddy and white rice of the two varieties Fajr and Tarom. The principal dimensions, geometric mean diameter, thousand kernel weight and bulk density increased linearly with increasing moisture content for the two varieties, while sphericity decreased in a very gentle linear direction except for the Tarom variety. Kernel density and porosity decreased linearly with an increase in moisture content. The terminal velocity of paddy and white rice increased linearly with an increase in moisture content from 5 to 37% (w.b.). The drag coefficient of white rice decreased linearly while for paddies the two varieties showed a quadratic trend with moisture content increase. The relationships between the measured properties and moisture content of paddy and white rice varieties were obtained and represented by regression equations.

Keywords: aerodynamic properties, moisture content, paddy, physical properties, rice

1. Introduction

Rice (*Oryza sativa* L.) is one of the leading food crops in the world and the staple food for more than half the world's population (Champagne, 2004). World rice production was estimated at 651.7 million tonnes in 2007, while Iran's rice production was 3.5 million tonnes (FAO, 2007).

Knowledge of the physical properties of agricultural products and foods is important for designing the equipment for processing, transportation, sorting, separation and storing. Designing such equipment without taking these into consideration may yield poor results (Kashaninejad *et al.*, 2006). The major moisture-dependent physical properties of biological materials are shape, size, mass, bulk density, true density and porosity (Mohsenin, 1980).

Principle axial dimension of seeds are useful in selecting sieve separators and calculating grinding power during size reduction. Bulk density is used in the design of drying and aeration systems because it affects the resistance to airflow of a stored bulk. Bulk density, kernel density and porosity can be useful in sizing grain hoppers and storage facilities. They can also affect the rate of heat and mass transfer of moisture during aeration and drying process. Such information is useful in sizing motor requirements for seed transportation and handling. Therefore the determination and consideration of these properties plays an important role in the rice industry (Kashaninejad *et al.*, 2008; White and Jayas, 2001).

Aerodynamic properties such as the terminal velocity of agricultural products are important and required for the design of air conveying systems and the separation equipment. Physical properties such as density, shape and size, etc. need to be known for calculating the terminal velocity and drag coefficient for separating the desirable products from unwanted materials. As a result, aerodynamic properties such as terminal velocity and drag coefficient are needed for air conveying and pneumatic separation of materials (Gupta *et al.*, 2007).

The objective of this study was to determine some physical properties of two varieties of paddy and white rice (Tarom and Fajr) as a function of moisture content in the range from 5 to 37% (wet basis; w.b.). In this research three axial dimensions, geometric mean diameter, sphericity, thousand kernel weight, kernel density, bulk density and porosity for two varieties of paddy and white rice were investigated at five levels of moisture content. The aerodynamic properties of paddy and white rice have not yet been reported. In this study, the aerodynamic properties of paddy and white rice are measured with varying moisture content. With this information, the separation and cleaning of paddy and white rice can be better understood and the potential for developing separation machinery evaluated.

Theoretical considerations

For conveying agricultural material, the range of proper air streams should be used. With low air speed, there is stagnation in the system, and with high air speed, there is not only energy loss, but grains may also be broken.

The proper air speed can be determined from the aerodynamic properties of agricultural materials. These properties are terminal velocity and drag coefficient. If an object is dropped from a sufficient height, the force of gravity will accelerate it until the drag force exerted by the air balances the gravitational force. It will then fall at a constant velocity called the terminal velocity (V_t, m/s) (Mohsenin, 1980):

$$M\times g = \tfrac{1}{2}\rho_A V_t^2 \times C_d \times A_f \quad (1)$$

Where M is the mass (kg) of the kernel, g the gravitational acceleration (m/s), ρ_A the density of air (kg/m^3), C_d the drag coefficient and A_f the frontal area (m^2).

The drag coefficient of the material and its resistance to air flow depends upon the bed thickness of the material, shape and surface roughness of grain and orientation of the material (Gupta *et al.*, 2007). From Equation 1, the drag coefficient of an object is found from its terminal velocity:

$$C_d = \frac{2M\times g}{\rho_A A_f V_t^2} \quad (2)$$

$$A_f = \left(\frac{\pi}{4}\right)L_1 L_2 \quad (3)$$

L_1 and L_2 are the two largest dimensions of the grain.

Two commonly used methods of measuring the terminal velocity experimentally are the suspension and drag methods. The suspension method allows a particle to be suspended in a vertical duct by blowing air in a duct and measuring the air speed at the moment when the particle is suspended. Under these conditions the weight of the particle becomes equal to the drag force (Mohsenin, 1980). The drop method involves dropping the particle from a certain height whereby the particles will reach their terminal velocity after dropping a certain distance. Terminal velocity can be taken from the distance versus time curves where it begins to become linear. The advantage of the drop test for particles with lower terminal velocities is that it is less difficult to use than the suspension method (Shellard and MacMillan, 1978).

2. Materials and methods

Sample preparation

The two varieties (Tarom and Fajr) of paddy and white rice used in the present study were obtained from rice milling plants in Gorgan, Iran. The grains were manually cleaned to remove all foreign materials and broken grains. The initial moisture content of samples was determined by air convection oven drying at 105±2 °C until a constant weight was obtained and was found to be 6.34, 7.93, 5.33 and 8.15 g for paddy and white rice in Tarom and Fajr varieties, respectively (ASABE, 1997). The experiment was repeated three times to determine mean values.

