Physical properties of rough and brown rice of Japonica, Indica and NERICA types

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Abstract: This research involved a study of the physical properties of rough and brown rice of various types. The effect of kernel thickness on physical properties was analyzed. Fundamental physical properties, such as dimensions, mass, and frictional characteristics, were measured for different fractions of rough and brown rice of seven different varieties: Nanatsuboshi, Yumepirika, Oborozuki (Japonica type), IR-28, IR-50, IR-64 (Indica type), and NERICA-4 (NERICA type). Results showed that, in both rough and brown rice, the physical properties of the NERICA type showed a closer relationship with the Indica type than they did with the Japonica type. Moreover, statistical analysis indicated that the physical properties were affected by kernel thickness within each variety of rough and brown rice. Such information could be helpful in designing facilities and machines required for rice processing and storage.

Keywords: NERICA rice, Indica rice, Japonica rice, physical properties of rice, thickness fraction, processing levels

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1 Introduction

Information on physical properties of rice is most relevant to all stages of its production, preservation and utilization. Such information is essential to the design of equipment required for activities such as harvesting, drying, handling and storage, as well as that used for transportation and processing (e.g., milling, cooking, packaging and marketing). For this reason, determining the physical properties of rice is the most important factor in assessing its quality (Fofana et al., 2011).

Several authors have examined the physical properties of rice in the last decades, and most of them have been summarized and cited by Kunze et al. (2004) and Bhattacharya (2011). Recently, a new type of rice, "New Rice for Africa (NERICA)", is being adopted across the African continent. Not enough is known about the physical properties of this new type, and some studies have been carried out by Adebowale et al. (2011), Shittu and Olaniyi (2012), and Agu and Oluka (2013).

Furthermore, kernel thickness influences milling characteristics as well as physicochemical properties, as discussed by Wadsworth et al. (1979) and Sun and Siebenmorgen (1993).

Consequently, the objectives of this study are to measure some of the fundamental physical properties as well as to analyze the effect of kernel thickness on physical properties of rough and brown rice of various types.

2 Materials and methods

2.1 Rice samples and sample preparation

This study was conducted using rough rice of the Japonica type, varieties Nanatsuboshi, Yumepirika and Oborozuki, with average values of moisture content of approximately 15% (135^{o}C w.b.), produced at the Hokkaido University farm, Sapporo, Hokkaido; both rough and brown rice of the Indica type, varieties IR-28,

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IR-50 and IR-64, with average values of moisture content of approximately 12% (135^{o}C w.b.); and rough rice of the NERICA type, variety NERICA-4, with 13% moisture content (135^{o}C w.b.), produced in Japan International Cooperation Agency (JICA) Tsukuba International Center, Ibaraki prefecture, Japan.

Un-fractioned samples of brown rice were obtained with a laboratory rubber roll husker SATAKE type THU (SATAKE Engineering Co., Ltd, Japan). The average moisture content of brown rice in the Japonica, Indica and NERICA varieties were approximately 15.5%, 12.5% and 13.1 % (135 ^{o}C w.b.) respectively.

Fractioned samples of both rough and brown rice were created using a laboratory thickness grader SATAKE type TWS.

2.2 Devices and methods for measuring physical properties

The physical properties of all samples were measured using the same equipment. The measurement methods, as well as the devices used for measuring each physical property, are summarized below.

2.2.1 Dimensional characteristics

Dimensional characteristics of rice kernels are related to the individual grain properties (Kunze et al., 2004, Bhattacharya, 2011). As proposed by Mohsenin (1986), assuming rice grain as an ellipsoid, the slenderness ratio *L/W ratio* and sphericity S_p can be calculated using the Equations 1 and 2 respectively, as a function of the three principal diameters of rice grain, including length *L* in mm, width *W* in mm, and thickness *T* in mm.

– $$S_L = \frac{L}{W} \quad (1)$$

– $$S_p = \frac{(L \cdot W \cdot T)^{\frac{1}{3}}}{L} \quad (2)$$

The volume of the kernel K_v was determined by Equation 3, as suggested by Jain and Bal (1997).

– $$K_v = \frac{1}{4}\left[\left(\frac{\pi}{6}\right) L(W+T)^2\right] \quad (3)$$

Three principal dimensions, length *L*, width *W*, and thickness *T*, of rough and brown rice were measured manually using a dial caliper (Kori Seiki Ltd, Japan), with 0.05 mm of precision. One hundred well-distributed grains, randomly drawn from the test samples, were measured.

2.2.2 Composition analysis of rice samples

Components of rough and brown rice were divided by human observation and were expressed as a percentage of weight. Components of rough rice were divided into the following categories: regular kernels, empty kernels, immature kernels, damaged kernels, brown kernels, husk and foreign materials. Meanwhile, components of brown rice were divided into the following categories: sound whole kernels, immature kernels, chalky kernels, broken kernels, damaged kernels, discolored kernels and dead kernels, as suggested by Ohstubo (1995), and the Japan Rice Millers Association (1997).

2.2.3 Moisture content

Moisture content (*MC*) was determined by the Japanese Society of Agricultural Machinery (JSAM) standard method: about 10 g of whole grain rice was placed in a forced-air oven at 135^{o}C for 24 hours and moisture was computed on a wet basis.

2.2.4 Thousand-kernel weight

The thousand-kernel weight (*TKW*) was determined by weighing 1,000 randomly drawn rough rice regular kernels in an electronic balance (Sartorious, model BP 310 S, Germany), with 0.001g of precision.

2.2.5 Bulk density

Bulk density (*BD*) was determined using a grain volume-weight tester (Brauer type, Kiya Engineering, Tokyo, Japan). The total 150 grams of each rice sample was inserted inside the grain volume-weight tester. Bulk density was calculated from the volume measured (V_m) as

– $$BD = \left(\frac{150}{V_m \cdot 1.5}\right) \cdot 1000 \quad (4)$$

where V_m is the volume measured, expressed as grams per liter (g/L).

2.2.6 Static angle of repose

Static angle of repose (θ_s) was obtained using a perspex box as proposed by Bhattacharya (2011).

The box was designed and built at the Laboratory of Agricultural and Food Process Engineering in the Graduate School of Agriculture, Hokkaido University.

