American Journal of Applied Sciences, 2012, 9 (11), 1757-1768
ISSN 1546-9239

doi:10.3844/ajassp.2012.1757.1768 Published Online 9 (11) 2012 (http://www.thescipub.com/ajas.toc)

Physical Properties of Rice Residues as Affected by Variety and Climatic and Cultivation Onditions in Three Continents

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Received 2012-08-16, Revised 2012-08-29; Accepted 2012-08-29

ABSTRACT

Rice husk and straw are by-products of rice cultivation and processing industry and can be used as an energy source. Proper understanding of the physical properties of rice residues is necessary for utilizing them in thermochemical conversion processes such as gasification and combustion. The physical properties (moisture content, particle size, bulk density and porosity) of rice husks and straws obtained from three countries (Egypt, Cuba and China) were evaluated in this study. The moisture contents of rice husks and straws were in the ranges of 4.60-6.07% and 6.58-6.92%, respectively. For all rice varieties tested, the moisture content of the straws was higher than these of the husks. The particle sizes of rice husks and straws were in the ranges of 0.212-0.850 mm and 0-0.710 mm, respectively. All the rice husk varieties had a normal distribution of particle size around the main value of 0.6 mm while the particle size distribution for the rice straws showed a decreasing trend, the larger the particle size the higher was the weight percentage. The bulk density of rice husks and straws were in the ranges of 331.59-380.54 kg m^{-3} and 162.03-194.48 kg m^{-3}, respectively. The bulk density values of rice straws were lower than those of rice husks. A negative linear relationship between the bulk density and the average particle size was observed for rice husks and straws. The porosity of rice husks and straws were in the ranges of 63.64-68.94% and 71.21-85.28%, respectively. A positive linear relationship between the porosity and the average particle size was observed for rice husks and straws. Also, a negative linear relationship between the porosity and the bulk density was observed. The results obtained from this study showed significant differences in the physical properties of the rice husks and straws collected from different countries (located in three different continents). These differences may be due to variations in climatic conditions, soil type, methods of cultivation and type of fertilizer used. The results also indicated that different parts of rice plant (straw and husk) had different physical properties. Also, significant differences were observed among rice varieties even though they were grown under the same climatic conditions using same soil type and cultivation method as in the case of the long and short grain rice variety of Egypt.

Keywords: Bulk Density, Particle Size, Porosity, Moisture Content, Variety, Straw, Rice Husk

1. INTRODUCTION

Rice is a staple food of over half the world's population and about one-fifth of the world's population is engaged in rice cultivation (Reidy, 2011). The global paddy rice production continued to increase at an average rate of 16.48 million tonnes per year during the last ten years (**Fig. 1**), reaching about 718.3 million tonnes in 2011 (FAO, 2011), with an estimated value of US$ 240 billion. **Table 1** shows the rice production and yield for the important rice producing countries. China, Egypt and Cuba (countries used in this study) contribute 27.51, 0.63 and 0.07% to the global rice production and are ranked 1th, 16th and 39th, respectively. The per capita rice production, rice consumption and rice exports of the top 10 counties are presented in **Fig. 2-4**, respectively. Rice is the world's second largest cereal crop and produces the largest amount of crop residues (Soest, 2006). Rice, rice husk and rice straw are the main products of rice cultivation and processing (Binod *et al*., 2010). The average ratio of rice grain: rice husk: rice straw is 1:0.25:1.25 (Haefele *et al*., 2011).

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Table 1. Word paddy rice production (FAO, 2011; USDA, 2011; GS, 2011)

Country	Rice production			
	Weight (million tonnes)	Percentage (%)^a	Yield (tonnes ha^{-1})	Per capita (tonnes person^{-1})
China	197.6	27.51	6.60	0.147
India	150.0	20.88	3.33	0.121
Indonesia	68.1	9.48	5.60	0.281
Bangladesh	51.6	7.18	4.30	0.343
Viet Nam	41.0	5.71	5.43	0.462
Thailand	35.0	4.87	3.19	0.503
Myanmar	31.0	4.32	4.64	0.641
Philippines	17.3	2.41	3.76	0.182
Brazil	13.7	1.91	5.27	0.700
Japan	10.3	1.43	6.54	0.081
Pakistan	10.0	1.39	3.64	0.057
Cambodia	8.5	1.18	3.15	0.549
United States	8.5	1.18	8.03	0.027
Rep. Korea	6.0	0.84	7.03	0.124
Madagascar	4.7	0.65	3.51	0.221
Egypt	4.5	0.63	5.92	0.055
Nigeria	4.3	0.60	1.98	0.026
Sri Lanka	4.2	0.59	3.85	0.201
Lao	3.1	0.43	3.78	0.493
Peru	2.7	0.38	7.94	0.092
Iran	2.5	0.35	4.63	0.033
Dem. Korea	2.5	0.35	4.39	0.102
Colombia	2.5	0.35	5.32	0.033
Mali	2.4	0.33	3.36	0.148
Argentina	1.7	0.24	7.17	0.042
Uruguay	1.7	0.23	9.71	0.488
Italy	1.6	0.22	6.00	0.026
Taiwan	1.5	0.21	5.75	0.066
Ghana	1.5	0.21	9.06	0.062
Rep.Tanzania	1.4	0.19	2.00	0.030
Ecuador	1.4	0.19	4.00	0.095
Sierra Leone	1.2	0.17	1.78	0.200
Venezuela	1.1	0.15	7.86	0.037
Russia	1.1	0.15	5.24	0.008
Spain	1.0	0.13	7.00	0.020
Dominican	0.9	0.13	4.89	0.089
Australia	0.8	0.11	7.99	0.036
Bolivia	0.6	0.08	3.74	0.057
Cuba	0.5	0.07	2.55	0.045
Others	15.2	2.12	–	–