In order to obtain samples with a higher moisture content, a calculated quantity of distilled water must be added to the sample. The quantity of distilled water was calculated from the following equation:

$$W_2 = W_1 \times \left[\frac{M_1 - M_2}{100 - M_1}\right] \quad (4)$$

Where W_2 is distilled water weight (g), W_1 sample weight (g), M_1 the final moisture content (% w.b.) and M_2 the initial moisture content (% w.b.).

Then the sample was sealed and kept at 5 °C in a refrigerator for 10 days to enable the moisture to distribute uniformly throughout the product. It is necessary to let the samples warm up to room temperature before starting each test (Kashaninejad *et al.*, 2006). All the physical and aerodynamic properties of the grains were obtained for five moisture contents in the range 5-37% (w.b.). The tests were carried out with five replications for each moisture content level, unless stated otherwise, and the average values are reported.

Dimensions, sphericity, thousand kernel weight

In order to determine the dimensions and sphericity, one hundred paddy and white rice were randomly selected and for each, the three principal dimensions, namely minor diameter (thickness), intermediate diameter (width) and major diameter (length), were measured using an electronic digital calliper (Guanglu, Guilin, China) with a least count of 0.01 mm at each moisture level.

To obtain the unit mass, each seed was weighed on a precision electronic balance (TE313S; Sartorius, Mississauga, Canada) reading to 0.001 g. Geometric mean diameter (D) and degree of sphericity (Φ) were calculated at each moisture level by using the following equations (Mohsenin, 1980):

$$D = (LWT)^{\frac{1}{3}} \quad (5)$$

$$\Phi = \frac{(LWT)^{\frac{1}{3}}}{L \times 100} \quad (6)$$

Where L is the length (mm), W the width (mm) and T the thickness (mm) of the seed.

Thousand kernel weight (T_w) was determined by counting 1000 grains and weighting them on an electronic balance (TE313S) (Ghasemi Varnamkhasti *et al.*, 2008).

Bulk density, kernel density and porosity

Bulk density (ρ_b; kg/m^3) was calculated from the mass and volume of the circular container with known volume that was filled with the paddy and white rice. After filling the circular container, excess grains were removed by passing a stick across the top surface using five zigzag motions. The samples were not compacted in any way (Kashaninejad *et al.*, 2008).

The average kernel density (ρ_k; kg/m^3) was determined using the toluene displacement method. The volume of toluene displaced was found by immersing a weighed quantity of paddy and white rice in the toluene (Ogut, 1998; Singh and Goswami, 1996).

The porosity (ε; %) of the bulk is the ratio of the volume of internal pores in the kernel to its bulk volume and was determined by the following equation (Mohsenin, 1980):

$$\varepsilon = (1 - \frac{\rho_b}{\rho_k}) \times 100 \quad (7)$$

Terminal velocity and drag coefficient

The terminal velocities of paddy and white rice at different moisture content levels were measured using an air column (Figure 1). For each test, a sample (paddy or white rice) was dropped from the top of a 75 mm diameter, 1 m long glass tube. The air flowed upwards in the tube from the bottom to the top and the air velocity at which the sample suspended was recorded by an anemometer with at least 0.1 m/s sensitivity. Ten replications were taken for each moisture content level (Aydin and Ozcan, 2002; Kashaninejad *et al.*, 2006).

The drag coefficients were calculated according to Equation 2 by inserting the measured terminal velocities into it.

Statistical analysis

Each experiment was replicated five times, unless stated otherwise, and the average values are reported. Mean, maximum, minimum and standard deviation of dimensions of one hundred paddy and white rice were determined using the Microsoft Excel (2003) software program. The effect of moisture content on different physical and aerodynamic properties of paddy and white rice was determined using the analysis of variance (ANOVA) method and significant