The total of 400 grams was inserted into the box using a funnel. The detachable door of the perspex box was then flicked open, allowing the grain to fall. The angle that the top of the pile made to the horizontal was read from the angles etched on the transparent lateral wall of the box to determine the static angle of repose, expressed in degrees (^{o}).

2.2.8 Static friction coefficient

Static coefficient of friction (μ) was determined using an inclined plane coefficient of friction tester as suggested by Fraser et al. (1978), Dutta et al. (1988), and Baryeh (2002).

The device was designed and built at the Laboratory of Agricultural and Food Process Engineering in the Graduate School of Agriculture, Hokkaido University. The total 100 grams was loaded into a cylinder that would permit direct contact between the rice grains and the test surface, and was carefully placed on the test surface. The handle was rotated gradually and steadily for an accurate result. The angle at which the material started to slide down the test surface was read from the digital angle meter. The static coefficient of friction of the rice grain on the test surface was calculated as

– $$\mu = tan \cdot \alpha \quad (5)$$

where α is the angle at which the material starts to slide.

A conveyor belt made of a mixture of rubbers, the material used for transporting rice in the rice industry, was used as the test surface.

2.2.9 Grain fluidity

Grain fluidity (*GF*) was analyzed using a grain fluidity tester (Yamashita 1992), designed and built at Laboratory of Agricultural and Food Process Engineering in the Graduate School of Agriculture, Hokkaido University. The total 400 grams was inserted into a hopper closed with a stopper. The stopper was raised while the rice flow was timed with the help of a sensor situated near the exit of the hopper. Grain fluidity was expressed as the weight of rice that flows in 1 second, (*g/s*).

2.3 Data analysis

The means of the physical properties of rough and brown rice by thickness fraction within each variety were analyzed by one-way analysis of variance (ANOVA) and Tukey-Kramer's test to determine significant differences among them with 95% of confidence. Linear regression analysis was computed to assess the relationship among physical properties.

3 Results and discussion

3.1 Thickness distribution of rough and brown rice

Frequency distribution for rough and brown rice kernel thickness for each variety is shown in Figures 1 and 2 respectively. Samples of rough rice were divided into four thickness fractions for each variety, with the exception of the variety IR-64, which was divided into three fractions. The variety IR-64 showed the biggest difference in the percentage of each thickness fraction in comparison with other varieties, which were more uniform (Figure 1).

Meanwhile, samples of brown rice were divided into three thickness fractions. The variety IR-50 indicated the biggest difference in the percentage of each thickness fraction in comparison with other varieties, which were more uniform (Figure 2). Additionally, thickness distribution showed that the NERICA type was more closely related to the Indica types than it was with the Japonica type. For both rough and brown rice, NERICA thickness distribution was found to be between the higher thickness fractions of the Indica type and lower thickness fractions of the Japonica type. For rough rice, the NERICA type indicated similar thickness distribution to variety IR-28 and, for brown rice, indicated distribution closer to that of the IR-28 and IR-62 varieties. The NERICA and Indica types showed lower thickness distribution in comparison with the Japonica type for rough and brown rice.

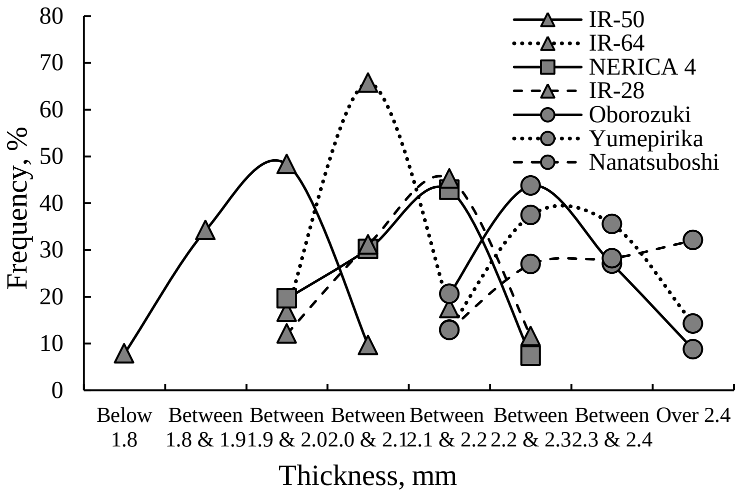

Figure 1 Frequency distribution for rough rice kernel thickness.

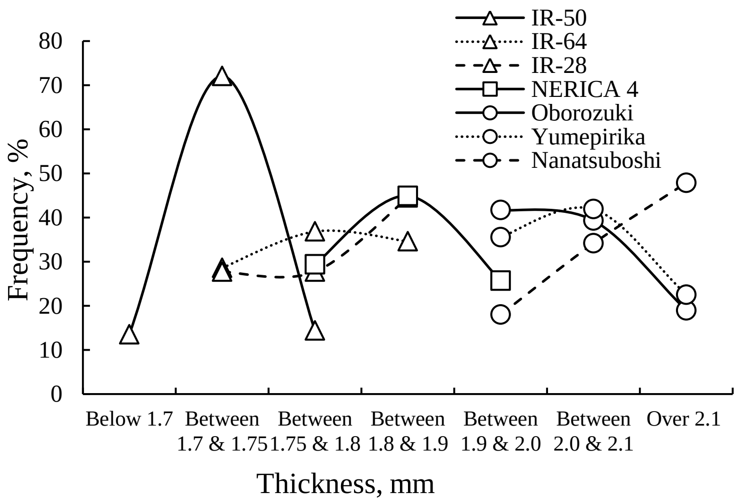

Figure 2 Frequency distribution for brown rice kernel thickness.

3.2 Composition analysis

One-way ANOVA showed that the mean of regular kernel, damaged kernel, and immature kernel were significantly different among the thickness fractions within each variety. Significant differences were mostly found between thinner and thicker kernels. Within each variety, the fraction containing thinner kernels had a lower regular kernel percentage as well as a higher percentage of damaged and immature kernels than the fraction containing thicker kernels of rough rice (Table 1).