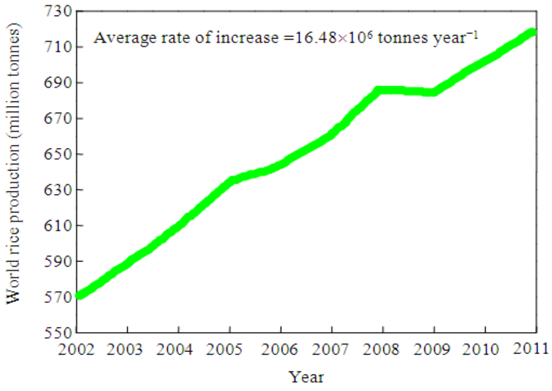


Fig. 1. World rice production and trend (FAO, 2011)

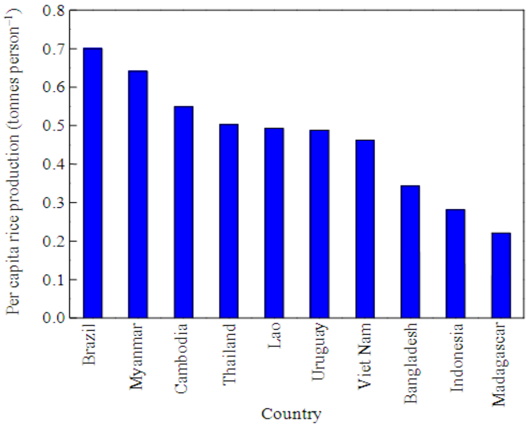


Fig. 2. Per capita rice production of the top 10 countries (FAO, 2011; GS, 2011)

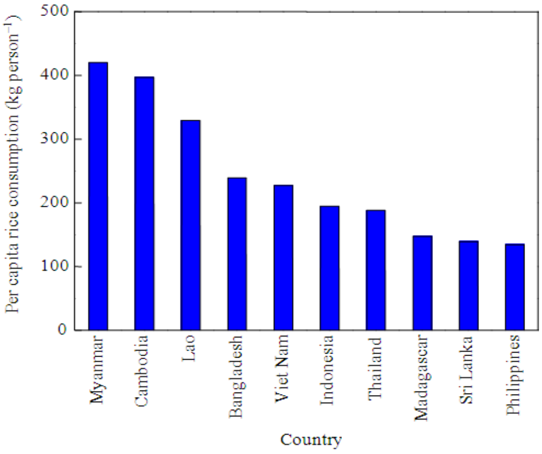


Fig. 3. Per capita rice consumption of the top 10 countries (FAO, 2011; GS, 2011)

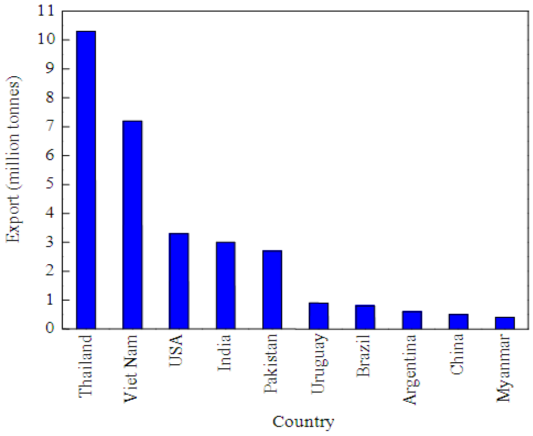


Fig. 4. Rice exports by the top 10 countries (FAO, 2011)

Currently, the two rice residues (husk and straw) have limited applications. Rice husk can be used as a fertilizer while rice bran can be used as an animal feed (Vadiveloo *et al*., 2009) and rice straw is used as a roughage in animal feeding (Dong *et al*., 2008).

However, most of the rice straws are burnt in the field causing significant environmental and health problems as well as serious traffic accidents in addition to the loss of valuable resource (Chou *et al*., 2009). Rice residues are abundantly available and renewable and can be used as an energy source in thermochemical conversion processes such as gasification and combustion (Yoon *et al*., 2012; Delivand *et al*., 2011) or in bioconversion processes for production of bioethanol (Karimi *et al*., 2006) and biogas (Teghammar *et al*., 2012). The ash produced from gasification and combustion processes can be used as a supplementary material in cement and ceramic manufacturing (Zain *et al*., 2011) and the spent material from bioconversion can be used as an animal feed (Bisaria *et al*., 1997).

