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PHYSICAL PROPERTIES OF WHEAT STRAW VARIETIES CULTIVATED UNDER DIFFERENT CLIMATIC AND SOIL CONDITIONS IN THREE CONTINENTS

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ABSTRACT

Over 500 million tonnes of wheat straw are produced annually worldwide, the majority of which are burnt in the field causing significant environmental and health problems as well as serious traffic accidents in addition to loss of a valuable resource. Wheat straw is abundantly available and renewable and can be used as an energy source in gasification and combustion systems. Proper understanding of the physical properties of wheat straw is necessary for utilizing these materials in thermochemical conversion processes. Wheat straws were collected from Egypt (Africa), Canada (North America) and Guyana (South America) and ground using medium size Wiley Mill. The physical properties (moisture content, particle size, bulk density and porosity) of wheat straws were determined using standard procedures. The moisture contents of wheat straws were in the range of 5.02-7.79%. The majority (56.87-93.36%) of the wheat straws particles were less than 0.85 mm and the average particle sizes were in the range of 0.38-0.69 mm. The average bulk density of the wheat straws were in the range of 97.52-177.23kg m^{-3}. A negative linear relationship between the bulk density and the average particle size was observed for the wheat straws. The average porosity of the wheat straws were in the range of 46.39-84.24%. A positive linear relationship between the porosity and the average particle size for the wheat straws was also observed. The wheat straw varieties collected from different countries had different physical properties due to variations in climatic conditions, soil type and used fertilizer. Also, significant differences were observed among the varieties grown under same climatic and cultivation conditions.

Keywords: Bulk Density, Particle Size, Moisture Content, Physical Property, Climatic Condition, Variety, Wheat Straw, Porosity

1. INTRODUCTION

Wheat is a staple food for 2.45 billion people (35 percent of the world's population) and about 30 million people are engaged in wheat cultivation (Lumpkin, 2011). The world population increased from 6.16 to 6.92 billion (12.34% increase) during the period of 2001-2011 (USCB, 2012) and although the global wheat production fluctuated during the same period and lacked behind the population growth, it increased from 589.3 to 694.5 million tonnes (17.84% increase) as shown in **Fig. 1** (FAO, 2011). The estimated value of wheat was US$ 208 billion in 2011. **Table 1** shows the wheat production of the important wheat producing countries. Canada, Egypt and Guyana (countries used in this study) ranked 6^{th}, 13^{th} and 100^{th} of the global production, respectively. The European countries (27 countries) produce 137.49 million tonnes of wheat collectively which is 16.59% higher than that produced by China. The per capita wheat production, wheat consumption and wheat exports of the top 10 counties are presented in **Fig. 2-4**, respectively.

For every 1.3 kg of wheat grain produced, about 1 kg of straw is produced (Ruiz *et al*., 2012). This resulted in about 534.23 million tonnes of wheat straw in 2011. Wheat straw is abundantly available and renewable and is currently used in some limited applications including feed stuff (Shrivastava *et al*., 2012), fertilizer (Xie *et al*., 2011), pulp and paper (Hedjazi *et al*., 2009), nano-materials (Chen *et al*., 2010) and bioethanol (Talebnia *et al*., 2010). However, most of the straws are burnt in the field which causes significant environmental and health problems as well as traffic accidents in addition to loss of a valuable resource (Mittal *et al*., 2009; Yang *et al*., 2008). Wheat straw is an important energy source and can be used in thermochemical conversion processes such as pyrolysis (Wild *et al*., 2012; Yang *et al*., 2010), combustion (Wang *et al*., 2009; Olsson, 2006) and gasification (Zhu *et al*., 2008; Ren *et al*., 2010).

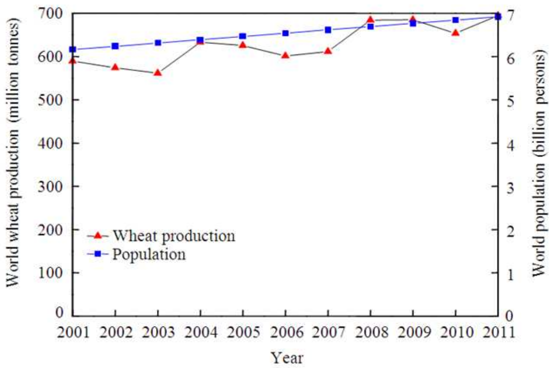

Fig. 1. World population and wheat production (FAO, 2011; USCB, 2012)