On the other hand, one-way ANOVA indicated that mean sound whole kernel fractions, mean broken kernel fractions, mean immature kernel fractions and mean chalky kernel fractions were significantly different among the fractions within each variety of brown rice. Significant difference was mostly found between thinner and thicker kernels among fractions within each variety. Thinner kernels had a lower sound whole kernel percentage, as well as a higher percentage of immature kernel, broken kernel and chalky kernel than thicker kernels within each variety (Table 2).

Composition analysis results could be helpful in the handling process. Thinner kernels have been reported to have distinct chemical and physicochemical properties compared with thicker kernels (Wadsworth et al., 1979, Bhattacharya 2011). Removing the thinner kernel could reduce losses in the milling process as well as improve its efficiency (Luh 1991). Removing thinner kernels of rough rice could be helpful in increasing the efficiency of the cleaning process as well as in minimizing undesirable kernels such as damaged, immature and chalky.

Table 1 Average value of components of rough rice

Variety	Thickness fraction	Regular kernel (*RK*)		Damaged kernel (*DK*)		Immature kernel (*IK*)	
	mm	%					
NERICA 4	Unfractionated	95.0	a	2.3	c	1.9	bc
	Between 1.9&2.0	78.5	c	6.2	ab	8.7	a
	Between 2.0&2.1	92.1	b	4.5	b	3.2	b
	Between 2.1&2.2	93.6	ab	4.4	b	1.9	bc
	Between 2.2&2.3	94.1	ab	5.2	b	0.5	c
IR-28	Unfractionated	96.4	bc	1.8	b	1.2	b
	Between 1.9&2.0	83.4	d	5.9	a	5.6	a
	Between 2.0&2.1	96.2	c	2.2	b	1.5	b
	Between 2.1&2.2	98.0	a	1.4	b	0.6	c
	Between 2.2&2.3	97.5	ab	2.2	b	0.3	c
IR-50	Unfractionated	95.5	a	1.5	b	1.6	b
	Below 1.8	61.0	b	11.1	a	10.3	a
	Between 1.8&1.9	95.4	a	2.7	b	1.8	b
	Between 1.9&2.0	97.3	a	1.7	b	0.9	b
	Between 2.0&2.1	97.1	a	1.8	b	0.9	b
IR-64	Unfractionated	98.1	a	1.7	c	0.1	a
	Between 1.9&2.0	94.0	c	5.6	a	0.0	b
	Between 2.0&2.1	96.6	b	3.4	b	0.0	b
	Between 2.1&2.2	97.1	b	2.9	b	0.0	b
Nanatsubos hi	Unfractionated	98.3	a	0.9	c	0.5	b
	Between 2.1&2.2	86.6	c	8.1	a	2.0	a
	Between 2.2&2.3	96.6	ba	3.5	b	0.0	b
	Between 2.3&2.4	96.5	b	3.5	b	0.0	b
	Over 2.4	97.0	ba	3.0	b	0.0	b
Yumepirika	Unfractionated	97.3	a	0.8	c	1.6	cb
	Between 2.1&2.2	79.2	c	11.1	a	5.5	a
	Between 2.2&2.3	92.8	b	4.7	b	2.4	b
	Between 2.3&2.4	94.8	b	1.2	bc	1.2	c
	Over 2.4	94.9	b	3.7	bc	1.4	c
Oborozuki	Unfractionated	95.8	a	1.6	d	2.2	b
	Between 2.1&2.2	76.0	c	11.5	a	9.4	a
	Between 2.2&2.3	91.6	b	5.7	bc	2.7	b
	Between 2.3&2.4	93.6	ab	4.8	c	1.6	b
	Over 2.4	95.7	ab	2.8	dc	1.4	b

For each test, the mean followed by the same letter in the column within each type of rice do not differ statistically at 5% probability through the one-way ANOVA and/or Tukey-Kramer's Test.

3.3 Dimensional characteristics of rough and brown rice

The NERICA and Indica types of rough rice can be classified as long and slender classes of grain, as their length exceeds 7.5 mm, and their slenderness exceeds 3 mm. Meanwhile, the Japonica type of rough rice can be classified as a long and medium class of grain, since its length comes within the range of 6.6-7.5 mm, and slenderness within the range of 2.1-3 mm (Table 3). On the other hand, NERICA-Indica types of brown rice can be classified as long and medium classes of grain, as their length is within the range of 6.61-7.5 mm, and their slenderness within the range of 2.1-3 mm.

In addition, the Japonica type of brown rice can be classified as short and round, as its length is 5.5 mm or less and its shape is less than 2.0 (Table 4), as suggested by Luh (1991), Matsuzaki (1995), and Bhattacharya (2011). Similar dimensional values of NERICA, Indica and Japonica types of rough and brown rice were reported by Bamrungwong et al. (1987), Matsuzaki (1995), Klush (2005), Shittu and Olaniyi (2012) and Agu and Oluka (2013).

Moreover, rough and brown rice of the NERICA-Indica types and rough rice of the Japonica type as well as brown rice of the Japonica type could produce "plug" and "funnel" flow considering that their slenderness is greater than 1.5 to 2.0 and less than 1.5 to 2.0 respectively as referred to by Bucklin et al. (2007). These kinds of flow patterns must be controlled because they transmit dynamic load from the grain to the structure during the emptying of the bins.

One-way ANOVA showed that mean thickness fractions, mean length fractions, and mean width fractions, are significantly different among the fractions within each variety. Thinner kernels were shorter in length and width than thicker kernels of rough and brown