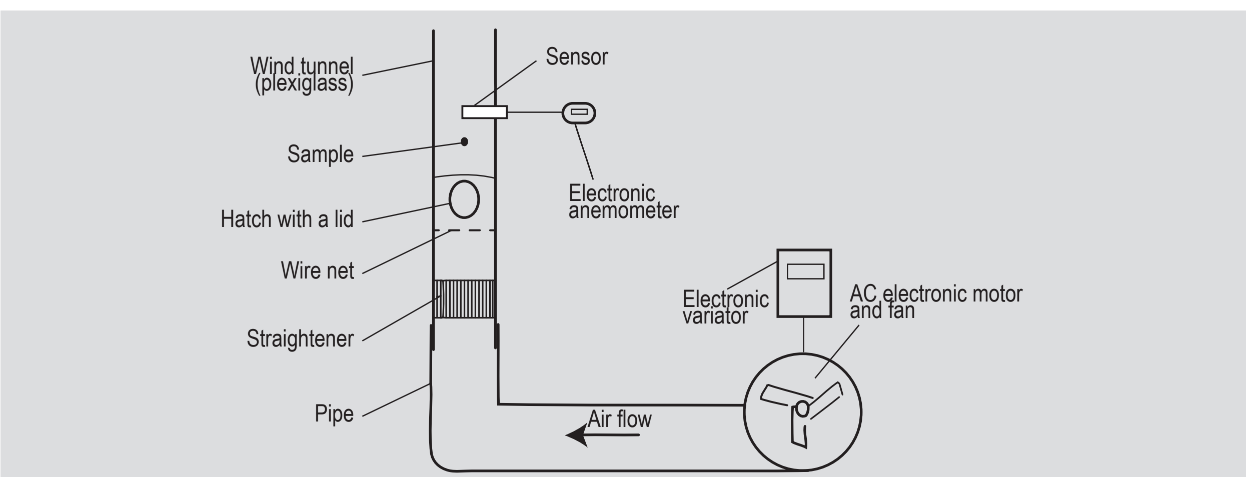

Figure 1. Schematic representation of the experimental apparatus used to determine the terminal velocity of paddy and white rice.

differences of means were compared using the Duncan's test at 1% significant level using SAS software (2001; SAS Institute, Cary, NC, USA) program. The best relationship between moisture content and physical and aerodynamic properties of paddy and white rice was also determined using regression analysis of the SAS software program.

3. Results and discussion

Dimensions

The results showed that both paddy and white rice expand in three dimensions as moisture content increased from 5-37% (w.b.) (Figures 2-4).

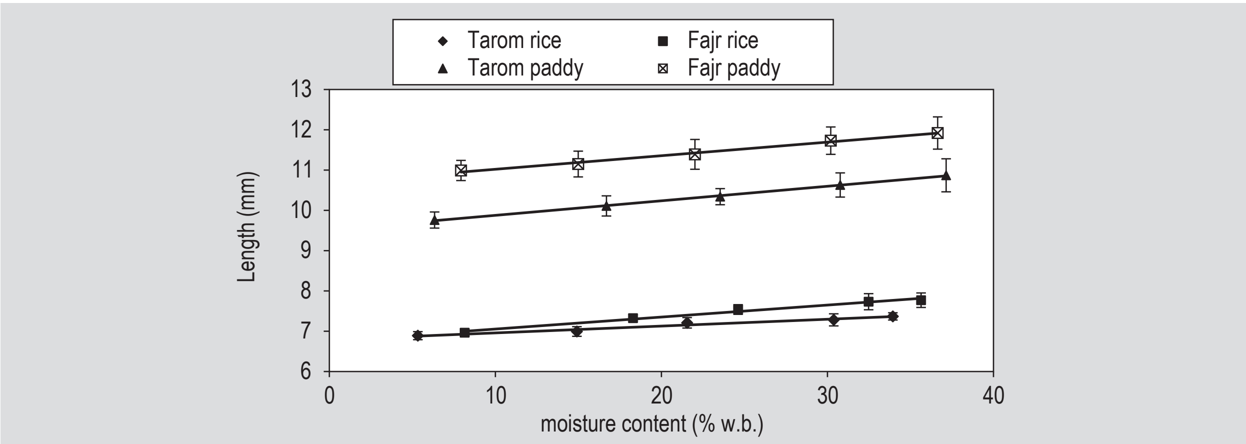

Figure 2. Effect of moisture content (% wet basis; w.b.) on the kernel length of paddy and white rice varieties.

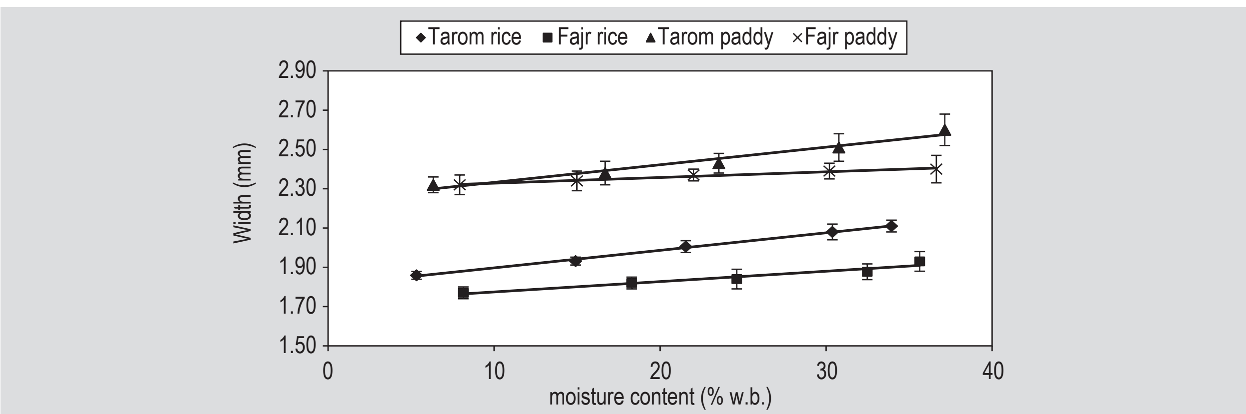

Figure 3. Effect of moisture content (% wet basis; w.b.) on kernel width of paddy and white rice varieties.