The physical properties of biomass materials such as rice husk and straw influence the design and operation of thermochemical conversion systems. High moisture content decreases the heating value of fuel, which in turn reduces the conversion efficiency as a large amount of energy would be used for initial drying step during the conversion processes (Mansaray and Ghaly, 1997). Particle size distribution substantially affects the flowability of material and other properties such as heating, diffusion and rate of reaction (Guo *et al*., 2012; Hernández *et al*., 2010). The bulk density of rice residues makes the collection, transportation and storage economically unattractive (Natarajan *et al*., 1998). It also makes feeding the material into the thermochemical conversion system difficult. Porosity changes the interstitial airflow velocity and the heat and mass transfer conditions and ultimately influences combustion parameters such as heat conductivity, burning rate, conversion efficiency and emissions (Igathinathane *et al*., 2010; Hamel and Krumm, 2008). Therefore, full understanding of the physical properties of rice residues is essential for the design and operation of efficient thermochemical conversion systems such as gasifiers and combustors. The main objectives of this study were: (a) to investigate the physical properties (moisture content, particle size distribution, bulk density and porosity) of rice residues (husk and straw) obtained from three different continents (Africa, south America and Asia) as related to pre-processing and design of thermochemical conversion systems, (b) to compare the physical properties of husks and straws and (c) to determine the effect of rice variety and climatic and cultivation conditions on the physical properties of rice husks and straws obtained from different countries (Egypt, Cuba and China) in these continents.

2. MATERIALS AND METHODS

2.1. Sample Collection

The rice residues (husks and straws) from four varieties of rice were used in this study. Long grain rice husk and straw and short grain rice husk and straw were obtained from Egypt. Cascara de arroz rice husk and straw were obtained from Cuba. Japonica rice husk and straw were obtained from China. The rice production, climatic and soil conditions and rice cultivation methods for Egypt, Cuba and China are shown in **Table 2**.

2.2. Sample Preparation

Rice residues were ground through a coarse sieve (12.7 mm) and a 20-mesh sieve (0.85 mm) on a medium size Wiley Mill (Model X876249, Brook Crompton Parkinson Limited, Toronto, Ontario). The coarse ground samples were then reground through a 40-mesh sieve (0.425 mm) on the Wiley Mill in order to narrow the range of particle size and thus obtain homogeneous samples.

2.3. Moisture Content

Moisture content was determined using the oven-drying method (ASTM 2010). A large aluminum dish was weighed using a digital balance (Model PM 4600, Mettler Instrument AG, Greifensee, Zurich). The ground sample was placed in the dish and the dish and sample were weighed. The dish and sample were then placed in an air-forced drying oven (Heratherm, Thermo Fisher Scientific Inc., Waltham, USA) and kept at 105°C until a constant weight was achieved. The dish containing the dried sample was cooled to the room temperature in a desiccator and then weighed. The moisture content was calculated on a wet basis as follows Equation 1:

$$MC = \frac{WW - DW}{WW} \times 100 \tag{1}$$

Where:
MC = The moisture content (%)
WW = The wet weight of the sample and dish (g)
DW = The dry weight of the sample and dish (g)

2.4. Particle Size Distribution

The particle size distribution was determined using seven standard sieves (Canadian Standard Sieve Series, W.S. Tyler Company of Canada Limited, St. Catharines, Ontario) and a bottom pan that collected everything that passes though the seventh sieve. The sieves were mounted on an electrical sieve shaker driven by a 0.25-hp electric motor running at 1725 rpm (Model Rx-86, Hoskin Scientific Limited, Gastonia, North Carolina).

Table 2. Rice production, climatic and soil conditions and cultivation methods for Egypt, Cuba and China

Parameter	Egypt	Cuba	China
Rice yield (t ha^{-1})	5.92	2.55	6.60
Rice production ^{a}	3.60	0.40	158.08
Husk ^{a}	0.90	0.10	39.52
Straw ^{a}	4.50	0.50	197.60
Precip. (mm y^{-1})	26	1243	619
Min Tem. (°C)	9	18	-10
Max Tem. (°C)	35	32	31
Average (°C)^{b}	23.67	24.33	22.50
Soil type	Alluvial	Luvisols	Black soil
Fertilizer	N	Ammonium	Urea
Planting time	4-5	4-7	5-6
Harvesting time	9-11	10-12	8-9
Growing duration^{c}	110-160	118-140	120-140
Cultivation method	Transplanting	Direct seeding	Transplanting

^{a}: million tonnes; ^{b}: During harvesting season; ^{c}: days

Table 3. Sieve number, mesh number and mesh size

Sieve number	Mesh number	Mesh size (mm)
1	20	0.850
2	25	0.710
3	35	0.500
4	40	0.425
5	45	0.355
6	50	0.300
7	70	0.212
pan	-	0.000

A sample weighed 250 g was placed in sieve 1, which was then covered with the sieve lid. The shaker was operated at the speed of 350 rpm for 30 minutes. The particles collected in each sieve were weighed. The sieve number, mesh number and mesh size of the seven sieves are shown in **Table 3**.