Table 2 Average values of components of brown rice

Variety	Thickness fraction	S. Whole kernel (*SWK*)		Immature kernel (*IK*)		Broken kernel (*BK*)		Chalky kernel (*CK*)	
	mm	%							
NERICA 4	Unfractionated	69.7	b	4.3	b	14.6	ba	8.0	a
	Between 1.75 & 1.8	69.0	b	8.1	a	17.0	a	2.4	bc
	Between 1.8 & 1.9	82.3	a	2.3	cd	11.9	c	1.3	c
	Between 1.9 & 2.0	83.9	a	0.7	d	12.1	cb	1.1	c
IR-28	Unfractionated	50.4	b	0.7	b	45.7	b	2.0	a
	Between 1.7 & 1.75	24.2	c	2.0	a	69.5	a	1.0	a
	Between 1.75 & 1.8	51.7	b	0.9	b	45.4	b	0.8	a
	Between 1.8 & 1.9	67.2	a	0.4	b	30.1	c	1.3	a
IR-50	Unfractionated	61.2	c	1.5	b	31.8	b	2.6	a
	Below 1.7	28.9	d	2.2	a	62.9	a	1.3	b
	Between 1.7 & 1.75	67.7	b	1.4	b	26.4	c	1.3	b
	Between 1.75 & 1.8	78.4	a	1.5	b	17.8	d	0.7	b
IR-64	Unfractionated	85.6	b	0.0	b	10.8	b	1.8	a
	Between 1.7 & 1.75	73.6	c	0.3	a	21.1	a	0.8	b
	Between 1.75 & 1.8	83.8	b	0.0	b	11.3	b	1.2	b
	Between 1.8 & 1.9	90.8	a	0.0	b	5.5	c	0.8	b
Nanatsub oshi	Unfractionated	95.5	b	0.7	b	0.1	b	2.1	a
	Between 1.9 & 2.0	86.2	c	2.2	a	0.4	a	5.2	b
	Between 2.1 & 2.0	95.6	b	0.7	b	0.1	b	1.9	b
	Over 2.1	97.0	a	0.2	c	0.0	b	1.8	b
Yumepir ika	Unfractionated	93.1	b	2.3	b	0.3	b	2.4	ba
	Between 1.9 & 2.0	88.2	c	3.8	a	0.6	a	2.6	a
	Between 2.1 & 2.0	95.4	a	1.8	b	0.3	b	1.4	b
	Over 2.1	96.2	a	1.7	b	0.1	b	1.4	b
Oborozu ki	Unfractionated	92.3	b	3.5	b	0.1	a	2.1	a
	Between 1.9 & 2.0	85.8	c	7.1	a	0.1	a	1.8	a
	Between 2.1 & 2.0	94.3	a	2.5	c	0.0	a	1.3	a
	Over 2.1	95.5	a	1.7	c	0.0	a	1.8	a

For each test, the mean followed by the same letter in the column within each type of rice do not differ statistically at 5% probability through the one-way ANOVA and/or Tukey-Kramer's Test.

rice within each variety (Table 3 and 4). The regressions of mean width on mean thickness are significant for rough and brown rice of the NERICA-Indica types and the Japonica type. The linear equations for the regression of mean width on mean thickness for the NERICA-Indica types are

$$W_r = 0.83 \cdot T_r + 1.01 \quad r^2 = 0.77 \quad P = 0.01$$

$$W_b = 0.91 \cdot T_b + 0.64 \quad r^2 = 0.46 \quad P = 0.01$$

and for the Japonica type is

$$W_r = 0.48 \cdot T_r + 2.32 \quad r^2 = 0.46 \quad P = 0.01$$

$$W_b = 0.41 \cdot T_b + 2.14 \quad r^2 = 0.63 \quad P = 0.001$$

where W = width (mm) and T = thickness (mm). The subscripts r and b represent rough and brown rice respectively. The regression of mean length on thickness was only significant for rough rice of the NERICA-Indica types. The linear regression equation is

$$L_r = 2.19 \cdot T_r + 4.88 \quad r^2 = 0.69 \quad P = 0.001$$

where L = length (mm).

Such information could be useful in the cleaning process of rough rice, which works based on differences in physical properties between grain and foreign materials. Rice-cleaning machines such as scalping and screen separators function based on the size and shape of the objects to be separated, as reported by Wimberly (1983), and Luh (1991).

In addition, one-way ANOVA indicated that mean sphericity fractions are significantly different among fractions within each variety of rough and brown rice.

Significant difference was mostly found between thinner and thicker kernels among the fractions within each variety (Table 3 and 4). The regression of mean

Table 3 Average values of dimensional characteristics of rough rice

Variety	Thickness fraction	Length (L)	Width (W)	Thickness (T)	L/W ratio	Sphericity (S_p)	Volume (K_v)
	mm	mm	mm	mm	(-)[a]	(-)[a]	mm^3
		n = 100	n = 100	n = 100	n = 100	n = 100	n = 100
NERICA- 4	Unfractionated	9.4 ab	2.8 b	2.1 c	3.4 a	0.40 b	29.5 b
	Between 1.9&2.0	9.1 c	2.8 ab	1.9 e	3.2 c	0.40 b	26.9 c
	Between 2.0&2.1	9.3 b	2.9 a	2.0 d	3.2 c	0.41 ab	29.4 b
	Between 2.1&2.2	9.4 ba	2.9 a	2.1 b	3.3 bc	0.41 a	31.1 a
	Between 2.2&2.3	9.5 a	2.9 ab	2.2 a	3.4 b	0.41 a	32.2 a
IR-28	Unfractionated	9.6 a	2.8 dc	2.1 c	3.4 a	0.40 c	30.3 b
	Between 1.9&2.0	9.4 c	2.9 a	1.9 e	3.3 dc	0.40 c	28.8 c
	Between 2.0&2.1	9.4 c	2.8 c	2.0 d	3.3 cb	0.40 bc	29.3 c
	Between 2.1&2.2	9.5 bc	2.8 cb	2.1 b	3.4 b	0.41 ba	30.6 b
	Between 2.2&2.3	9.6 ab	2.9 b	2.2 a	3.4 ba	0.41 a	32.3 a
IR-50	Unfractionated	9.0 b	2.4 d	1.9 c	3.7 a	0.39 d	22.2 c
	Below 1.8	8.7 c	2.5 ba	1.8 e	3.4 d	0.39 cb	21.1 d
	Between 1.8&1.9	8.7 c	2.5 cb	1.9 d	3.5 c	0.39 bc	21.6 cd
	Between 1.9&2.0	9.0 ba	2.5 c	1.9 b	3.6 ba	0.39 cd	23.0 b
	Between 2.0&2.1	9.1 a	2.5 a	2.0 a	3.6 bc	0.40 ab	24.9 a
IR-64	Unfractionated	9.6 b	2.6 b	2.0 c	3.8 b	0.38 ba	26.7 c
	Between 1.9&2.0	9.3 c	2.6 b	2.0 d	3.6 c	0.39 a	25.2 d
	Between 2.0&2.1	9.7 b	2.6 ab	2.1 b	3.7 b	0.39 ba	27.6 b
	Between 2.1&2.2	10.2 a	2.6 a	2.1 a	3.8 a	0.38 b	30.5 a
Nanatsuboshi	Unfractionated	7.3 a	3.4 c	2.4 c	2.2 a	0.53 c	31.6 bc
	Between 2.1&2.2	7.1 b	3.3 d	2.2 e	2.1 ba	0.52 c	28.2 d
	Between 2.2&2.3	7.2 a	3.4 bc	2.3 d	2.1 ba	0.53 c	30.7 c
	Between 2.3&2.4	7.2 a	3.4 b	2.4 b	2.1 cb	0.54 b	32.3 b
	Over 2.4	7.3 a	3.5 a	2.5 a	2.1 dc	0.55 a	34.6 a
Yumepirika	Unfractionated	7.4 bc	3.5 b	2.3 c	2.1 ab	0.53 ab	32.5 c
	Between 2.1&2.2	7.3 c	3.5 b	2.2 d	2.1 b	0.52 b	30.9 d
	Between 2.2&2.3	7.5 b	3.5 b	2.3 c	2.1 a	0.52 b	32.5 c
	Between 2.3&2.4	7.5 b	3.5 b	2.4 b	2.1 ab	0.53 a	33.8 b
	Over 2.4	7.7 a	3.6 a	2.5 a	2.2 a	0.53 a	36.4 a
Oborozuki	Unfractionated	7.4 a	3.4 c	2.3 c	2.2 a	0.52 c	31.2 c
	Between 2.1&2.2	7.2 b	3.3 d	2.2 d	2.2 ba	0.52 c	28.5 d
	Between 2.2&2.3	7.3 b	3.4 cb	2.3 c	2.2 cb	0.53 b	31.0 c
	Between 2.3&2.4	7.5 a	3.4 b	2.4 b	2.2 ba	0.53 b	32.9 b
	Over 2.4	7.5 a	3.5 a	2.4 a	2.1 cb	0.53 a	34.3 a

