

Comprehensive Investigation into the Exergy Values of Six Rice Husks

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ABSTRACT

Exergy is a measurement of how far a certain system or material deviates from a state of equilibrium with the environment and it is a useful tool for improving the efficiency of energy-resource use. Based on the previous work, the exergy values of six rice husks were investigated in this study. The effects of physical and chemical properties were also detailed. These included moisture content, ash content, S, C, O, H and N contents. The moisture related exergy of the six rice husks ranged in 241.432-290.304 kJ per kg rice husk, accounting for 1.563-1.758% of the exergy of rice husks. An exponential relationship between exergy value and moisture content was observed. The exergy of ash varied between 37.419 kJ per kg rice husk and 61.217 kJ per kg rice husk, making up 0.233-0.401% of the exergy of rice husks. An exponential linear relationship between exergy value and ash content was observed. The S related exergy ranged from 1.217 kJ per kg rice husk to 2.993 kJ per kg rice husk, accounting for 0.007-0.018% of the exergy of rice husks. The O/C, H/C and N/C atomic ratios varied in ranges of 0.592-0.662, 1.404-1.730 and 0.008-0.011, respectively, whereas the correlation factors varied slightly in the range of 1.118-1.127. The exergy values of the six rice husks ranged in 15.053-18.407 MJ/kg. They were mainly determined by the correlation factors and the LHVs. A positive linear relationship between exergy value and LHV was observed.

Keywords: Exergy, Rice Husk, Moisture, Ash, S, C, O, H, N, Correlation Factor

1. INTRODUCTION

Rice is a staple food for over half of 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 (Zhang *et al.*, 2012), reaching about 718.3 million tonnes in 2011 (FAO, 2011). This paddy rice produces the largest amount of crop residues in the forms of rice straw and rice husk (Soest, 2006).

Rice husk is one of the main residues from rice cultivation and processing. It is abundantly available and renewable and has been used as fertilizer and animal feed (Vadiveloo *et al.*, 2009). It can also be used as an energy source in thermochemical conversion processes such as gasification and combustion (Zhao *et al.*, 2012; Martínez *et al.*, 2011) or in bioconversion

processes for production of bio-oil (Lu *et al.*, 2012) and biogas (Kuo *et al.*, 2011). The ash produced from gasification and combustion processes can be used as a supplementary material in cement and ceramic manufacturing (Zain *et al.*, 2011).

The physical and chemical properties of rice husk are widely studied. These include moisture content, bulk density, particle size, porosity, heating values, proximate analysis, ultimate analysis, ash composition and ash characteristics (Mansaray and Ghaly, 1997; Zhang *et al.*, 2012; Shen *et al.*, 2012; Kaewkhao and Limsuwan, 2012). However, the exergy of rice husk has not been reported. The main objectives of this study were: (a) to investigate the exergy values of rice husks from six varieties of rice and (b) to determine the effects of physical and chemical properties (moisture content, ash content, S, C, O, H and N contents) on the exergy values of rice husks.

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2. EXERGY ANALYSIS OF BIOMASS FUELS

Exergy is the amount of work obtainable when a matter is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings such as environmental condition by means of reversible processes, involving interaction only with the above mentioned components of nature (Szargut, 1980). Wall (1986) stated that exergy is a measurement of how far a certain system deviates from a state of equilibrium with its environment. Unlike energy, exergy is not subject to conservation law (except for ideal or reversible processes). It is consumed or destroyed due to unavoidable irreversibilities in any real process. The exergy consumption during a process is proportional to the entropy created due to irreversibilities associated with the process (Rosen and Bulucea, 2009).

Exergy analysis is a methodology that uses the conservation of energy principle (embodied in the first law of thermodynamics) together with non-conservation of entropy principle (embodied in the second law) for the analysis, design and improvement of energy and systems (Rosen and Bulucea, 2009; Dincer, 2002). The exergy method is useful for improving the efficiency of energy-resource use, for it quantifies the locations, types and magnitudes of wastes and losses. In general, more meaningful efficiencies can be evaluated with exergy analysis rather than energy analysis, since exergy efficiencies are always a measure of the approach to the ideal condition (Rosen and Bulucea, 2009).