2.5. Bulk Density

An empty container (150 mL) was weighed using a digital Mettler balance (Model PM 4600, Mettler Instrument AG, Greifensee, Zurich) to the nearest 0.0001g. The container was filled with the sample and the material was slightly compacted to ensure absence of large void spaces. The container and the sample were then weighed. Three replicates were carried out. The wet bulk density of the sample was calculated from the following Equation 2:

$$\rho_b = \frac{(W_2 - W_1)}{V} \qquad (2)$$

Where:

ρ_b = The bulk density of the sample (g cm^{-3})
W_2 = The weight of the container and sample (g)
W_1 = The weight of the container (g)
V = The volume of the container (cm^{3})

2.6. Porosity

The porosity of biomass was determined using the water pycnometer method. A sample of approximately 33 mL was placed in a 100 mL graduated cylinder. A wire mesh screen was placed on the top of the sample to prevent material from floating once submerged in water. Distilled water was slowly poured over the sample until the water level was above the top of the sample. The cylinder was gently rocked from side to side ten times to free trapped air bubbles before recording the final water level. The amount of added water and the water level were recorded to the nearest 1 mL. The cylinder was emptied and cleaned thoroughly after each test. Three replicates were carried out. The porosity of biomass was calculated from the following Equation 3:

$$P(\%) = \frac{V_i - V_f}{V_s} \times 100 \qquad (3)$$

Where:

P = The porosity of the sample (%)
V_i = The combined volume of the sample plus added water (mL)
V_f = The final total volume of the sample and added water (mL)
V_s = The volume of the sample (mL)

3. RESULTS AND DISCUSSION

3.1. Moisture Content

Table 4 shows the results of the moisture content of the rice residues. The moisture content was 4.72% for the long grain rice husk, 5.63% for the short grain rice husk, 4.60% for the cascara de arroz rice husk and 6.07% for the japonica rice husk. These values are lower than the value of 8.1% reported by Subramanian *et al.* (2011) for the rice husk from India, the value of 9.8% reported by Velez *et al.* (2009) for the rice husk from Colombia, the value of 10.7% reported by Zhou *et al.* (2009) for the rice husk from China, the values of 8.68-10.44% reported by Mansaray and Ghaly (1997) for the rice husks from Louisiana (USA) and Sierra Leone and the values of 9.8-10.7% reported by Casaca and Costa (2009) for the rice husks from Portugal. They are, however, higher than the value of 4.2% reported by Kalderis *et al.* (2008) for the rice husk from India.

The moisture content was 6.58% for the long grain rice straw, 6.92% for the short grain rice straw, 6.82% for the cascara de arroz rice straw and 6.89% for the japonica rice straw. These values are in the ranges of 2-10% reported by Chang *et al.* (2011) and 3-15% reported by Chiueh *et al.* (2012) for the rice straws from Taiwan. They are, however, much lower than the values of 12.1-12.6% reported by Chou *et al.* (2009) for the rice straws from Taiwan and much higher than the values of 3-5% reported by Park *et al.* (2011) for the rice straws from Japan.

Table 4. Moisture content of rice residues

Rice residues	Variety	Moisture content (%)[a]
Husk	Long grain	4.72
	Short grain	5.63
	Cascara de arroz	4.60
	Japonica	6.07
Straw	Long grain	6.58
	Short grain	6.92
	Cascara de arroz	6.82
	Japonica	6.89

[a]: Average of three replicates

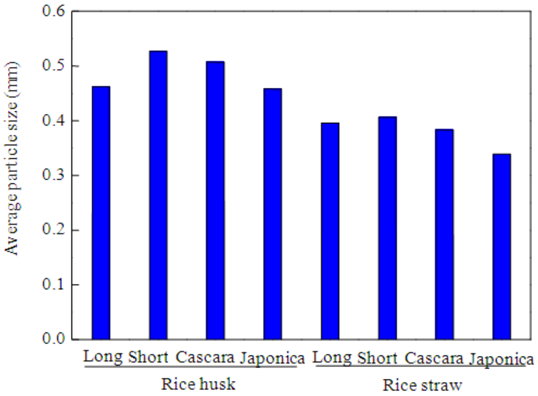
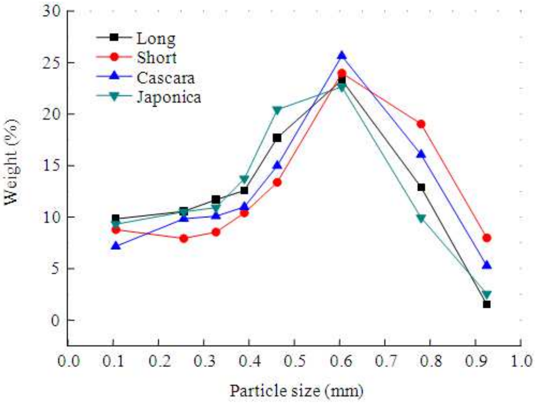