For each test, the mean followed by the same letter in the column within each type of rice do not differ statistically at 5% probability through the one-way ANOVA and/or Tukey-Kramer’s Test.

[a] (—) = non dimensional.

sphericity on thickness was only significant for rough rice of Japonica types. The linear regression equation is

$$Sp_r = 0.06 \cdot T_r + 0.38 \qquad r^2 = 0.60 \qquad P = 0.001$$

where Sp = sphericity (-).

Sphericity of the NERICA-Indica types was approximately 75% of that of the Japonica type. This result was expected considering the lower slenderness of the Japonica type in comparison with the NERICA-Indica types. This sphericity data could be important for determining terminal velocity, drag coefficient, and Reynolds number important parameters, which are necessary for designing pneumatic conveying systems, fluidized bed dryers, as well as for cleaning the rough rice of impurities, as maintained by Sablani and Ramaswamy (2003).

The same results were reached by Khush (2005), Adebowale et al. (2011), and Bhattacharya (2001).

According to one-way ANOVA study, the mean thousand-kernel weight fractions are significantly different among fractions within each variety of rough and brown rice. Thinner kernels had lower weight than thicker kernels of rough and brown rice within each variety. The regression of mean thousand-kernel weight on thickness was highly significant ($P < 0.001$) for rough and brown rice. The linear regression lines are shown in Figures 3 and 4 respectively.

The Japonica type indicated higher values of grain weight than the NERICA-Indica types in both rough and brown rice.

This result was expected due to its higher kernel volume, as reported by Wadsworth et al. (1979). The regression of mean thousand-kernel weight on volume kernel was highly significant for rough and brown rice. The linear regression equations for the NERICA-Indica types are