The exergy of a material can be calculated from its chemical potential and concentrations in its actual state and reference state (Wall, 1986). For irregular materials such as compounds with unknown chemical potential, the exergy values can not be obtained. Szargut *et al.* (1988) proposed a statistical method for representing the exergy of biomass fuels:

$$ex = \beta(LHV + \eta_w h_w + 9683\eta_s + ex_{ash}\eta_{ash} + ex_w\eta_w) \quad (1)$$

where:

- ex is the exergy of the fuels (kJ/kg)
- β is the correlation factor
- h_w is the evaporation enthalpy of moisture (2442kJ/kg (Szargut *et al.*, 1988))
- η_w is the moisture content (%)
- η_s is the weight percentage of sulfur (%)
- η_{ash} is the weight percentage of ash (%)

- ex_{ash} is the exergy of ash (kJ/kg)
- ex_w is the exergy of water (900 kJ/kmol)
- LHV is the lower heating value of biomass fuels (kJ/kg)

Moran *et al.* (2011) reported the exergy of water was 900 kJ/kmol. Szargut *et al.* (1988) gave the following equations for the correlation factor:

(a) For solid hydrocarbons Equation 2:

$$\beta = 1.0435 + 0.0159 \frac{H}{C} \quad (2)$$

(b) For solid fuels containing C, H and O (Equations 3 and 4):

$$\beta = 1.0438 + 0.0158 \frac{H}{C} + 0.0813 \frac{O}{C} \quad (O/C \leq 0.5) \quad (3)$$

$$\beta = \frac{1.0414 + 0.0177 \frac{H}{C} - 0.3328 \frac{O}{C} \left(1 + 0.0537 \frac{H}{C}\right)}{1 - 0.4021 \frac{O}{C}} \quad (4)$$

(O / C ≤ 2)

(c) For solid fuels containing C, H, O and N (Equations 5 and 6):

$$\beta = 1.0437 + 0.0140 \frac{H}{C} + 0.0968 \frac{O}{C} - 0.0467 \frac{N}{C} \quad (O/C \leq 0.5) \quad (5)$$

$$\beta = \frac{1.044 + 0.0160 \frac{H}{C} - 0.3493 \frac{O}{C} \left(1 + 0.05631 \frac{H}{C}\right) + 0.00493 \frac{N}{C}}{1 - 0.4124 \frac{O}{C}} \quad (6)$$

(O / C ≤ 2)

(c) For wood (Equation 7):

$$\beta = \frac{1.0412 + 0.2160 \frac{\eta_H}{\eta_C} - 0.2499 \frac{\eta_O}{\eta_C} \left(1 + 0.7884 \frac{\eta_H}{\eta_C}\right) + 0.0450 \frac{\eta_N}{\eta_C}}{1 - 0.3035} \quad (7)$$

Where:

- C is the number of carbon in the molecular formula of fuel
- H is the number of hydrogen in the molecular formula of fuel

O	is the number of oxygen in the molecular formula of fuel
N	is the number of nitrogen in the molecular formula of fuel
η_C	weight percentage of carbon (%)
η_H	weight percentage of hydrogen (%)
η_O	weight percentage of oxygen (%)
η_N	weight percentage of nitrogen (%)

3. MATERIALS

The six rice husks reported by Mansaray and Ghaly (1997) were used in this study. They were Lemont, ROK 14, ROK 16, ROK 32, CP 4 and Pa Potho. Lemont rice husk was obtained from Broussard Rice Mills in Louisiana and the other five rice husks were obtained from the West African Rice Research Station, Rokupr, Sierra Leone. The collection and processing procedures were described in the previous study (Mansaray and Ghaly, 1997).

4. CHARACTERISTICS OF RICE HUSKS

4.1. Moisture Content

The moisture contents of the six rice husks are shown in **Table 1**. The moisture contents of the six rice husks varied from 8.68% to 10.44%. The ROK 14 rice husk had the lowest moisture content (8.68%) whereas the ROK 16 rice husk had the highest moisture content (10.44%). These differences may be due to variations in climatic conditions, soil type, methods of cultivation and type of used fertilizer as well as different collection and storage (Zhang *et al.*, 2012).

4.2. Lower Heating Value

The LHV's of the six rice husks are presented in **Table 1**. The average LHV for the rice husk varieties ranged from 13.24 MJ/kg (ROK 14) to 16.20 MJ/kg (ROK 16). The reasonably good energy content of ROK 16 rice husk could be attributed to its lower ash content (**Table 1**) compared to the other rice husks. The LHV is also affected (significantly) by the S, C, O, H and N contents.

4.3. Ash Content and Compositions

Ash content is an important thermochemical property of an energy resource. The ash contents of the six rice husks are shown in **Table 1**. The CP 4 rice husk had the highest ash content (22.386%) whereas the ROK 16 rice husk had the lowest ash content (13.703%).

Table 1. Moisture contents, LHVs and ash contents of rice husks (Mansaray and Ghaly, 1997).