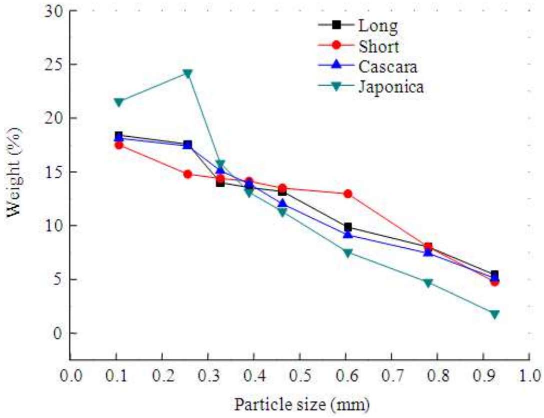
Fig. 5. Average particle size of rice husks and straws

Differences in moisture content could have resulted from using different collection, storage and drying procedures. For example, the samples used in this study were dried in an oven at 105°C for one day whereas the samples reported by Chou *et al*. (2009) were dried in air for two weeks and the samples reported by Park *et al.* (2011) were dried at 70°C for 5 days. For all rice varieties tested, the moisture content of the rice straw (6.58-6.92%) was higher than these of the rice husk (4.60-6.07%), which indicates that different parts of the rice plant maintain different moisture content.

The moisture content provides a medium for the transport of dissolved nutrients required for the metabolic and physiological activities of microorganisms in the solid fuels (Liang *et al*., 2003). Pommier *et al*. (2008) stated that an increase in moisture content showed a linear increasing effect on the biodegradation rate of organic material which resulted in the loss of solid fuels. The moisture content of rice residues also substantially affects its quality as a fuel source. Mansaray and Ghaly (1997) and Chen *et al.* (2009) reported that an increase in moisture content of the rice residues decreased their heating value, which in turn reduced the conversion efficiency and performance of the system, because a large amount of energy would be used for vaporization of the fuel moisture during the conversion processes.



(a)



(b)

Fig. 6. Particle size distribution of rice husks and straws (a) Rice husks; (b) Rice straws

A dry material is thus preferred for efficient storage and combustion, whereas a certain amount of moisture in the fuel is beneficial for gasification or combustion (Shao *et al*., 2012; Kuprianov *et al*., 2010).

3.2. Particle Size Distribution

The results of the particle size distribution of rice residues are presented in **Table 5**. The majority (83.25-88.66%) of rice husk particles were in the range of 0.212-0.850 mm. These values are within the range of 0.1-1 mm reported by Casaca and Costa (2009) for the rice husks from Portugal, the range of 0.075-3 mm reported by Subramanian *et al.* (2011) for the rice husk from India and the range of 0-10 mm reported by Fang *et al*. (2004) for the rice husk from China. However, the particle size range obtained in this study is higher than the range of 0.05-0.3 mm reported by Kuo *et al*. (2011) for the rice husk from Taiwan and lower than the range of 1.40-2.36 mm reported by Mansaray and Ghaly (1997) for the rice husks from Louisiana (USA) and Sierra Leone.

Table 5. Particle size distribution of rice residues

	Weight percentage (%)^a							
	Rice husks				Rice straws			
Size range (mm)	Long grain	Short grain	Cascara	Japonica	Long grain	Short grain	Cascara	Japonica
0~0.212	9.82	8.78	7.15	9.31	18.42	17.50	18.12	21.53
0.212~0.300	10.54	7.92	9.83	10.51	17.58	14.78	17.41	24.20
0.300~0.355	11.67	8.54	10.09	10.92	13.99	14.38	15.11	15.80
0.355~0.425	12.57	10.41	10.98	13.72	13.54	14.13	13.89	13.11
0.425~0.500	17.70	13.37	14.98	20.43	13.17	13.49	12.01	11.30
0.500~0.710	23.30	23.98	25.64	22.65	9.86	12.95	9.13	7.52
0.710~0.850	12.88	19.03	16.05	9.93	8.02	8.01	7.42	4.73
>0.850	1.52	7.97	5.28	2.53	5.42	4.76	5.11	1.81

^{a}: Average of three replicates

Most particle sizes (76.16-77.74%) of the rice straw samples were in the range of 0.212-0.850 mm, which is within the range of 0-0.833 mm reported by Karimi *et al.* (2006) for the rice straw from Iran and the range of 0-4 mm reported by Chen *et al.* (2003) for the rice straw from the Netherlands. It is, however, higher than the range of 0-0.3 mm reported by Asadullah *et al.* (2004) for the rice straw from Japan, the range of 0-0.5 mm reported by Sangnark and Noomhorm (2004) for the rice straw from Thailand, the range of 0.15-0.45 mm reported by Shi *et al.* (2012) for the rice straw from China and the range of 0.25-0.45 mm reported by Chou *et al.* (2009) for the rice straws from Taiwan and much lower than the range of 3-5 mm reported by Lei *et al.* (2010) for the rice straw from China and the range of 3-6 mm reported by Rashad *et al.* (2010) for the rice straw from Egypt.