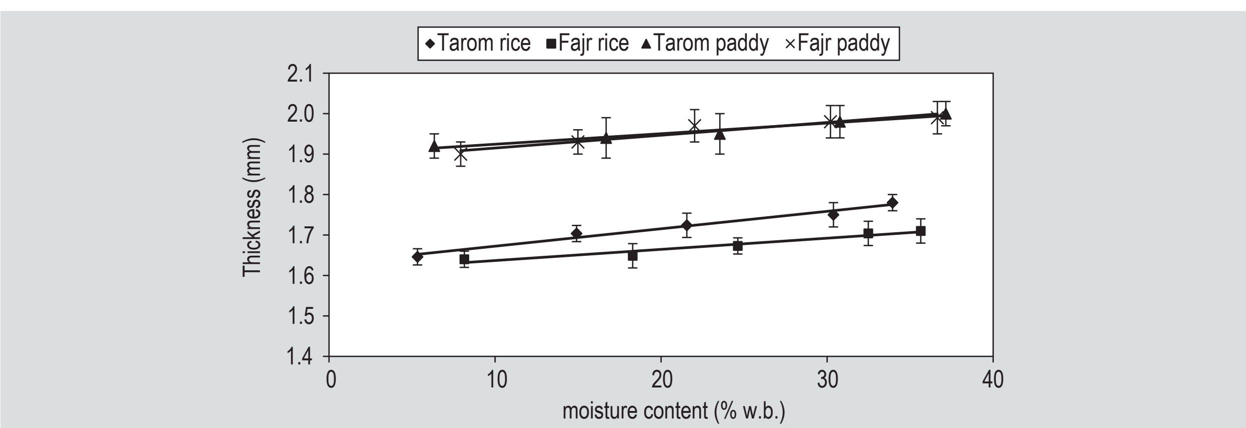

Figure 4. Effect of moisture content (% wet basis; w.b.) on kernel thickness of paddy and white rice varieties.

This indicates that during the moisture absorption process (such as parboiling), the white rice will show some increase in length, width and thickness with moisture. Similar results were found for pistachio nut and its kernel (Kashaninejad *et al.*, 2006), soybean (Kashaninejad *et al.*, 2008), lentil seeds (Carman, 1996), roselle seeds (Sánchez-Mendoza *et al.*, 2008), barley seeds (Aghajani *et al.*, 2012a,b), pomegranate seeds (Daraei Garmakhany *et al.*, 2013) and cucumber (Mousavizadeh *et al.*, 2010).

Results also showed that length, width and thickness values for paddies were higher than those of white rice; moreover, paddy of the Fajr variety was longer than the Tarom paddy.

Regression equations and their coefficients of determination (R^2) obtained for length, width and thickness as a function of moisture content are presented in Table 1. There was a significant correlation between the moisture content and axial dimensions of paddy and white rice of both varieties. Similar trends have been reported for soybean (Kashaninejad *et al.*, 2008), cucurbit seeds (Milani *et al.*, 2007) and coriander seeds (Coskuner and Karababa, 2007).

Geometric mean diameter and sphericity

The geometric mean diameter and sphericity for paddy and white rice of two rice varieties with a moisture range between 5 and 37% (w.b.) are shown in Figures 5 and 6, respectively. The geometric mean diameters of all samples were slightly increased with increase in moisture content, while sphericity decreased very gently.

Table 1. Regression equations obtained for dimensions (length, width and thickness; L, W and T), geometric mean diameter (D), sphericity (Φ) and thousand kernel weight (T_w) of two paddy varieties and two white rice varieties.

Variety	Paddy			Rice		
	Moisture content (% w.b.)	Equation	R^2	Moisture content (% w.b.)	Equation	R^2
Fajr	7.93-36.64	L = 0.0337mc + 10.683	0.99	8.15-35.64	L = 0.0298mc + 6.7568	0.98
		W = 0.0029mc + 2.2993	0.98		W = 0.0053mc + 1.7217	0.94
		T = 0.0032mc + 1.8834	0.92		T = 0.0028mc + 1.6093	0.94
		D = 0.0072mc + 3.5858	0.99		D = 0.0081mc + 2.653	0.99
		Φ = -0.0331mc + 33.517	0.90		Φ = -0.0456mc + 39.212	0.78
		Tw = 0.2866mc + 19.081	0.95		Tw = 0.2313mc + 13.01	0.99
Tarom	6.34-37.15	L = 0.0361mc + 9.5156	0.99	5.33-33.94	L = 0.017mc + 6.7888	0.96
		W = 0.0009mc + 2.2427	0.96		W = 0.0089mc + 1.78	0.99
		T = 0.0026mc + 1.8983	0.96		T = 0.0043mc + 1.6293	0.97
		D = 0.0104mc + 3.4311	0.98		D = 0.009mc + 2.712	0.99
		Φ = -0.024mc + 36.031	0.88		Φ = -0.0303mc + 39.969	0.87
		Tw = 0.2677mc + 18.066	0.99		Tw = 0.1689mc + 15.683	0.96

mc = moisture content (% wet basis; w.b.); R^2 = coefficients of determination.