Rice husk	Moisture content (%)	LHV (MJ/kg)	Ash content (%) ^a
Lemont	9.08	14.22	21.275
ROK 14	8.68	13.24	17.168
ROK 16	10.44	16.20	13.703
ROK 32	10.20	14.60	16.793
CP 4	9.00	13.40	22.386
Pa Potho	10.16	14.12	16.351

^a On as received basis.

However, these values (13.703-22.386%) are much higher than the 9.40% for rice straw reported by Singha and Das (2011), the 3-5% for wheat straw reported by Ghaly and Al-taweel (1990) and the 6.57% for coal reported by Yuan *et al.* (2012).

The ash content affects the property of a fuel as an energy resource. It indicates the potential for the formation of undesirable bonded deposits on combustor surfaces (Ghaly and Al-taweel, 1990).

The rice husk ashes are mainly composed of mineral oxides. The measured mineral oxides are usually SiO₂, K₂O, CaO, P₂O₅, MgO, Al₂O₃, Fe₂O₃, Na₂O, SO₃, TiO₂ and ZnO. The detailed ash compositions of the six rice husks were transferred and shown in **Table 2**. All the rice husk varieties have high content of SiO₂ (2.0982-3.3992 mol/kg fuel) and low content of ZnO (0.0002-0.0003 mol/kg fuel). The differences in mineral oxide concentrations could be the result of the variations in climatic conditions, soil type, methods of cultivation and type of used fertilizer (Zhang *et al.*, 2012).

4.4. S, C, O, H and N Contents

Table 3 shows the S, C, O, H and N contents of the six rice husks. Although different rice husk varieties had different S, C, O, H and N contents, all the rice husk varieties had high content of C (34.186-39.854 wt.%) followed by O (28.665-31.525 wt.%), H (4.277-4.935 wt.%), N (0.345-0.458 wt.%) and S (0.013-0.031 wt.%). Wen *et al.* (2012) reported that the S, C, O, H and N contents for coal were 0.6-1.4%, 53.6-73.7%, 3.2-16.7%, 3.2-5.4% and 0.8-1.0%, respectively. These S, C, O, H and N contents make the rice husks have much lower LHVs than coals. Shirai *et al.* (2012) reported a LHV range of 26.3-27.3 MJ/kg for coals.

5. RESULTS AND DISCUSSION

5.1. Exergy Values of Rice Husks

Fig. 1 shows the exergy values of the six rice husks. The exergy value was 16.290 MJ/kg for the Lemont rice husk, 15.053 MJ/kg for the ROK 14 rice husk, 18.407 MJ/kg for the ROK 16 rice husk, 16.607 MJ/kg for the ROK 32 rice husk, 15.262 MJ/kg for the CP 4 rice husk and 16.068 MJ/kg for the Pa Potho rice husk.

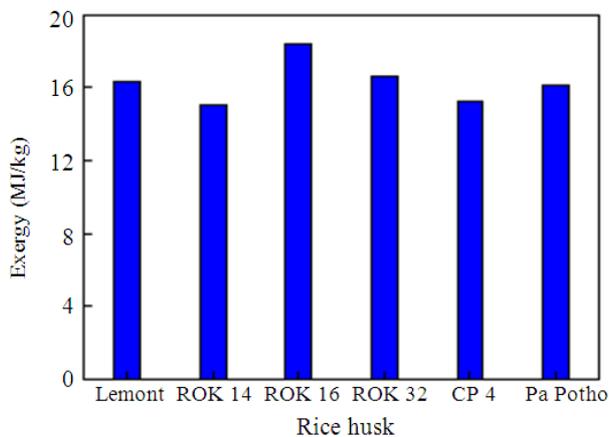
Table 2. Mineral oxide compositions of rice husks (Mansaray and Ghaly, 1997)

Mineral oxide	Mineral oxide composition (mol per kg of rice husk)					
	Lemont	ROK 14	ROK 16	ROK 32	CP 4	Pa Potho
SiO ₂	3.3992	2.6858	2.0982	2.5154	3.3532	2.6397
K ₂ O	0.0474	0.0419	0.0364	0.0499	0.0475	0.0312
CaO	0.0182	0.0181	0.0489	0.0135	0.0136	0.0096
P ₂ O ₅	0.0088	0.0069	0.0116	0.0105	0.0095	0.0003
MgO	0.0232	0.0175	0.0136	0.0187	0.0167	0.0122
Al ₂ O ₃	0.0010	0.0019	0.0034	0.0021	0.0020	0.0021
Fe ₂ O ₃	0.0012	0.0011	0.0023	0.0014	0.0013	0.0016
Na ₂ O	0.0027	0.0064	0.0020	0.0062	0.0011	0.0021
SO ₃	0.0027	0.0189	0.0185	0.0231	0.0313	0.0022
TiO ₂	0.0009	0.0009	0.0007	0.0011	0.0017	0.0004
ZnO	0.0002	0.0002	0.0003	0.0002	0.0002	0.0002