The differences in particle size distributions resulted from using different pretreatment and grinding procedures of the samples. In our laboratory, the samples were ground through 3 sieves: a coarse sieve (12.7 mm), a 20-mesh sieve (0.85 mm) and a 40-mesh sieve (0.425 mm), whereas Mansaray and Ghaly (1997) ground their samples through 2 sieves: a 20-mesh sieve (0.85 mm) and a 40-mesh sieve (0.425 mm). Kuo *et al.* (2011) milled the samples using balls in a ceramic milling jar. Lei *et al.* (2010) cut their samples, Rashad *et al.* (2010) chopped their samples, Sangnark and Noomhorm (2004) soaked their samples in water, Asadullah *et al.* (2004) used ball mill to grind their samples, Shi *et al.* (2012) milled their samples through 40-100 mesh sieves and Chou *et al.* (2009) milled their samples through 40-60 mesh sieves. The samples used in this study were ground though 20-40 mesh sieves.

Figure 5 shows the average particle size of rice husks and straws while **Fig. 6** shows the particle size distribution. The average particle sizes for the husk and straw of the rice varieties long, short, cascara and japonica were 0.462, 0.527, 0.507 and 0.458 mm and 0.396, 0.406, 0.383 and 0.339 mm, respectively. All the rice husk varieties had a normal distribution of particle size around the main value of 0.6 mm. About 83.25-88.66% of the rice husk particles were in the range of 0.212-0.850 mm while the dust (<0.212 mm) and large particles (>0.850 mm) were in the ranges of 1.52-7.97% and 7.15-9.82%, respectively. The particle size distribution for the rice straw showed a decreasing trend, the larger the particle size the higher was the weight percentage. About 76.16-77.74% of the particles were in the range of 0.212-0.850 mm and the dust (<0.212 mm) was in the range of 1.81-5.42%. The ground rice straws had 17.50-21.53% smaller particles (<0.212 mm) which is higher than those of the ground rice husks (7.15-9.82%). This indicates that different parts of rice plant had different particle size distributions even if they were processed by the same equipment using the same procedures. This may be the results of differences in the chemical compositions of rice husk and straw. The ash, lignin, holocellulose, cellulose, hemicellulose and extractive contents reported by Raveendran *et al.* (1995) for rice husk and straw were 23.5, 14.3, 49.4, 31.3, 24.3 and 8.4% and 19.8, 13.6, 52.3, 37.0, 22.7 and 13.1%, respectively.

Ryu *et al.* (2006) stated that large particles are thermally thick thereby having slow devolatilization rate and more distributed heat transfer to the nearby particles. On the other hand, small particles of fuel may enhance the reaction area and result in high burning rates and ignition front speeds (Kwong *et al*., 2007). Small particle size can also significantly increase the bulk density of biofuels (Sangnark and Noomhorm, 2004) and eventually increase the energy density and reduce the cost of transport and storage (Chiueh *et al*., 2012; Deng *et al*., 2009). Size reduction therefore appears to be beneficial and important for pretreatment of biofuels before the utilization (Zhang and Zhang, 1999).

3.3. Bulk Density

Table 6 shows the bulk density of the rice residues. The average bulk density was 377.24 kg m^{-3} for the long grain rice husk, 331.59 kg m^{-3} for the short grain rice husk, 344.97 kg m^{-3} for the cascara de arroz rice husk and 380.54 kg m^{-3} for the japonica rice husk. These values are similar to the value of 348.8 kg m^{-3} reported by Velez *et al.* (2009) for the rice husk from Colombia, the value of 353 kg m^{-3} reported by Bishnoi *et al.* (2004) for the rice husk from India and are within the range of 100-400 kg m^{-3} reported by Sridhar *et al.* (1996) for the rice husk from India.

Table 6. Bulk density of rice residues

Rice residues	Variety	Bulk density (kg m^{-3})^a
Husk	Long grain	377.24
	Short grain	331.59
	Cascara de arroz	344.97
	Japonica	380.54
Straw	Long grain	166.29
	Short grain	162.03
	Cascara de arroz	177.23
	Japonica	194.48

^{a}: Average of three replicates

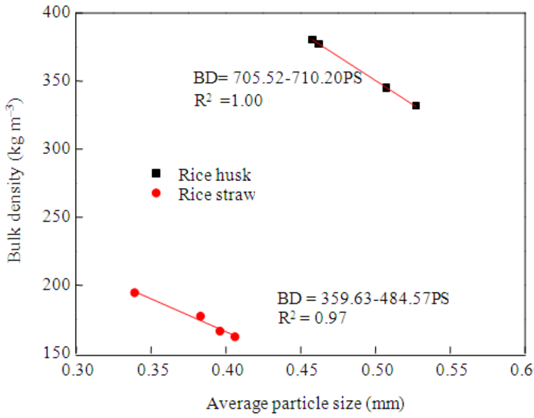


Fig. 7. Relationship between bulk density and average particle size

They are, however, lower than the value of 832 kg m^{-3} reported by Sahu *et al*. (2009) for the rice husk from India and higher than the values of 82.98-92.77 kg m^{-3} reported by Tirawanichakul *et al*. (2008) for the rice husk from Thailand, the values of 86-114 kg m^{-3} reported by Mansaray and Ghaly (1997) for the rice husks from Louisiana (USA) and Sierra Leone, the values of 72.2-293.4 kg m^{-3} reported by Angelova *et al*. (2011) for the rice husks from Bulgaria, the value of 122 kg m^{-3} reported by Fang *et al*. (2004) for the rice husk from China and the value of 126.56 kg m^{-3} reported by Subramanian *et al*. (2011) for the rice husk from India.