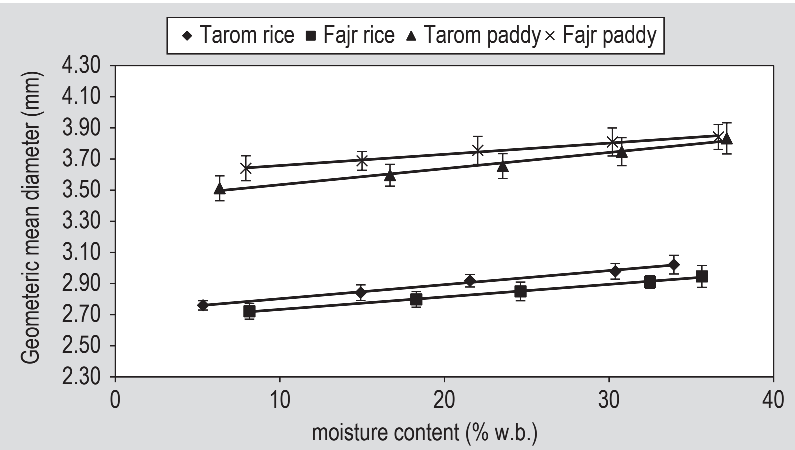

Figure 5. Effect of moisture content (% wet basis; w.b.) on kernel geometric mean diameter of paddy and white rice varieties.

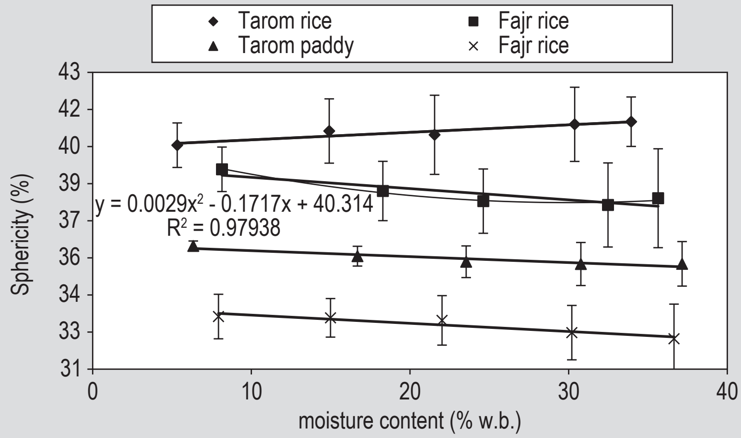

Figure 6. Effect of moisture content (% wet basis; w.b.) on kernel sphericity of paddy and white rice varieties.

Regression equations and their coefficients of determination (R^2) obtained for geometric mean diameter and sphericity of paddy and white rice as a function of moisture content are presented in Table 1. The positive linear relationship of geometric mean diameter with moisture content was also observed by other research workers for soybean (Kashaninejad *et al.*, 2008), pistachio nut and its kernel (Kashaninejad *et al.*, 2006), and millet (Baryeh, 2002).

Thousand kernel weight

Thousand kernel weight was linearly increased for Fajr paddy from 22.07 to 29.45 g, for Tarom paddy from 19.81 to 27.83 g, for Fajr white rice from 15.11 to 21.5 g, and for Tarom white rice from 16.96 to 21.72 g, as the moisture content increased from 5 to 37% w.b. (Figure 7).

The regression relationships between thousand kernel weight and moisture content for each variety of paddy and white rice are presented in Table 1.

A linear increase in thousand kernel weight with increase in moisture content has also been reported for barbunia bean (Cetin, 2007), lentil (Carman, 1996), quna seeds (Aviara *et al.*, 1999) and cumin seeds (Singh and Goswami, 1996).

Kernel density

The experimental results for the kernel density of paddy and white rice at various moisture levels are shown in Figure 8. The highest value of kernel density was obtained for Tarom paddy (2,377.90 kg/m^3) at 6.34% (w.b.). The kernel density of paddy and white rice showed a decreasing trend with moisture content for two paddy and white rice varieties. Kernel density of Fajr and Tarom paddies at different moisture levels (5-37%) ranged from 1,785.92 to 1,652.61 kg/m^3 and 2,377.9 to 1,906.53 kg/m^3, respectively. Their respective white rice showed the kernel density of 1,495.64 to 1,308.45 kg/m^3 and 1,507.42 to 1,312.66 kg/m^3, respectively. Moreover, kernel density of Tarom paddy was significantly higher than that of other samples at all moisture content levels.

The effect of moisture content on kernel density of paddy and white rice showed a linear decrease with increasing moisture content. The regression equations obtained and

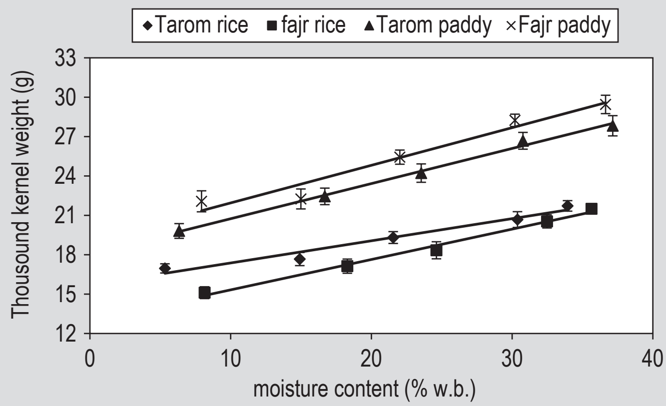

Figure 7. Effect of moisture content (% wet basis; w.b.) on one thousand kernel weight of paddy and white rice varieties.