Table 3. S, C, O, H and N contents of rice husks (Mansaray and Ghaly, 1997)

Rice husk	C	H	O	N	S
Lemont	34.186	4.928	30.185	0.345	0.031
ROK 14	38.446	4.548	30.775	0.365	0.022
ROK 16	39.854	4.935	31.525	0.412	0.019
ROK 32	37.985	4.445	30.173	0.413	0.013
CP 4	35.217	4.277	28.665	0.455	0.014
Pa Potho	38.272	4.582	30.186	0.458	0.022

Values are in units of wt.%, on as received basis

**Fig. 1.** Exergy values of rice husks.

The ROK 16 rice husk had the highest exergy value (18.407 MJ/kg) whereas the ROK 14 rice husk had the lowest exergy value (15.053 MJ/kg). These values (15.053-18.407 MJ/kg) are lower than the exergy values (21.04-38.88 MJ/kg) of coals reported by Bilgen *et al.* (2004) due to their heating values (18.70-36.73 MJ/kg).

5.2. Effect of LHV

Equation 1 shows that the exergy of a fuel depends on the LHV of the fuel. The higher LHV of a fuel the

higher exergy of the fuel. In this study, a positive linear relationship between exergy value and LHV was observed as shown in **Fig. 2**. The relationship can be described by the following linear Equation 8 ($R^2 = 0.998$):

$$ex = 0.164 + 1.127 \text{ LHV} \quad (13.24 \leq \text{LHV} \leq 16.20) \quad (8)$$

Bilgen *et al.* (2004) stated that the exergy value of coal varies proportionally with the heating value. Bilgen and Kaygusuz (2008) used the HHVs to calculate the exergy of coals. Hosseini *et al.* (2012) and Hepbasli (2008) used the LHVs to calculate the exergy of biomass fuels. In this study, a positive linear relationship between exergy value and LHV was observed for biomass fuel (rice husk). Both exergy value and heating value therefore can be used to evaluate a kind of fuel.

5.3. Effect of Moisture Content.

The moisture related exergy was detailed in this study. The moisture related exergy value was 254.534 kJ/Kg for the Lemont rice husk, 241.432 kJ/kg for the ROK 14 rice husk, 290.304 kJ/kg for the ROK 16 rice husk, 283.574 kJ/kg for the ROK 32 rice husk, 250.681 kJ/kg for the CP 4 rice husk and 282.412 kJ/kg for the Pa Potho rice husk.

It can be seen from Eq. 1 that the moisture related exergy value is proportional to the moisture content of biomass fuel. The ROK 16 rice husk had the highest moisture content (10.44%) and the highest moisture related exergy value (290.304 kJ/kg) whereas the ROK 14 rice husk had the lowest moisture content (8.68%) and the lowest moisture related exergy value (241.432 kJ/kg). In this study, an exponential relationship between exergy value (of rice husk) and moisture content was observed as shown in Fig. 3. The relationship can be described by the following exponential Equation 9 ($R^2 = 0.772$):

$$ex = 15.466 + 1.274 \times 10^{-18} \exp(-M/0.247) \quad (8.68 \leq M \leq 10.44) \quad (9)$$

Where:

M is the moisture content (%)

Bilgen and Kaygusuz (2008) and Song *et al.* (2012) stated that the contribution of moisture content to the exergy of coal and biomass is negligible because the change in exergy due to moisture content is quite small compared with the total exergy of the fuel. In this study, an exponential relationship between exergy value and moisture content was observed for biomass. Increasing the moisture content from 8.68% to 10.44% increased the exergy of rice husk from 15.053 MJ/kg to 18.407 MJ/kg. However, the moisture content of biomass can substantially affect its quality as a fuel source (Zhang *et al.*, 2012). 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. A dry material is thus preferred for storage and combustion (Zhang *et al.*, 2012).