The average bulk density was 166.29 kg m^{-3} for the long grain rice straw, 162.03 kg m^{-3} for the short grain rice straw, 172.23 kg m^{-3} for the cascara de arroz rice straw and 194.48 kg m^{-3} for the japonica rice straw. These values are similar to the value of 177.6 kg m^{-3} reported by Yuan *et al*. (2012) for the rice straw from China and the value of 182 kg m^{-3} reported by Chiueh *et al*. (2012) for the rice straw from Taiwan and lower than the value of 227 kg m^{-3} reported by Kadam *et al*. (2000) for the rice straw from USA.

The bulk density values of rice straws are lower than those of rice husks. Higher ash and lignin contents in the rice husk may contribute to higher bulk density. The lignin and SiO_2 reported by Soest (2006) for rice husk and straw were 160 g kg^{-1} and 230 g kg^{-1} and 52±16 g kg^{-1} and 130 g kg^{-1}, respectively. The ash contents reported by Xu *et al*. (2012) for rice husk and straw were 22.1 and 14.6%, respectively. The ash contents reported by Singha and Das (2011) for rice husk and straw were 11.80 and 9.40%, respectively.

In this study, a negative linear relationship between the bulk density and the average particle size was observed for the rice husks and straws (**Fig. 7**), the larger the particle size the more void will be in the material and the lower the bulk density. These relationships can be described by the following Equation 4 and 5:

$$BD = 705.52 - 710.20PS \ (R^2 = 1.00 \text{ for rice husk}) \quad (4)$$

$$BD = 359.63 - 484.57PS \ (R2 = 0.97\text{for rice straw}) \quad (5)$$

Where:
BD = The bulk density (kg m^{-3})
PS = The average particle size (mm)

The bulk density of rice husk affects its residence time in the reactor. Rozainee *et al*. (2008) stated that lower bulk density may result in lower conversion efficiency, as it gives rise to poor mixing characteristics and a nonuniform temperature distribution, both of which create unfavorable operating conditions of the thermochemical conversion systems. Densification of the rice husk and straw by briquetting or pelletizing can increase its density to more than 600 kg m^{-3} (Ryu *et al*., 2006) and densification of rice straw can increase its density to 270-730 kg m^{-3} (Kadam *et al*., 2000; Okasha, 2007). The major advantages of this technique include high volumetric density and energy content, lower transportation and storage costs and lower emissions during combustion (Ryu *et al*., 2006; Kadam *et al*., 2000; Khan *et al*., 2009). The high investment on equipment and energy input required for briquetting and pelletization are the major constrains of the densification process. However, the high cost of oil, current high demand for biomass utilization and technology improvement will make the process of densification more attractive.

3.4. Porosity

Table 7 shows the porosity of the rice residues. The average porosity was 64.20% for the long grain rice husk, 73.23% for the short grain rice husk, 70.45% for the cascara de arroz rice husk and 63.64% for the japonica rice husk.

Table 7. Porosity of rice residues

Rice residues	Variety	Porosity (%)[a]
Husk	Long grain	64.20
	Short grain	73.23
	Cascara de arroz	70.45
	Japonica	63.64
Straw	Long grain	83.20
	Short grain	85.28
	Cascara de arroz	80.29
	Japonica	71.21

[a]: Average of three replicates

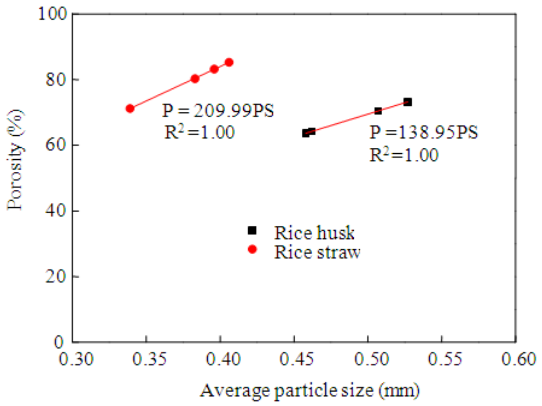


Fig. 8. Relationship between porosity and average particle size

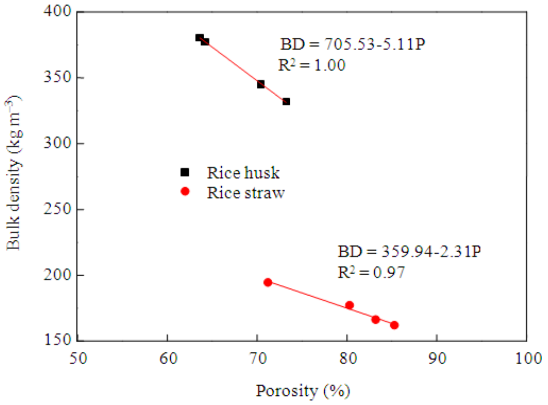


Fig. 9. Relationship between porosity and bulk density

These values are similar to the value of 64.08% (calculated from the apparent density and real density) presented by Velez *et al*. (2009) for the rice husk from Colombia but lower than the value of 75% reported by Subramanian *et al*. (2011) for the rice husk from India, the values of 75.4-75.6% represented by Zhou *et al*. (2009) and Fang *et al*. (2004) for the rice husks from China and the values of 94.22-98.42% reported by Tirawanichakul *et al*. (2008) for the rice husk from Thailand.