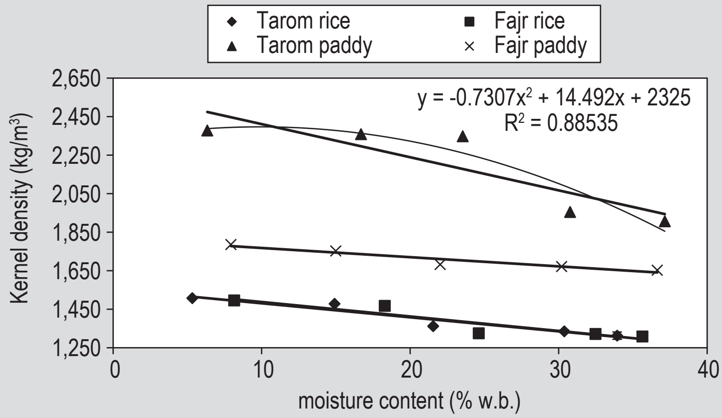

Figure 8. Effect of moisture content (% wet basis; w.b.) on kernel density of paddy and white rice varieties.

their high R^2 values confirmed these linear behaviours (Table 2).

A decrease in kernel density with an increase in moisture content has been reported for chickpea seed (Konak *et al.*, 2002) and cotton seed (Ozarslan, 2002).

Bulk density

Figure 9 shows the bulk density variation of paddy and white rice at different moisture levels. Both the paddies and white rice grains showed a relatively similar increasing pattern in their bulk density with an increase in moisture content. The lowest values belonged to the paddy of Fajr variety, while white rice of Tarom variety had the highest values.

The equations representing the relationship between bulk density of paddy and white rice and moisture content for each variety and their coefficient of determination (R^2) are presented in Table 2. As is shown, there was a positive relationship with a very high correlation between bulk density and moisture content for two paddy and white rice varieties. The increase in bulk density of both paddy and white rice with an increase in moisture content indicates that the increase in mass owing to moisture grain in the sample is greater than the accompanying volumetric expansion of the bulk. The positive relationship between bulk density and moisture content was observed by various research workers for lentil seeds (Carman, 1996), cumin seed (Singh and Goswami,1996), pumpkin seeds (Joshi *et al.*, 1993), pistachio nut and its kernel (Kashaninejad *et al.*, 2006) and neem nuts (Visvanathan *et al.*, 1996).

Table 2. Regression equations obtained for kernel density (ρ_k), bulk density (ρ_b), porosity (ε), terminal velocity (V_t) and drag coefficient (C_d) of two paddy varieties and two white rice varieties.

Variety	Paddy			Rice		
	Moisture content (% w.b.)	Equation	R^2	Moisture content (% w.b.)	Equation	R^2
Fajr	7.93-36.64	ρk = -4.7724mc + 1815.7	0.92	8.15-35.64	ρk = -7.5123mc + 1562.7	0.85
		ρb = 3.9938mc + 392	0.99		ρb = 4.0036mc + 700.24	0.99
		ε = -0.3106mc + 78.688	0.99		ε = -0.5897mc + 56.207	0.95
		Vt = 0.0177mc + 6.0028	0.97		Vt = 0.0108mc + 6.3541	0.97
		Cd = 0.0001mc² - 0.0065mc + 0.6188	0.84		Cd = -0.0025mc + 0.7114	0.80
Tarom	6.34-37.15	ρk = -17.208mc + 2583.3	0.76	5.33-33.94	ρk = -7.2825mc + 1553.6	0.92
		ρb = 4.6966mc + 433.74	0.99		ρb = 3.6688mc + 727.94	0.99
		ε = -0.4246mc + 84.539	0.89		ε = -0.4246mc + 84.539	0.90
		Vt = 0.0134mc + 6.3153	0.90		Vt = 0.0071mc + 6.517	0.99
		Cd = 0.0001mc² - 0.0046mc + 0.5218	0.67		Cd = -0.0027mc + 0.6898	0.90

mc = moisture content (% wet basis; w.b.); R^2 = coefficients of determination.

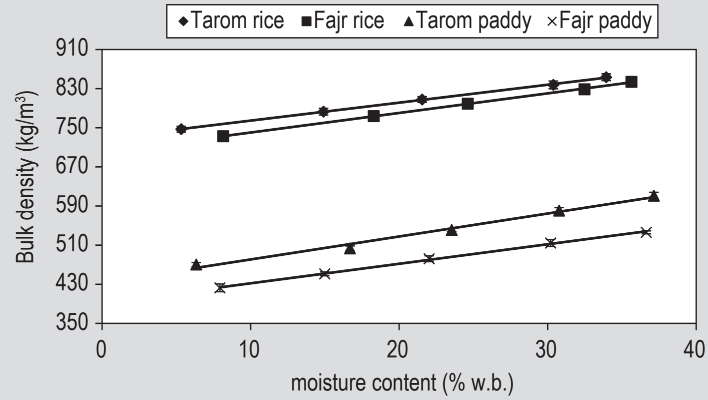

Figure 9. Effect of moisture content (% wet basis; w.b.) on kernel bulk density of paddy and white rice varieties.