5.4. Effect of Ash

The exergy values of mineral oxides (SiO₂, K₂O, CaO, P₂O₅, MgO, Al₂O₃, Fe₂O₃, Na₂O, SO₃, TiO₂ and ZnO) are presented in Table 4. Based on the exergy values of mineral oxides and the ash compositions of rice husks (Table 2), the values and fractions of exergy of mineral oxide compositions were obtained for different rice husks as shown in Table 5. SiO₂, K₂O, CaO, MgO, SO₃, Na₂O, P₂O₅, Al₂O₃, Fe₂O₃, TiO₂ and ZnO contributed 34.105-55.728%, 30.912-37.054%, 2.444-11.080%, 1.818-2.801%, 1.195-12.743%, 0.524-3.662%, 0.382-9.837%, 0.377-1.385%, 0.034-0.078%, 0.024-0.059% and 0.007-0.017% to the exergy values of ash, respectively.

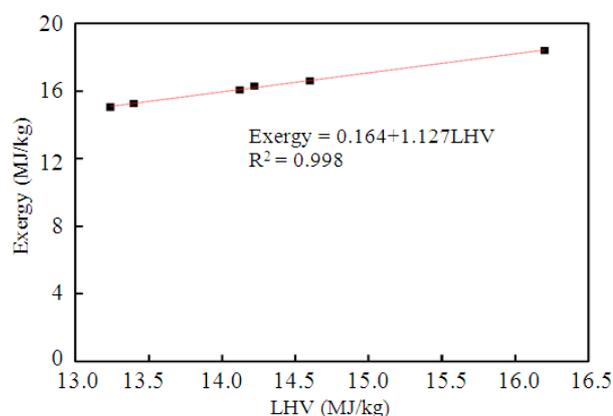


Fig. 2. Relationship between exergy value and LHV

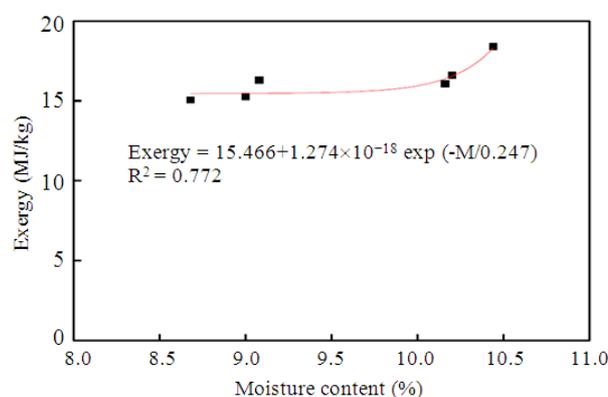


Fig. 3. Relationship between exergy value and moisture content

Although SiO₂ had the lowest exergy value (7.9 kJ/mol), it contributed the most (34.105-55.728%) to the exergy values of ash for all the rice husk varieties. This was due to the fact that SiO₂ was the main component of the ash. The weight fraction of SiO₂ reported by Mansaray and Ghaly (1997) ranged from 90% (ROK 32 and CP 4) to 97% (Pa Potho).

The total exergy value was 55.382 kJ/kg for the Lemont rice husk ash, 51.535 kJ/kg for the ROK 14 rice husk ash, 48.600 kJ/kg for the ROK 16 rice husk ash, 55.646 kJ/kg for the ROK 32 rice husk ash, 61.217 kJ/kg for the CP 4 rice husk ash and 37.419 kJ/kg for the Pa Potho rice husk ash. The CP 4 rice husk ash had the highest exergy (61.217 kJ/kg) whereas the Pa Potho rice husk ash had the lowest exergy (37.419 kJ/kg). This did not agree with the ash contents of rice husks (Table 1) where the CP 4 rice husk had the highest ash content (22.386%) and the ROK 16 rice husk had the lowest ash content (13.703%).

Table 4. Exergy values of mineral oxides (Szargut *et al.*, 1988)

Mineral oxide	Exergy value (kJ/mol)
SiO ₂	7.90
K ₂ O	413.10
CaO	110.20
P ₂ O ₅	412.65
MgO	66.80
Al ₂ O ₃	200.40
Fe ₂ O ₃	16.50
Na ₂ O	296.20
SO ₃	249.10
TiO ₂	21.40
ZnO	22.90

This shows that the exergy of ash is not only determined by the ash content but also by the ash composition.