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

	Wheat production			
Country	Weight (million tonnes)	(%)[a]	Yield (tonnes ha^{-1})	Per capita (tonnes $person^{-1}$)
China	117.92	16.98	4.87	0.088
India	85.93	12.37	2.92	0.069
Russian Federation	56.23	8.10	2.19	0.394
United States	54.41	7.83	2.94	0.174
Australia	28.30	4.07	2.01	1.252
Canada	25.26	3.64	2.96	0.735
Pakistan	24.00	3.46	2.67	0.136
Kazakhstan	22.50	3.24	1.63	1.388
Ukraine	22.00	3.17	3.28	0.487
Turkey	18.80	2.71	2.44	0.255
Argentina	14.50	2.09	2.90	0.356
Iran	13.75	1.98	2.02	0.184
Egypt	8.70	1.25	6.59	0.105
Uzbekistan	6.30	0.91	4.50	0.227
Brazil	5.80	0.84	2.67	0.029
Morocco	5.80	0.84	1.91	0.180
Mexico	3.78	0.54	5.35	0.033
Syrian Arab Republic	3.25	0.47	2.17	0.157
Algeria	2.80	0.40	1.40	0.078
EU-27	137.49	19.80	5.34	0.274
Other countries	36.99	5.31	–	–

[a] Percentage of world production.

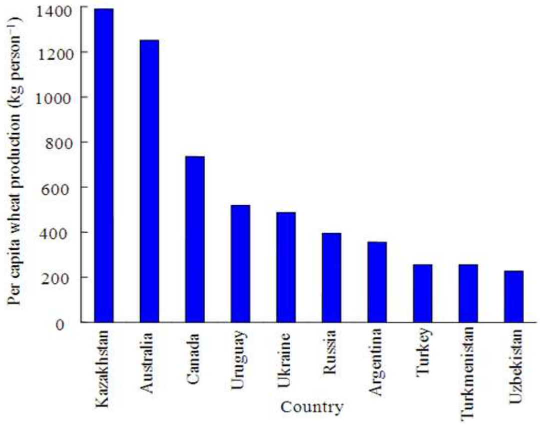

Fig. 2. Per capita wheat production of the top 10 countries (USDA, 2011; GS, 2011).

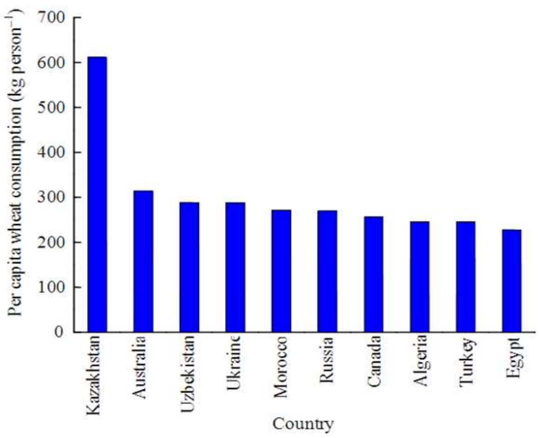

Fig. 3. Per capita wheat consumption of the top 10 countries (USDA, 2011; GS, 2011).

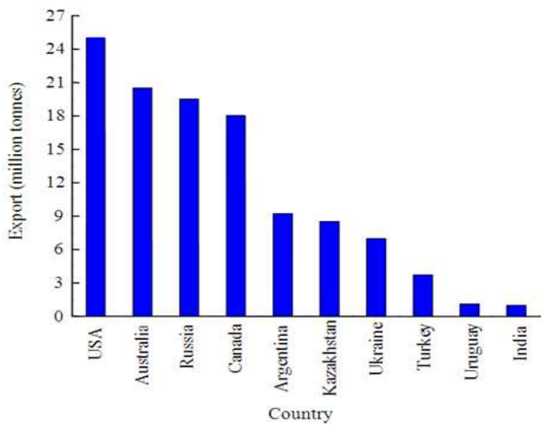

Fig. 4. Wheat exports by the top 10 countries (USDA, 2011).