Porosity

Since the porosity depends on the bulk as well as kernel densities, the magnitude of variation in porosity depends on these factors only. Thus, the porosity of paddy and white rice for two varieties was found to decrease with an increase in moisture content.

The results showed that porosity of paddy ranged from 76.33 to 67.56% for the Fajr variety, and 80.22 to 67.95% for the Tarom variety. (Figure 10). Also the porosity values of white rice ranged from 51.01 to 35.5% and 50.44 to 34.98% for Fajr and Tarom varieties, respectively.

Other studies reported a similar decrease in porosity for pumpkin seeds (Joshi *et al.*, 1993), chickpea seeds (Konak *et al.*, 2002) and neem nuts (Visvanathan *et al.*, 1996) when the moisture content increased. The relationship between porosity and moisture content for two paddy and white rice varieties is presented in Table 2. As shown, a linear correlation was obtained in all cases.

Terminal velocity

The variation in terminal velocity of paddy and white rice with moisture content of the sample are presented in Figure 11 for paddy and rice variety of Fajr and Tarom. It can be seen that the terminal velocity of paddy and white rice for each variety increased as the moisture content increased. The terminal velocity of white rice grains was also higher than that of paddies in two varieties. These differences in results can be attributed to the increase in mass of the individual paddy or the white rice per unit, when their frontal areas were presented to the air stream to suspend the material. The other reason is probably that the drag force is affected by the moisture content of the particle. Kashaninejad *et al* (2006) showed that as the moisture content increased from 4.10 to 38.10% (w.b.), the terminal velocity of pistachio nut and its kernel was found to increase. Similar results were also reported by Joshi *et al* (1993) for pumpkin seeds, Carman (1996) for lentil seeds, Singh and Goswami (1996) for cumin seeds, Suthar and Das (1996) for karingda seed, Gezar *et al* (2002) for apricot pit and kernel, Akar and Aydin (2005) for gumbo fruit, Khoshtaghaza and Mehdizadeh (2006) for wheat kernel and strew materials and Zewdu (2007) for tef grain and straw material.

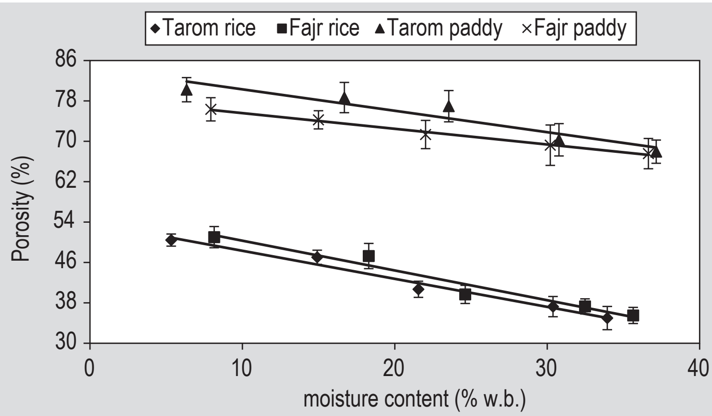

Figure 10. Effect of moisture content (% wet basis; w.b.) on kernel porosity of paddy and white rice varieties.

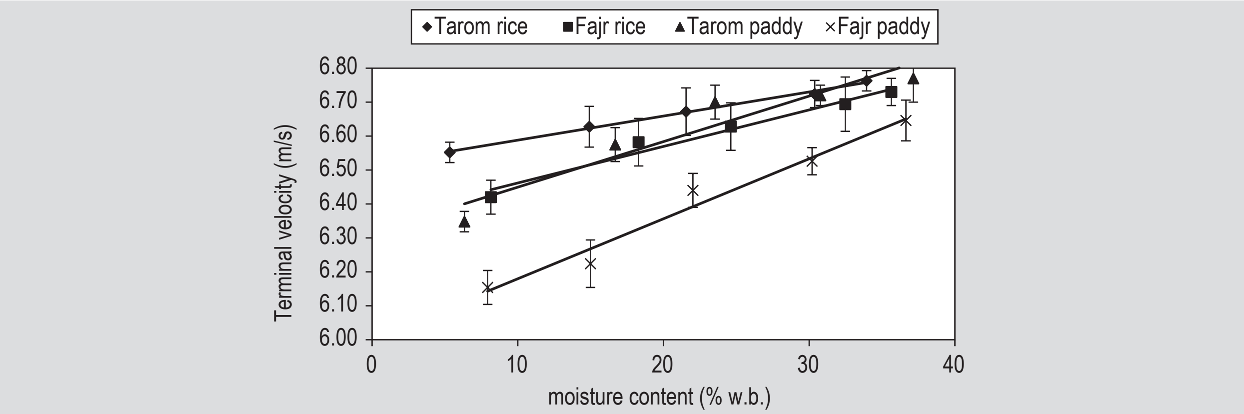

Figure 11. Effect of moisture content (% wet basis; w.b.) on kernel terminal velocity of paddy and white rice varieties.