An exponential relationship between exergy value (of rice husk) and ash content was observed as shown in **Fig. 4**. The relationship can be described by the following exponential Equation 10 ($R^2 = 0.616$):

$$ex = 15.685 + 83001.827 \exp(-A/1.327) \quad (13.703 \leq A \leq 22.386) \quad (10)$$

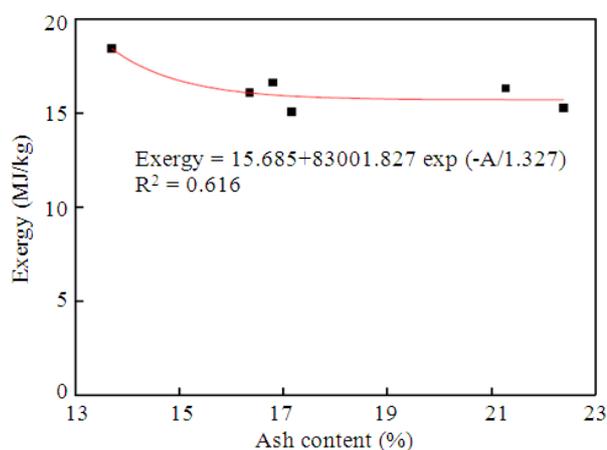
Where:

A is the ash content (%)

Hepbasli (2008) and Szargut *et al.* (1988) stated that the exergy of ash can usually be neglected because the change in total exergy of fuel due to the change in ash content is very small. However, Song *et al.* (2012) estimated the exergy of solid and liquid fuels and reported decreases in exergy when the ash content increased. On the other hand, higher ash content can reduce the heating value of a fuel and cause agglomeration for a system (Vargas-Moreno *et al.*, 2012; Zhao *et al.*, 2012). Lower ash content fuels are therefore preferred.

5.5. Effects of S

The S related exergy value was also detailed in this study. The S related exergy value was 2.993 kJ/kg for the Lemont rice husk, 2.122 kJ/kg for the ROK 14 rice husk, 1.821 kJ/kg for the ROK 16 rice husk, 1.217 kJ/kg for the ROK 32 rice husk, 1.322 kJ/kg for the CP 4 rice husk and 2.175 kJ/kg for the Pa Potho rice husk. These values were directly determined by the weight fractions of S (**Table 3**), which can be easily seen from Eq. 1. In **Table 3**, the Lemont rice husk had the highest S content (0.031%) whereas the ROK 32 rice husk had the lowest S content (0.013%), leading to the result that the Lemont rice husk had the highest S related exergy value (2.993 kJ/kg) whereas the ROK 32 rice husk had the lowest S related exergy value (1.217 kJ/kg).

**Fig. 4.** Relationship between exergy value and ash content

Bilgen *et al.* (2004) calculated the exergy of coals and reported increases in exergy when S content increased. Govin *et al.* (2000) estimated the exergy of liquid substances and reported decreases in exergy when S content increased. However, it appears from the results of this study that the S content did not have significant effect on the exergy of rice husk. While the S content varied from 0.013% to 0.031% (138.462%), the exergy of rice husks fluctuated between 15.053 MJ/kg and 18.407 MJ/kg (22.281%) without any clear trend.

5.6. Exergy Distribution

The percentages of moisture related exergy, ash exergy and S related exergy are shown in **Table 6**. The percentage of moisture related exergy is defined as the moisture related exergy divided by the exergy of rice husk. It indicates the fraction of the moisture related exergy in the total exergy of rice husk. The percentage of moisture related exergy was 1.563% for the Lemont rice husk, 1.604% for the ROK 14 rice husk, 1.577% for the ROK 16 rice husk, 1.708% for the ROK 32 rice husk, 1.642% for the CP 4 rice husk and 1.758% for the Pa Potho rice husk. These values were determined by the exergy values of rice husks and the moisture related exergy values. The percentages of moisture related exergy were between 1.563% and 1.758%, indicating that the moisture related exergy (241.432-290.304 kJ/kg) was a small part of the exergy (15.053-18.407 MJ/kg) of rice husks.

The percentage of ash exergy is defined as the exergy of ash divided by the exergy of rice husk. It represents the fraction of the ash exergy in the total exergy of rice husk.

Table 5. Values and fractions of exergy of mineral oxide compositions.