The physical properties (moisture content, particle size, bulk density and porosity) of a given biomass material such as wheat straw greatly 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 the initial drying step during the conversion processes (Mansaray and Ghaly, 1997). The particle size distribution affects the flowability, heating, diffusion and rate of reaction (Guo *et al*., 2012; Hernández *et al*., 2010). The bulk density affects the economics of collection, transportation and storage as well as feeding the material into the thermochemical conversion system (Natarajan *et al*., 1998). Porosity affects 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 wheat straw 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 wheat straws obtained from three different continents (Africa, North America and South America) as related to pre-processing and the design of thermochemical conversion systems and (b) to determine the effect of wheat variety and climatic and cultivation conditions on the physical properties of wheat straws obtained from different countries (Egypt, Canada and Guyana) in these continents.

2. MATERIALS AND METHODS

2.1. Sample Collection

Six wheat straws were collected from different continents and used in this study. Giza and Sakha wheat straws were obtained from Egypt (Africa). Max and Monopol wheat straws were obtained from Canada (North America). Atlanta and Valcha wheat straws were obtained from Guyana (South America). The wheat production, climatic and soil conditions for Egypt, Canada and Guyana are shown in **Table 2**.

2.2. Sample Preparation

Wheat straw samples 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:

$$MC = \frac{WW - DW}{WW} \times 100 \quad (1)$$

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 collects everything that passed 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). The sample 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 min. 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**.

Table 2. Wheat production, climatic, soil and cultivation conditions for Egypt, Canada and Guyana.

Parameter	Egypt	Canada	Guyana
Wheat production [a]	8.70	25.26	NA
Wheat straw [a]	6.69	19.43	NA
Wheat yield (t ha^{-1})	6.59	2.96	NA
Precip. (mm y^{-1})	26.00	865.00	2418
Minimum Tem. (°C)	9.00	-16.00	24
Maximum Tem. (°C)	35.00	27.00	32
Average Tem. (°C)[b]	23.00	20.00	28
Soil type	Alluvial	Podzolic	Alluvial
Fertilizer	Ammonium	Nitrogen	Natural
Planting time	9-11	4-5	4-5
Harvesting time	4-5	6-8	6-7
Growing duration [c]	120-140	80-100	80-110

[a]: Million tonnes; [b]: During harvesting season; [c]: Days; NA: Not Available.

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

2.5. Bulk Density

An empty container (150 mL) was weighed using a digital 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:

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

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:

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

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 moisture content results of the wheat straws the moisture content was 5.16% and 7.79% for the Giza and Sakha wheat straws from Egypt, 5.79% and 5.02% for the Max and Monopol wheat straws from Canada and 5.79% and 5.25% for the Atlanta and Valcha wheat straws from Guyana, respectively. Giza (5.16%) and Sakha (7.79%) wheat straws have different moisture content even though they were obtained from the same country (Egypt) and grown and harvested under same soil and climatic conditions. Similar results were observed with the straws obtained from Canada and Guyana which emphasize the fact that different varieties had different moisture contents even if they were cultivated, collected and stored under same conditions.

The moisture content values obtained in this study (5.02-7.79%) are higher than the value of 4.0% reported by Adapa *et al*. (2009) for the wheat straw from Canada, but lower than the value of 8.30% reported by Mani *et al*. (2006), the value of 8.52% reported by Jiménez *et al*. (2000) and the values of 10-13% reported by Ghaly and Al-Taweel (1990) for the wheat straws from Canada. These variations could be explained as due to storage under different conditions and the use of different techniques to determine the moisture content. The sample reported by Adapa *et al*. (2009) was acquired during the summer and kept for a long time, the sample reported by Mani *et al*. (2006) was oven-dried for 1 hour at 130°C, the sample reported by Jiménez *et al*. (2000) was sun-dried, the samples reported by Ghaly and Al-Taweel (1990) were collected from the field after harvesting while the samples used in this study were oven-dried at 105°C for about 24 hours.

Liang *et al*. (2003) and Pommier *et al*. (2008) stated that 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 and an increase in moisture content will increase the biodegradation rate of organic material, resulting in the loss of solid fuels. High moisture content of wheat straw substantially affects its quality as a fuel source and decreases its heating value, which in turn reduces 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 (Chen *et al*., 2009; Ghaly and Al-Taweel, 1990). A dry material is thus preferred for storage, gasification and combustion, although a certain amount of moisture in the fuel is beneficial for gasification (Swierczynski *et al*., 2007).

Table 4. Moisture content of wheat straws.