$$TKW_r = 0.90 \cdot Vk_r - 0.31 \qquad r^2 = 0.87 \qquad P = 0.001$$

$$TKW_b = 1.18 \cdot Vk_b + 2.21 \qquad r^2 = 0.78 \qquad P = 0.001$$

and for Japonica type

$$TKW_r = 10.1 \cdot Vk_r - 6.5 \qquad r^2 = 0.85 \qquad P = 0.001$$

$$TKW_b = 1.28 \cdot Vk_b - 0.41 \qquad r^2 = 0.86 \qquad P = 0.001$$

where TKW = thousand-kernel weight (g), and V_k =

Table 4 Average values of dimensional characteristics of brown rice

Variety	Thickness fraction	Length (L)	Width (W)	Thickness (T)	L/W ratio	Sphericity (S_p)	Volume (K_v)
	mm	mm	mm	mm	(-)[a]	(-)[a]	mm^3
		n = 100	n = 100	n = 100	n = 100	n = 100	n = 100
NERICA 4	Unfractionated	6.9 a	2.4 a	1.9 b	3.0 a	0.46 b	17.0 a
	Between 1.75 & 1.8	6.6 c	2.4 a	1.8 d	2.8 c	0.46 ba	15.3 c
	Between 1.8 & 1.9	6.7 b	2.4 a	1.9 c	2.8 c	0.47 a	16.5 b
	Between 1.9 & 2.0	6.9 a	2.4 a	2.0 a	2.9 b	0.46 a	17.1 a
IR-28	Unfractionated	6.7 a	2.4 b	1.9 b	2.8 a	0.46 b	15.8 b
	Between 1.7 & 1.75	6.5 c	2.4 a	1.7 d	2.7 b	0.46 b	14.8 c
	Between 1.75 & 1.8	6.6 b	2.4 a	1.8 c	2.7 b	0.46 b	15.5 b
	Between 1.8 & 1.9	6.6 b	2.4 a	1.9 a	2.7 b	0.47 a	16.3 a
IR-50	Unfractionated	6.5 b	2.0 b	1.6 c	3.2 a	0.43 b	11.5 c
	Below 1.70	6.3 c	2.1 a	1.6 c	3.0 c	0.44 a	11.6 c
	Between 1.7 & 1.75	6.5 b	2.2 a	1.7 b	3.0 c	0.45 a	12.7 b
	Between 1.75 & 1.8	6.6 a	2.1 a	1.8 a	3.1 b	0.44 a	13.3 a
IR-64	Unfractionated	7.2 ab	2.2 b	1.8 b	3.3 a	0.42 c	14.7 b
	Between 1.7 & 1.75	6.9 c	2.2 a	1.7 c	3.1 c	0.43 b	14.3 c
	Between 1.75 & 1.8	7.1 b	2.2 a	1.8 b	3.2 b	0.43 b	15.0 b
	Between 1.8 & 1.9	7.3 a	2.2 a	1.9 a	3.3 a	0.43 b	15.8 a
Nanatsuboshi	Unfractionated	5.1 a	3.0 a	2.1 b	1.7 a	0.63 b	17.7 a
	Between 1.9 & 2.0	4.9 c	2.9 b	2.0 d	1.7 b	0.62 b	15.6 c
	Between 2.1 & 2.0	5.0 b	3.0 a	2.1 c	1.7 ab	0.63 ab	17.0 b
	Over 2.1	5.1 a	3.0 a	2.2 a	1.7 ab	0.64 a	18.1 a
Yumepirika	Unfractionated	5.3 a	3.0 a	2.1 b	1.7 a	0.61 bc	18.5 a
	Between 1.9 & 2.0	5.1 b	3.0 b	2.0 d	1.7 a	0.61 c	16.6 b
	Between 2.1 & 2.0	5.2 a	3.1 a	2.1 c	1.7 a	0.62 b	18.1 a
	Over 2.1	5.2 a	3.0 ab	2.2 a	1.7 a	0.62 ab	18.6 a
Oborozuki	Unfractionated	5.2 ba	3.0 b	2.1 b	1.8 a	0.61 b	17.8 b
	Between 1.9 & 2.0	5.1 c	2.9 c	2.0 c	1.8 a	0.60 c	16.2 c
	Between 2.1 & 2.0	5.2 b	3.0 ba	2.1 b	1.7 a	0.61 b	17.7 b
	Over 2.1	5.3 a	3.0 a	2.2 a	1.7 a	0.62 a	18.9 a

For each test, the mean followed by the same letter in the column within each type of rice do not differ statistically at 5% probability through the one-way ANOVA and/or Tukey-Kramer's Test.

[a] (—) = non dimensional.

volume of the kernel (mm^3).

Differences in grain weight between the Japonica type and the NERICA-Indica types identified in this work could be used in the design of storage structures, as mentioned by Bucklin et al. (2007).

The weight of stored grain produces dead loads within bins or storage buildings. These loads are different from static and dynamic loads that appear during filling or emptying of the storage structures. An example of dead load would be the vertical load transmitted by the weight on the foundation. Grain weight could also be used in the design of structures to resist the effects of ground motion caused by earthquakes.

The Japonica type showed the highest values of bulk density, with rough rice showing ranges between 603 and 628 g/L, and brown rice showing ranges between 791 and 811 g/L, values which reflect those obtained by Ohstubo (1995), Kunze et al. (2004), and Bhattacharya (2011). Moreover, the NERICA-Indica types showed ranges between 492 and 585 g/L, and between 749 – 791 g/L, in rough and brown rice respectively, which were similar to the values reached by Correa et al. (2007), and Shittu et al. (2012) (Tables 5 and 6).

One-way ANOVA indicated that mean bulk density was significantly different among fractions within each variety of rough and brown rice. Significant differences were mostly found between thinner and thicker kernel fractions within each variety.

The regression of mean bulk density on thickness was highly significant for rough and brown rice. The linear regression equations are

$$BD_r = 173.75 \cdot T_r + 211.16 \quad r^2 = 0.77 \quad P = 0.001$$

$$BD_b = 84.73 \cdot T_b + 625.81 \quad r^2 = 0.65 \quad P = 0.001$$

where BD = bulk density (g/L).

Differences in values between rough and brown rice could be attributed to the air between the inner part of the husk and the outer part of the grain in rough rice, as reported by Wadsworth et al. (1979), Correa et al. (2007), and Bhattacharya (2011). In addition, differences in ranges between the NERICA-Indica types and the Japonica type could be related to grain slenderness, as suggested by Bhattacharya (2011).

The regression of mean bulk density on slenderness was highly significant for rough and brown rice. The linear regression equations are

$$BD_r = -38.27 \cdot Sl_r + 696.41 \quad r^2 = 0.52 \quad P = 0.001$$

$$BD_b = -22.73 \cdot Sl_b + 844.35 \quad r^2 = 0.67 \quad P = 0.001$$

where Sl = slenderness (-).

The information obtained about bulk density could be useful in predicting the vertical pressure at any point within storage structures, as the higher the bulk density, the higher the vertical pressure.

Moreover, it can be used to predict the required air velocity in the design of pneumatic conveyors, and can be used in conjunction with other properties to estimate impact pressure in chutes, which is directly proportional to bulk density, as reported by Bucklin et al. (2007).

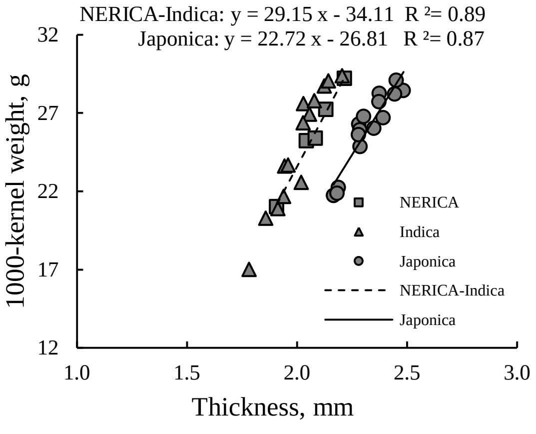

Figure 3 Relationship between weight and thickness of rough rice.