Mineral oxide	Values and fractions											
	Lemont		ROK 14		ROK 16		ROK 32		CP 4		Pa Potho	
	Value (kJ/kg)	Fraction (%)	Value (kJ/kg)	Fraction (%)	Value (kJ/kg)	Fraction (%)	Value (kJ/kg)	Fraction (%)	Value (kJ/kg)	Fraction (%)	Value (kJ/kg)	Fraction (%)
SiO ₂	26.854	48.489	21.218	41.172	16.575	34.105	19.872	35.711	26.490	43.272	20.853	55.728
K ₂ O	19.592	35.376	17.316	33.600	15.023	30.912	20.619	37.054	19.634	32.073	12.907	34.493
CaO	2.007	3.624	1.990	3.861	5.385	11.080	1.485	2.669	1.496	2.444	1.060	2.833
P ₂ O ₅	3.649	6.589	2.845	5.521	4.781	9.837	4.345	7.808	3.905	6.379	0.143	0.382
MgO	1.551	2.801	1.166	2.263	0.908	1.868	1.252	2.250	1.113	1.818	0.813	2.173
Al ₂ O ₃	0.209	0.377	0.371	0.720	0.673	1.385	0.429	0.771	0.396	0.647	0.418	1.117
Fe ₂ O ₃	0.020	0.036	0.018	0.035	0.038	0.078	0.023	0.041	0.021	0.034	0.027	0.072
Na ₂ O	0.813	1.468	1.887	3.662	0.589	1.212	1.846	3.317	0.321	0.524	0.625	1.670
SO ₃	0.662	1.195	4.701	9.122	4.605	9.475	5.747	10.328	7.801	12.743	0.560	1.497
TiO ₂	0.020	0.036	0.018	0.035	0.015	0.031	0.023	0.041	0.036	0.059	0.009	0.024
ZnO	0.005	0.009	0.005	0.009	0.008	0.017	0.005	0.010	0.004	0.007	0.004	0.011
Total	55.382	100	51.535	100	48.600	100	55.646	100	61.217	100	37.419	100

Table 6. Percentages of moisture, ash and S related exergy.

Rice husk	Percentage (%)			
	Moisture	Ash	S	Total
Lemont	1.563	0.340	0.018	1.921
ROK 14	1.604	0.342	0.014	1.960
ROK 16	1.577	0.264	0.010	1.851
ROK 32	1.708	0.335	0.007	2.050
CP 4	1.642	0.401	0.009	2.052
Pa Potho	1.758	0.233	0.014	2.005

The percentage of ash exergy was 0.340% for the Lemont rice husk, 0.342% for the ROK 14 rice husk, 0.264% for the ROK 16 rice husk, 0.335% for the ROK 32 rice husk, 0.401% for the CP 4 rice husk and 0.233% for the Pa Potho rice husk. The percentage of ash exergy ranged from 0.233% (Pa Potho rice husk) to 0.401% (CP 4 rice husk), being very small amounts.

The percentage of S related exergy is defined as S related exergy divided by the exergy of rice husk. It indicates the fraction of the S related exergy in the total exergy of rice husk. The percentage of S related exergy was 0.018% for the Lemont rice husk, 0.014% for the ROK 14 rice husk, 0.010% for the ROK 16 rice husk, 0.007% for the ROK 32 rice husk, 0.009% for the CP 4 rice husk and 0.014% for the Pa Potho rice husk. These values were mainly determined by the S related exergy values. The Lemont rice husk had the highest S related exergy value (2.993 kJ/kg) whereas the ROK 32 rice husk had the lowest S related exergy value (1.217 kJ/kg), resulting in the fact that the Lemont rice husk had the highest percentage of S related exergy (0.018%) whereas the ROK 32 rice husk had the lowest percentage of S related exergy (0.007%). These values ranged in 0.007-0.018%, therefore can be neglected.

Song *et al.* (2012) stated that exergies of ash and inorganic matter for both solid and liquid fuels could be ignored. In our present study, the moisture related exergy, ash exergy and S related exergy accounted for 1.563-1.758%, 0.233-0.401% and 0.007-0.018% of the exergy of rice husks, respectively, making up 1.851-2.052% collectively. The exergy values of the six rice husks were therefore determined by the LHV and the correlation factors. In some studies (Hosseini *et al.*, 2012; Hepbasli, 2008; Zhang *et al.*, 2011), the exergy of biomass was even derived directly from the product of LHV and correlation factor.

5.7. The Correlation Factor (β)

The effects of C, O, H and N can be demonstrated by studying the correlation factors. Based on the C, O, H and N contents (Table 3), the C, H, O and N atomic structure was determined as shown in Table 7. The numbers of C, H and O atoms varied among the various rice husks. For every atom of N, the rice husks contained 90-123 atoms of C, 132-200 atoms of H and 55-77 atoms of O. The O/C, H/C and N/C atomic ratios are shown in Table 8. The O/C atomic ratio was 0.662 for the Lemont rice husk, 0.600 for the ROK 14 rice husk, 0.593 for the ROK 16 rice husk, 0.596 for the ROK 32 rice husk, 0.610 for the CP 4 rice husk and 0.592 for the Pa Potho rice husk. These values (0.592-0.662) were higher than 0.5. Therefore, Eq. 6 was selected for determination of the correlation factors.