Wheat straw	Moisture content (%)[a]
Giza	5.16
Sakha	7.79
Max	5.79
Monopol	5.02
Atlanta	5.79
Valcha	5.25

[a] Average of three replicates.

Table 5. Particle size distribution of wheat straws.

Size range (mm)	Weight percentage (%)[a] Egypt 1	Egypt 2	Canada 3	Canada 4	Guyana 5	Guyana 6
0~0.212	26.76	17.66	6.61	3.30	3.86	3.66
0.212~0.300	17.09	16.65	7.13	4.76	5.17	4.49
0.300~0.355	11.77	14.17	7.84	5.42	6.32	5.23
0.355~0.425	10.29	12.05	8.78	7.60	7.22	6.46
0.425~0.500	10.13	11.28	9.33	8.25	8.36	7.74
0.500~0.710	9.64	10.60	13.37	16.02	12.79	14.22
0.710~0.850	7.68	9.08	14.11	16.25	13.15	19.15
>0.850	6.64	8.51	32.83	38.40	43.13	39.05

[a] Average of three replicates; 1, 2, 3, 4, 5 and 6 represent the Giza, Sakha, Max, Monopol, Atlanta and Valcha wheat straws, respectively.

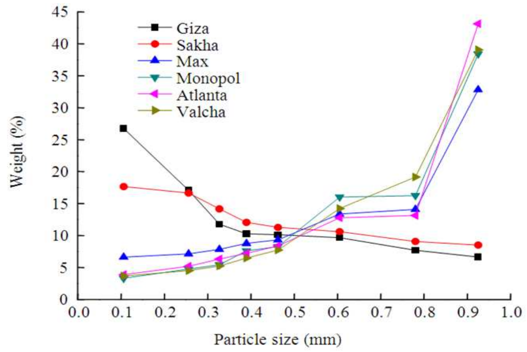

Fig. 5. Particle size distribution.

3.2. Particle Size Distribution

The results of the particle size distribution of wheat straws are presented in **Table 5** and **Fig. 5**. The majority (56.87-93.36%) of the wheat straw particles were less than 0.85 mm. These values are within the range of 0-1.190 mm reported by Adapa *et al*. (2009) for the wheat straw from Canada. However, they are lower than the value of 3.17-12.27 mm presented by Chevanan *et al*. (2010) for the wheat straw from USA and higher than the value of 0-0.1 mm reported by Lequart *et al*. (2000) for the wheat straw from France. These differences could be the result of using different grinding procedures and different sieves. The sample presented by Chevanan *et al*. (2010) was chopped in a knife mill, the sample reported by Lequart *et al*. (2000) was processed by a rotative knife mill and then homogenized by a short ball milling whereas the samples in this study 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).

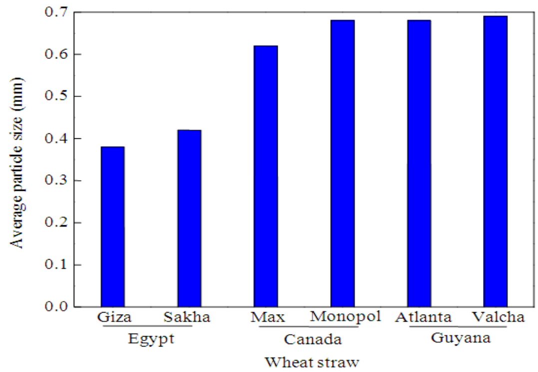

Fig. 6. Average particle size.

Figure 6 shows the average particle size of the wheat straws. The average particle sizes for Giza, Sakha, Max, Monopol, Atlanta and Valcha wheat straws were 0.38 mm, 0.42, 0.62, 0.68, 0.68 and 0.69 mm, respectively. The Egyptian varieties had more fine particles than the Canadian and Guyanese varieties. The results showed that the varieties grown under the same climatic, soil and cultivation conditions had different particle size distribution and different average particle size as a result of differences in the climatic, soil and cultivation conditions of the three countries used in this study.

The average particle sizes (0.38-0.69 mm) of the wheat straws observed in this study are similar to the value of 0.398 mm reported by Adapa *et al*. (2009) and the values of 0.281-0.639 mm reported by Mani *et al*. (2006). They are within the range of 0.325-1.350 mm presented by Mani *et al*. (2010) and lower than the values of 1.33-1.37 mm reported by Shaw *et al*. (2009) for the wheat straws from Canada. These variations could be explained as due to the use of different grinding and pretreatment techniques. The samples in this study were ground through 12.7, 0.85 and 0.425 mm sieves, whereas the samples reported by Mani *et al*. (2006) were milled through 3.2, 1.6 and 0.8 mm sieves, the samples reported by Shaw *et al*. (2009) were pretreated under steam autohydrolysis at 200°C and 1.45-1.50 MPa for 4 min.