The values of terminal velocity of Fajr and Tarom paddies at different moisture content levels varied between 6.15-6.65 m/s and 6.35-6.77 m/s, respectively. However, the terminal velocity of Fajr and Tarom white rice grains ranged from 6.42-6.73 m/s and 6.55-6.76 m/s, respectively. The results show that the Tarom white rice had the highest terminal velocity, whereas the lowest terminal velocity of paddy and white rice was found for Fajr paddy.

The mathematical equations and their R^2 values obtained by fitting the experimental data of terminal velocity of paddy and white rice as a function of moisture content are listed in Table 2. It can be found that there were positive relationships with a very high correlation between terminal velocity and moisture content in all case studies. These linear behaviours were in accordance with similar results reported for pistachio nut and its kernel (Kashaninejad *et al.*, 2006), cumin seed (Singh and Goswami, 1996), wheat kernel (Khoshtaghaza and Mehdizadeh, 2006) and tef grain (Zewdu, 2007).

Drag coefficient

The variations in drag coefficient of paddy and white rice with moisture content of the sample are presented in Figure 12 for both varieties. The drag coefficient for Fajr and Tarom varieties of paddy and white rice slowly decreased from 0.57 to 0.53, 0.50 to 0.48, 0.71 to 0.63 and 0.68 to 0.61, respectively, when the moisture content level increased from 5 to 37% (w.b.).

It is observed in Figure 12 that the value of the drag coefficient for Fajr and Tarom variety of white rice was more when compared to the Fajr and Tarom variety of paddy respectively, in the moisture content range between 5 to 37% (w.b.). The decrease in drag coefficient is related to the increase in mass as well as the increased frontal area.

The equations representing the relationship between drag coefficient of paddy and white rice and moisture content for each variety and their coefficient of determination (R^2) are presented in Table 2. As shown, there was a linear relationship between drag coefficient and moisture content for all cases studies. These linear behaviours are in accordance with research published in similar papers for sunflower seed (Gupta *et al.*, 2007) and tef grain (Zewdu, 2007).

4. Conclusions

The following conclusions are drawn from this investigation into the properties of paddy and white rice: all the physical and aerodynamic properties of paddy and white rice for different varieties were significantly dependent on their moisture content. All the linear dimensions, geometric mean diameter and thousand kernel weight of paddy and white rice increased linearly with an increase in moisture content, with a high correlation for two varieties. Paddy had more linear dimensions, geometric mean diameter and thousand kernel weight than white rice during moisture content analysis. Sphericity decreased very gently with an increase in paddy and white rice moisture content, except for Tarom rice which increased very slightly with an increase in moisture content from 5 to 37% (w.b.). The bulk density increased linearly with increasing moisture content for each variety, whereas kernel density and porosity decreased linearly with increasing moisture content of two paddy and white rice varieties. In the investigation of aerodynamic properties, terminal velocity increased linearly with an increase in moisture content from 5 to 37% (w.b.) for each variety of paddy and white rice. At all moisture content levels, the terminal velocity of paddy and white rice was the greatest for the Tarom rice variety (6.55-6.76 m/s) and the lowest for the Fajr paddy variety (6.15-6.65 m/s). The drag coefficient of paddy and white rice decreased with an increase in moisture content for two varieties. The drag coefficient of white rice grains decreased linearly and the drag coefficient of paddies showed a quadratic trend for two varieties when the moisture content increased.

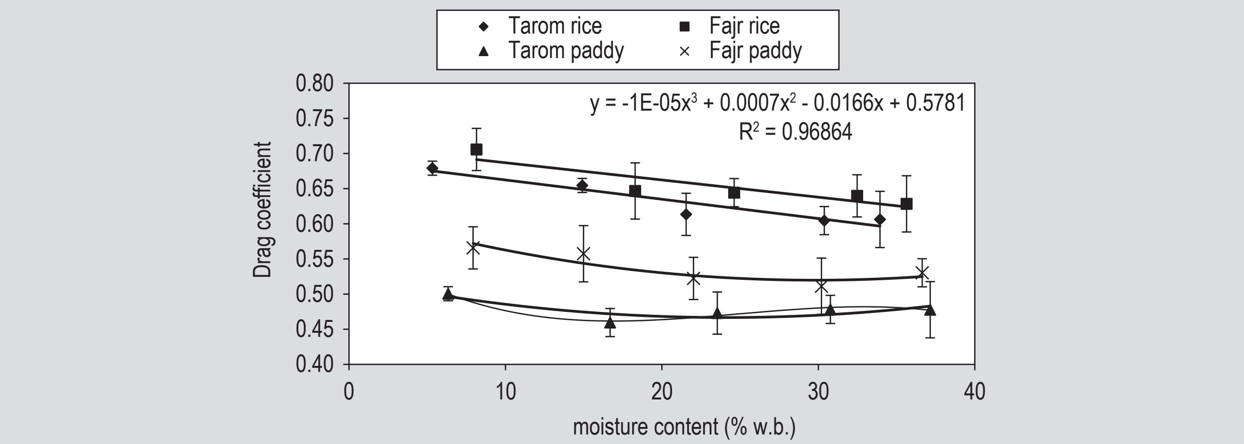

Figure 12. Effect of moisture content (% wet basis; w.b.) on drag coefficient of kernels of paddy and white rice varieties.

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