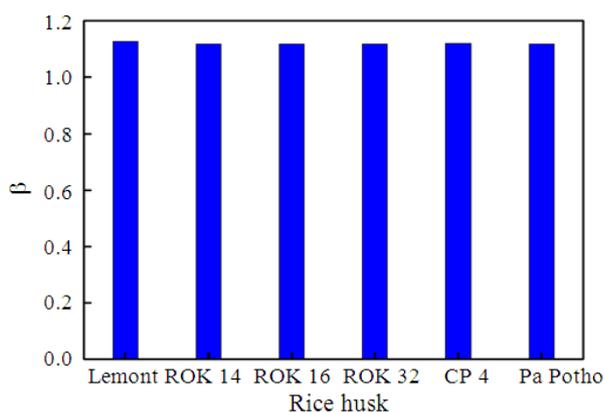
Figure 5 shows the correlation factors of the six rice husks. The correlation factor was 1.127 for the Lemont rice husk, 1.119 for the ROK 14 rice husk, 1.118 for the ROK 16 rice husk, 1.118 for the ROK 32 rice husk, 1.120 for the CP 4 rice husk and 1.118 for the Pa Potho rice husk.

Table 7. C, H, O and N atomic structure of rice husks.

Rice husk	Atomic structure				Molecular structure
	C	H	O	N	
Lemont	116	200	77	1	C ₁₁₆ H ₂₀₀ O ₇₇ N
ROK 14	123	174	74	1	C ₁₂₃ H ₁₇₄ O ₇₄ N
ROK 16	113	168	67	1	C ₁₁₃ H ₁₆₈ O ₆₇ N
ROK 32	107	151	64	1	C ₁₀₇ H ₁₅₁ O ₆₄ N
CP 4	90	132	55	1	C ₉₀ H ₁₃₂ O ₅₅ N
Pa Potho	97	140	58	1	C ₉₇ H ₁₄₀ O ₅₈ N

Table 8. O/C, H/C and N/C atomic ratios of rice husks.

Rice husk	Atomic ratios		
	O/C	H/C	N/C
Lemont	0.662	1.730	0.009
ROK 14	0.600	1.420	0.008
ROK 16	0.593	1.486	0.009
ROK 32	0.596	1.404	0.009
CP 4	0.610	1.457	0.011
Pa Potho	0.592	1.437	0.010

**Fig. 5.** Correlation factors of rice husks

Similar results were also reported by various researches. The correlation factors between exergy values and HHVs reported by Bilgen *et al.* (2004) ranged in 1.0587-1.1260 for coals. The correlation factors between exergy values and LHVs reported by Zhang *et al.* (2011) varied in 1.05-1.19 for biomass fuels. Nilsson (1997) reported the correlation factor between exergy value and LHV was 1.16 for a moist straw.

Although the O/C, H/C and N/C atomic ratios varied in ranges of 0.592-0.662 (11.82%), 1.404-1.730 (23.22%) and 0.008-0.011 (37.50%), respectively, the correlation factors varied slightly in the range of 1.118-1.127 (0.008%). These values are more concentrated than the values (1.0587-1.1260) of coals reported by Bilgen *et al.* (2004) and the values (1.05-1.19) of biomass fuels reported by Zhang *et al.* (2011).

6. CONCLUSION

The exergy values of the six rice husks were investigated and the effects of moisture content, ash content, S, C, O, H and N contents were also studied. The following conclusions can be obtained. The moisture related exergy of the six rice husks ranged between 241.432 kJ/kg (ROK 14) and 290.304 kJ/kg (ROK 16), accounting for 1.563-1.758% of the exergy of rice husks. An exponential relationship between exergy value and moisture content was observed. The exergy of ash varied between 37.419 kJ/kg (Pa Potho) and 61.217 kJ/kg (CP 4), making up 0.233-0.401% of the exergy of rice husks. An exponential relationship between exergy value and ash content was observed. The S related exergy ranged from 1.217 kJ/kg (ROK 32) to 2.993 kJ/kg (Lemont), accounting for 0.007-0.018% of the exergy of rice husks. The O/C, H/C and N/C atomic ratios varied in ranges of 0.592-0.662, 1.404-1.730 and 0.008-0.011, respectively, whereas the correlation factors varied slightly in the range of 1.118-1.127. The exergy values of the six rice husks were between 15.053 MJ/kg (ROK 14) and 18.407 MJ/kg (ROK 16). They were mainly determined by the correlation factors and the LHVs. A positive linear relationship between exergy value and LHV was observed.

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