Ryu *et al*. (2006) stated that large particles are thermally thick thereby having slow devolatilization rate and more distributed heat transfer to 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 and eventually increase the energy density and reduce the cost of transport and storage (Sangnark and Noomhorm, 2004; 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).

Table 6. Bulk density of wheat straws.

Wheat straw	Bulk density (kg m^{-3})[a]
Giza	177.23
Sakha	160.75
Max	108.66
Monopol	99.04
Atlanta	98.82
Valcha	97.52

[a] Average of three replicates.

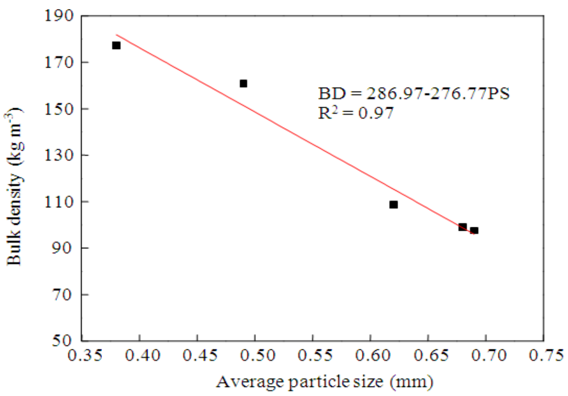

Fig. 7. Relationship between bulk density and average particle size.

3.3. Bulk Density

Table 6 shows the bulk density of the wheat straws. The average bulk density was 177.23 kg m^{-3}, 160.75 kg m^{-3}, 108.66 kg m^{-3}, 99.04 kg m^{-3}, 98.82 kg m^{-3} and 97.52 kg m^{-3} for Giza, Sakha, Max, Monopol, Atlanta and Valcha wheat straws, respectively. These values (97.52-177.23 kg m^{-3}) are similar to the values of 97.37-121.29 kg m^{-3} reported by Mani *et al.* (2006) and the values of 88-117.57 kg m^{-3} reported by Shaw *et al.* (2009) for the wheat straws from Canada. However, they are higher than the values of 25.06-62.75 kg m^{-3} presented by Chevanan *et al.* (2010) for the wheat straw from USA and lower than the value of 269 kg m^{-3} reported by Adapa *et al.* (2009) for the wheat straw from Canada. These differences could be the result of using different grinding procedures and equipment. The samples reported by Chevanan *et al.* (2010) were chopped in a knife mill, the samples reported by Adapa *et al.* (2009) were chopped using a pair of scissors and then subsequently ground using a forage grinder, whereas the samples in this study were ground in a Hammer mill (12.7, 0.85 and 0.425 mm).

In this study, a negative linear relationship between the bulk density and the average particle size was observed (**Fig. 7**), the larger the particle size the more void will be in the material and the lower the bulk density. This relationship can be described by the following equation:

$$BD = 286.97 - 276.77\,PS \quad (R^2 = 0.97) \qquad (4)$$

where:

BD = The bulk density (kg m^{-3})

PS = The average particle size (mm)

Rozainee *et al.* (2008) stated that the bulk density of fuel affects its residence time in the reactor. 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 wheat straw by pelletizing can increase its density to more than 600 kg m^{-3} (Theerarattananoon *et al.*, 2011) and compaction of wheat straw can increase its density to 813-931 kg m^{-3} (Adapa *et al.*, 2009). 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; Mani *et al.*, 2006; Khan *et al.*, 2009). The high investment on equipment and energy input required for pelletization and compaction are the major constrains of the densification process (Adapa *et al.*, 2009). However, the high cost of oil, current demand for biomass utilization and technology improvement will make the processes of densification and compaction more attractive.

3.4. Porosity

Table 7 shows the porosity results of the wheat straws. The average porosity was 46.39, 51.25, 75.65, 82.89, 83.00 and 84.24% for Giza, Sakha, Max, Monopol, Atlanta and Valcha wheat straws, respectively. The results indicate that different wheat straws obtained from different countries have different porosities. Also, the varieties grown under the same soil and climatic conditions have different porosities.