The average porosity was 83.20% for the long grain rice straw, 85.28% for the short grain rice straw, 80.29% for the cascara de arroz rice straw and 71.21% for the japonica rice straw. These values are higher than the value of 60% reported by Chen *et al*. (2003) for the rice straw from the Netherlands. This was mainly due to the smaller particle sizes of the sample (0-4 mm) compared to those obtained in the present study (0-0.71 mm). No other reports were found in the literature on the porosity of rice straw.

The porosity of biomass samples depends on a number of factors including particle size distribution, particle shape, shaking and pressing (Igathinathane *et al*., 2010). Differences in average particle size can result from using different procedures and will significantly affect the porosity. The samples in the present study were soaked in distilled water and the cylinder was gently rocked from side to side ten times to free trapped air bubbles whereas the samples presented by other researchers were saturated in salt solution for approximately 12-20 days.

Figure 8 shows a positive linear relationship between the porosity and the average particle size for rice husks and straws (the smaller the particle size the lower the porosity of the material). These relationships can be described by the following Equation 6 and 7:

$$P = 138.95PS\left(R^2 = 1.00 \text{ for rice husk}\right) \quad (6)$$

$$P = 209.99PS\left(R^2 = 1.00 \text{ for rice straw}\right) \quad (7)$$

where, P is the porosity (%)

A negative linear relationship between the porosity and the bulk density of the rice husks and straws was observed in this study (**Fig. 9**), the larger the porosity the lower the bulk density of the material. These relationships can be described by the following Equation 8 and 9:

$$BD = 705.53 - 5.11P\left(R^2 = 1.00 \text{ for rice husk}\right) \quad (8)$$

$$BD = 359.94 - 2.31P\left(R^2 = 0.97 \text{ for rice straw}\right) \quad (9)$$

Igathinathane *et al*. (2010) and Hamel and Krumm (2008) stated that a decrease in the porosity will increase the interstitial airflow velocity and brings changes in heat and mass transfer conditions and ultimately influences the combustion parameters such as heat conductivity, burning rate, conversion efficiency and emissions. Briquetting or pelletizing can decrease the porosity of biomass samples. Igathinathane *et al*. (2010) reported the porosity values of 39.4-44.9% for cylindrical wood pellets. This is due to the fact that the cylindrical wood pellets are squeezed under pressure and heat and are, therefore, more compact (Igathinathane *et al*., 2010; Kaliyan and Morey, 2009; Demirbaş and Şahin, 1998).

3.5. Effect of Variety and Cultivation Conditions

The results obtained from this study showed significant differences in the physical properties of the rice husks and straws collected from different countries (Egypt, Cuba and China) located in three different continents (Africa, south America and Asia). These differences may be due to variations in climatic conditions (temperature, precipitation and length of cultivation season), soil type (alluvial, luvisols and black), methods of cultivation (transplanting and seeding) and type of fertilizer used as shown in **Table 2**. Also, significant differences were observed among the varieties grown under same climatic conditions using same soil type and cultivation method as in the case of the long and short grain rice varieties of Egypt.

4. CONCLUSION

The physical properties of rice residues (husk and straw) obtained from three countries (Egypt, Cuba and China) in different continents (Africa, South America and Asia) were determined. These included moisture content, particle size distribution, bulk density and porosity. The moisture contents of rice husks and straws were in the ranges of 4.60-6.07% and 6.58-6.92%, respectively. For all rice varieties tested, the moisture contents of the straws were higher than these of the husks. Most particle sizes of rice husks and straws were in the range of 0-0.850 mm. All the rice husk varieties had a normal distribution of particle size around the main value of 0.6 mm, while the particle size distribution for the rice straws showed a decreasing trend, the larger the particle size the higher was the weight percentage. The bulk density for rice husks and straws were in the ranges of 331.59-380.54 kg m^{-3} and 162.03-194.48 kg m^{-3}, respectively. The bulk density values of rice straws were lower than those of rice husks. A negative linear relationship between the bulk density and the average particle size was observed for rice husks and straws. The porosity of rice husks and straws were in the ranges of 63.64-68.94% and 71.21-85.28%, respectively. A positive linear relationship between the porosity and the average particle size was observed for rice husks and straws. The results obtained from this study showed significant differences in the physical properties of the rice husks and those of the rice straws indicating that different parts of rice plants had different physical properties. The results also showed significant differences among the rice residues collected from different countries located in three continents. These differences may be due to variations in climatic conditions, soil type, methods of cultivation and type of used fertilizer. Also, significant differences were observed among rice varieties as in the case of the long and short grain rice variety of Egypt, even though they were grown under the same climatic conditions using same soil type and cultivation method.

5. ACKNOWLEDGEMENT

The project was funded by National Science and Engineering Council (NSERC) of Canada. The authors would like to thank Mr. Rye Dube and Mr. Weida Shi for their technical support during the grinding experiments.

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