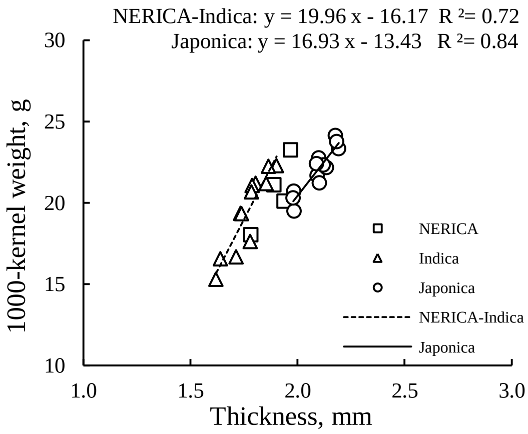

Figure 4 Relationship between weight and thickness of brown rice.

Furthermore, the differences in values of bulk density between rough and brown could be used in the operation of tray-type paddy separator machines to remove brown from rough rice kernel (Wimberly 1983, Luh 1991).

Values of grain fluidity for rough rice indicated ranges between 64 and 84 g/s, and between 104 and 114 g/s, for the NERICA-Indica types and the Japonica type respectively. Furthermore, grain fluidity values for brown rice showed ranges between 116 and 149 g/s, and between 163 and 169 g/s, respectively, as summarized in Tables 5 and 6. Differences in ranges between the NERICA-Indica types and the Japonica type could be caused by the differences in sphericity. The regression of mean grain fluidity on sphericity was highly significant for rough and brown rice. The linear regression equations are

$$GF_r = 244.99 \cdot Sp_r - 20.62 \quad r^2 = 0.89 \quad P = 0.001$$

$$GF_b = 132.63 \cdot Sp_b + 76.89 \quad r^2 = 0.75 \quad P = 0.001$$

where GF = grain fluidity (g/s).

Table 5 Average values of physical properties of rough rice

Variety	Thickness fraction	1000-kernel weight (TKW)		Bulk density (BD)		Static angle of repose (θ_s)		Grain fluidity (GF)		Static Coef. Frict. (μ)	
	mm	g		g/L		o		g/s		(-)[a]	
		n = 5		n = 5		n = 5		n = 5		n = 5	
NERICA-4	Unfractionated	25.4	c	565.0	a	40.6	cb	76.4	ba	0.52	ab
	Between 1.9&2.0	21.0	d	513.0	b	41.8	b	67.1	c	0.53	a
	Between 2.0&2.1	25.2	c	570.1	a	42.4	ab	79.6	a	0.54	a
	Between 2.1&2.2	27.2	b	571.5	a	43.2	a	73.4	b	0.51	b
	Between 2.2&2.3	29.2	a	561.2	a	42.4	ab	72.4	bc	0.53	a
IR-28	Unfractionated	27.8	c	572.1	b	40.0	b	79.0	ab	0.53	b
	Between 1.9&2.0	23.6	d	508.2	c	40.0	b	68.8	c	0.54	b
	Between 2.0&2.1	27.6	c	576.7	b	41.8	a	76.9	b	0.57	a
	Between 2.1&2.2	28.7	b	585.5	a	42.4	a	81.6	a	0.54	ba
	Between 2.2&2.3	29.4	a	575.4	b	42.2	a	74.5	b	0.51	b
IR-50	Unfractionated	20.9	c	559.3	a	40.2	b	80.0	a	0.53	b
	Below 1.8	17.0	e	492.2	b	40.0	b	70.4	b	0.54	b
	Between 1.8&1.9	20.3	d	556.8	a	40.6	ba	83.8	a	0.54	b
	Between 1.9&2.0	21.7	b	560.5	a	40.6	ba	79.7	a	0.54	b
	Between 2.0&2.1	22.6	a	553.8	a	41.8	a	64.4	b	0.59	a
IR-64	Unfractionated	26.4	c	584.2	a	40.6	b	81.6	ba	0.55	a
	Between 1.9&2.0	23.7	d	581.4	a	40.4	b	84.6	a	0.51	b
	Between 2.0&2.1	26.9	b	584.8	a	43.8	a	80.0	ba	0.53	ab
	Between 2.1&2.2	29.0	a	584.1	a	43.6	a	75.7	b	0.51	b
Nanatsuboshi	Unfractionated	26.0	c	627.4	a	39.0	cb	110.3	a	0.57	a
	Between 2.1&2.2	21.7	e	603.9	b	39.6	b	113.2	a	0.55	a
	Between 2.2&2.3	24.9	d	628.2	a	41.2	ab	114.1	a	0.54	a
	Between 2.3&2.4	26.7	b	631.3	a	41.0	ab	111.9	a	0.54	a
	Over 2.4	28.4	a	628.9	a	41.4	a	104.1	b	0.57	a
Yumepirika	Unfractionated	26.8	c	615.8	b	39.6	ba	109.7	a	0.56	a
	Between 2.1&2.2	22.2	e	586.2	c	38.6	b	111.1	a	0.55	ab
	Between 2.2&2.3	26.3	d	618.8	b	40.2	a	112.3	a	0.53	b
	Between 2.3&2.4	28.3	b	625.8	a	40.6	a	110.0	a	0.56	a
	Over 2.4	29.1	a	619.6	b	40.6	a	104.1	b	0.52	b
Oborozuki	Unfractionated	25.6	c	615.0	b	39.6	cb	109.6	a	0.54	b
	Between 2.1&2.2	21.9	d	579.4	c	40.8	b	102.9	c	0.52	b
	Between 2.2&2.3	25.9	c	625.0	a	42.0	ab	111.5	a	0.56	a
	Between 2.3&2.4	27.7	ba	628.9	a	41.6	ab	110.6	a	0.53	b
	Over 2.4	28.2	a	628.2	a	39.4	c	105.0	c	0.53	b

For each test, the mean followed by the same letter in the column within each type of rice do not differ statistically at 5% probability through the one-way ANOVA and/or Tukey-Kramer's Test.
[a] (—) = non dimensional.

One-way ANOVA indicated that mean grain fluidity was significantly different among fractions within each variety of rough and brown rice. Significant difference was mostly found between thinner and thicker kernels among fractions within each variety. The regression of mean grain fluidity on thickness was highly significant for rough and brown rice. The linear regression equations are

$$GF_r = 71.73 \cdot T_r - 63.79 \qquad r^2 = 0.58 \qquad P = 0.001$$

$$GF_b = 56.43 \cdot T_b + 37.42 \qquad r^2 = 0.53 \qquad P = 0.001$$

where *GF* = grain fluidity (g/s).