The porosity values (46.39-84.24%) obtained in this study are slightly higher than the values of 25.06-62.75% presented by Chevanan *et al.* (2010) for the wheat straw from USA and similar to the value of 83.03% (calculated from the bulk density and particle density of wheat straw) reported by Adapa *et al.* (2009) for the wheat straw from Canada. They are, however, lower than the values of 87.86-93.30% (non-treated) and 92.75-96.34% (steam exploded) reported by Adapa *et al.* (2011) for the wheat straw from Canada, the values of 90.52-91.52% reported by Mani *et al.* (2006) and the values of 91.50-92.81% reported by Shaw *et al.* (2009) for the wheat straws from Canada and the value of 96.97% presented by Biricik *et al.* (1999) for the wheat straw from Turkey. These variations may also be due to the use of different grinding procedures, pretreatment techniques and wheat straw variety.

Table 7. Porosity of wheat straws.

Wheat straw	Porosity (%)[a]
Giza	46.39
Sakha	51.25
Max	75.65
Monopol	82.89
Atlanta	83.00
Valcha	84.24

[a] Average of three replicates.

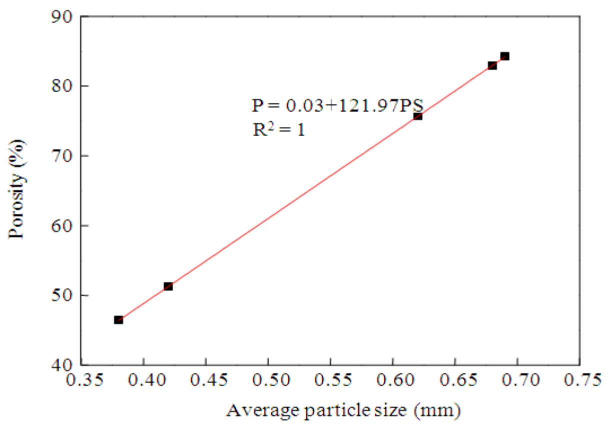

Fig. 8. Relationship between porosity and average particle size.

Igathinathane *et al*. (2010) stated that the porosity of biomass samples depends on a number of factors including particle size distribution, particle shape, shaking and pressing. Differences in average particle size can result from using different procedures and will significantly affect the porosity. A positive linear relationship between the porosity and the average particle size for the wheat straws is observed in this study and is shown in **Fig. 8**, the smaller the particle size the lower the porosity of the material. The relationship can be described by the following equation:

$$P = 121.97\ PS\ \left(R^2 = 1.00\right) \quad (5)$$

where:
P = The porosity (%)

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 (Igathinathane *et al*., 2010; Hamel and Krumm, 2008). Pelletizing or compacting can decrease the porosity of biomass samples. However, these dense materials may deteriorate the flow characteristics in the gasifier or combustor, thereby causing post-processing problems (Chen *et al*., 2009).

3.5. Effects of Variety and Climatic and Cultivation Conditions

The results obtained from this study showed significant differences in the physical properties of the wheat straws collected from different countries (Egypt, Canada and Guyana) located in three different continents (Africa, North America and South America). These may be due to variations in climatic conditions (temperature, precipitation and length of cultivation season) and cultivation conditions (soil type and used fertilizer) as shown in **Table 2**. Also, significant differences were observed among the varieties grown under same climatic and cultivation conditions.

4. CONCLUSION

The physical properties of wheat straws obtained from three countries Egypt (Africa), Canada (North America) and Guyana (South America) were determined. These included moisture content, particle size distribution, bulk density and porosity. The moisture contents of wheat straws were in the range of 5.02-7.79%. The majority (56.87-93.36%) of the wheat straw particles were less than 0.85 mm and the average particle sizes were in the range of 0.38-0.69 mm. The bulk density of the wheat straws was in the range of 97.52-177.23 kg m^{-3}. A negative linear relationship between the bulk density and the average particle size was observed. The porosity of the wheat straws was in the range of 46.39-84.24%. A positive linear relationship between the porosity and the average particle size was observed. The results obtained from this study indicate that the wheat straw varieties collected from different countries located in different continents have different physical properties due to variations in climatic conditions, soil type and fertilizer used. Also, significant differences were observed among varieties grown under same climatic and cultivation conditions.

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