Grain fluidity values of rough rice could be used to design the aeration system in both non-mixing thin-layer and continuous-flow dryers (Das and Chakraverty, 2003). In addition, grain fluidity of rough and brown rice could be helpful in determining the diameter of tube conveyors such as pneumatic conveyors and chutes (Bucklin et al., 2007).

3.4 Frictional characteristics

Values of static angle of repose showed ranges of approximately 34° to 44° among all fractions of rough rice, and 34° to 39° among all fractions of brown rice. These ranges of values are higher and lower than those described by Bhattacharya (2001) for rough and brown rice respectively, and higher than the values suggested by Kunze et al. (2004): 36° ±5° for rough rice from 12% to 16 % of moisture content (Tables 5 and 6). Higher values of static angle of repose in rough rice could be caused by the awns and pedicels of the spikelet feature of the rice husk, allowing more void space in the bulk grains.

Table 6 Average values of physical properties of brown rice

Variety	Thickness fraction	1000-kernel weight (*TKW*)	Bulk density (*BD*)	Static angle of repose (θ_s)	Grain fluidity (*GF*)	Static Coef. Frict. (μ)
	mm	g	g/L	°	g/s	(-)[a]
		n = 5	n = 5	n = 5	n = 5	n = 5
NERICA 4	Unfractionated	20.1 c	783.7 a	36.0 a	148.9 c	0.50 ba
	Between 1.75 & 1.8	18.0 d	748.5 c	38.2 a	130.8 b	0.49 ba
	Between 1.8 & 1.9	21.1 b	769.2 b	38.4 a	141.0 b	0.48 b
	Between 1.9 & 2.0	23.3 a	772.8 b	37.8 b	137.9 a	0.47 a
IR-28	Unfractionated	21.2 a	796.2 a	35.0 a	142.0 ba	0.48 b
	Between 1.7 & 1.75	19.4 d	782.5 c	38.8 b	141.4 cb	0.45 a
	Between 1.75 & 1.8	21.2 c	788.7 b	37.8 b	136.5 c	0.49 a
	Between 1.8 & 1.9	22.3 b	791.2 ab	37.2 c	134.8 a	0.50 a
IR-50	Unfractionated	16.6 b	786.2 a	34.6 a	147.4 bc	0.47 a
	Below 1.7	15.3 c	766.9 c	38.0 ba	139.7 ba	0.46 a
	Between 1.7 & 1.75	16.7 b	776.4 b	37.0 b	142.2 c	0.46 a
	Between 1.75 & 1.8	17.6 a	774.0 b	36.6 c	135.3 a	0.45 a
IR-64	Unfractionated	20.7 c	775.2 a	34.8 a	136.8 ba	0.48 a
	Between 1.7 & 1.75	19.3 d	766.9 b	38.2 ba	129.2 bc	0.47 a
	Between 1.75 & 1.8	21.1 b	772.8 ab	37.2 b	123.3 c	0.47 a
	Between 1.8 & 1.9	22.3 a	769.2 ab	36.4 c	116.0 a	0.46 a
Nanatsuboshi	Unfractionated	22.2 b	818.3 a	33.8 a	163.9 b	0.48 a
	Between 1.9 & 2.0	19.5 d	791.2 c	39.0 ba	152.7 ba	0.53 ba
	Between 2.1 & 2.0	21.7 c	805.2 b	38.2 b	158.3 b	0.52 b
	Over 2.1	23.3 a	806.5 b	37.4 c	157.4 a	0.51 c
Yumepirika	Unfractionated	22.3 c	818.3 a	34.6 a	169.1 c	0.49 b
	Between 1.9 & 2.0	20.7 d	797.5 d	38.4 ba	155.0 b	0.54 a
	Between 2.1 & 2.0	22.8 b	805.2 c	37.6 b	160.4 b	0.50 a
	Over 2.1	24.1 a	811.7 b	37.0 c	159.4 a	0.49 a
Oborozuki	Unfractionated	21.2 d	811.7 a	34.4 a	164.0 b	0.48 a
	Between 1.9 & 2.0	20.3 c	794.9 c	38.4 a	157.1 b	0.51 a
	Between 2.1 & 2.0	22.4 b	803.9 b	37.6 a	157.6 b	0.51 a
	Over 2.1	23.8 a	807.8 ba	37.6 b	153.2 a	0.50 a

For each test, the mean followed by the same letter in the column within each type of rice do not differ statistically at 5% probability through the one-way ANOVA and/or Tukey-Kramer's Test.
[a] (—) = non dimensional.

The difference in values between rough and brown rice is caused by the reduction in volume when the husk is removed by processing (Correa et al., 2007).

One-way ANOVA indicated that mean static angle of repose fractions and mean dynamic angle of repose fractions are significantly different among fractions within each variety of rough and brown rice. Significant difference was mostly found between thinner and thicker kernels among fractions within each variety.

Values of angle of repose achieved in conjunction with other properties could be helpful in predicting lateral pressure acting on the walls, as well as the equivalent grain height at the wall, data which is required for designing the walls of storage structures. When these types of rice are transported using chutes by means of gravity, the chute slope should exceed the angle of repose, as reported by Bucklin et al. (2007). Additionally, bucket elevator capacity could be based on the angle of repose of rough rice (Wimberly 1983).

Static coefficient of friction on a rubber surface indicated values between 0.51 and 0.59 for rough rice, and between 0.45 and 0.54 for brown rice. This result for rough rice on a conveyor belt is lower than the range of between 0.60 and 0.66 obtained by Suastawa et al. (1998). This result is expected given that the static coefficient of friction decreases as a result of the milling process independently of the variety and surface materials, as reported by Mohsenin (1986) (Table 5). One-way ANOVA indicated that the mean static coefficients of friction are not significantly different among fractions within each variety of rough and brown rice. Data on coefficients of friction could be used to determine the horsepower required to drive a conveyor belt.

4 Conclusions

From the results achieved in this experiment, it can be concluded that:

1) The NERICA type of rice showed a closer relationship with the Indica type than it did with the Japonica type.

2) Thinner kernels indicated different physical properties compared with thicker kernels. This information could be useful in improving and increasing the efficiency of processes such as cleaning and milling.

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