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Quality optimization in briquettes made from rice milling by-products

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ABSTRACT

In order to produce briquettes that meet the needs of consumers, different combinations of raw materials and methods were used to produce rice-husk briquettes using a locally fabricated multi-piston press. Particle size, husk–bran ratio, drying method, and water temperature for briquetting were the main influencers of the hardness of rice-husk briquettes at constant pressure. The briquetting process increased the density of rice husk from 120 to 600 kg/m^3. The average time for making nine briquettes (loading, compressing, ejection, and transfer to drying tray) was 3.6 min (150 briquettes/h) using the locally fabricated piston press. Briquettes produced using fine particles (<0.3 mm), hot (97 °C) water, husk–bran ratios of 0:1, 1:2, 1:1, 1:0, 2:1, and dried in the sun for 21 days had mean hardness values of 132, 89, 76, 62, and 31 N. Four types of fuel briquettes were produced: husk–bran–palm press fiber (HBF), husk–bran–palm press sludge (HBS), husk–bran only (HBO), and husk–biochar–clay (HBC). The four types of briquettes recorded shorter start-up time (<5 min) than charcoal (10 min). The average flame temperatures of HBF, HBS, and HBO during the first 20 min were higher (898 °C) than the average temperature of charcoal (546 °C). The characteristics of HBF and HBO briquettes provide the best option for consumers, especially those in the rice parboiling industry, as these briquettes recorded the following values for hardness (170 and 101 N, respectively), start-up time (2 and 3 min), burning rate (126 and 145 g/min), specific fuel consumption (121 and 136 g/l), and flame temperature (684 °C and 728 °C). It was concluded that briquettes could be produced from rice-milling by-products with acceptable quality using this affordable technology.

Introduction

Rice (*Oryza* spp.) is an important source of calories in sub-Saharan Africa (SSA) and production is likely to increase to satisfy the ever-increasing demand. In 2014, SSA produced about 22.1 million tonnes (Mt) of paddy, equivalent to 4.6% of the world's production (IRRI, 2015). On average, paddy consists of 72% rice, 5%–8% bran, and 20%–22% husk (Prasad et al., 2001). Thus, the milling of 22.1 Mt of paddy will generate about 4.8 Mt of husk. Since the 2007–2008 food crisis, African governments and their development partners have established programs for increasing rice production with an expected increase in rice milling by-products.

The generation of revenue from rice-milling by-products is very low in SSA. Although rice bran is highly nutritive (Saunders and Betschart, 1979; Amissah et al., 2003), this by-product is mainly used in SSA only as an ingredient in the production of livestock feed. However, when bran is mixed with husk, as is the case when rice is milled in Engelberg type mills, the use of this product as a livestock feed is not desirable due to the high amount of silica in husk (So et al., 2008). Studies have demonstrated the potential of using rice bran in the production of useful chemicals (Li et al., 2012), oil (Rohman, 2014), biodiesel (Saravanan et al, 2007; Lin et al., 2009; Gunawan et al., 2011), soluble fiber (Wan et al., 2012), phenolic compounds (Pourali et al., 2010), activated carbon (Suzuki et al., 2007), and beverages (Faccin et al., 2009). Unlike bran, the majority of rice husk produced in SSA is disposed of by burning in open fields or abandoned behind rice milling facilities. This pollutes the air and land, and generates greenhouse gases such as methane (CH_4), nitrous oxide (N_2O), and unburnt carbon (Lim et al., 2012a; Mai Thao et al., 2011). Very few of the technologies that add value to rice husk have been tested in SSA. These include the use of rice husk as biofuel for the generation of heat and electricity (Sookkumnerd et al., 2005; Goyal et al., 2008; Lim et al., 2012a), biosorption of heavy metals from

Abbreviations: ASTM, American Society for Testing and Materials; GLM, generalized linear model; HBC, husk–biochar–clay; HBF, husk–bran–palm press fiber; HBO, husk–bran only; HBS, husk–bran–palm press sludge; HHV, higher heating value; RHA, rice-husk ash; WBT, Water Boiling Test.

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single and mixed metal solutions (Krishnani et al., 2008; El-Shafey, 2010), vermicomposting for the production of organic fertilizer (Lim et al., 2012b), as animal feed after physical, chemical, or biological treatment (Vadiveloo et al., 2009), and as a support for solid-state fermentation (Kapilan and Arasaratnam, 2011). Rice husk ash (RHA), a product of rice-husk combustion, is useful as a material for building and construction (Khan et al., 2012; Yuzer et al., 2013), glass ceramic tiles and whiteware (Prasad et al., 2001; Andreola et al., 2013), reinforcement of aluminum alloy (Saravanan and Senthil Kumar, 2013), production of silica powder, activated carbon, and carbon–silica composite (Kumagai and Sasaki, 2009; An et al., 2011).

Fuelwood and farm residues are the most common cooking fuels in SSA, representing 74% and 12%, respectively, of the total fuel used. Firewood collection places a substantial time and labor burden on families, particularly women, and can place additional pressure on local forest resources, particularly in places where wood is scarce (Adkins et al., 2012). In communities where fuelwood is scarce, the use of rice husks to generate heat for households and the local artisanal food-processing industry will be a suitable alternative. In addition, the use of rice husk may serve as a first step toward valorizing the huge quantities of this rice-milling by-product.

Thermochemical conversion of rice husk to produce heat energy can be achieved via direct combustion, gasification, and pyrolysis (Lim et al., 2012a). High-tech systems exist for each of these processes, but their adoption and sustainability among smallholder processors in SSA remain to be seen. Small-scale rice-husk gasifier stoves—especially affordable ones that burn efficiently with a continuous fuel recharging system—appear to be promising in SSA. Rice-husk gasifier stoves will be more useful for households in the vicinity of rice milling facilities (Parmigiani et al., 2014), since the high volatility and low density of rice husk (120 kg/m^3) can cause challenges in handling and transportation. For households that are not within the vicinity of rice milling facilities or factories that may require husk or husk–bran mixtures as raw materials, these challenges can be overcome by densification (briquetting or pelleting) at husk production sites. In addition, it may be useful to convert the char produced from the gasification process into briquettes for use as clean fuel.

Briquetting technologies, such as the heated die screw press briquetting (Toan et al., 2000; Ahiduzzaman and Islam, 2013) and single piston and die press (Chin and Siddiqui, 2000; Bhattacharya et al., 2002), and the subsequent use of briquettes as fuel is common in China, India, Taiwan, Thailand, and Vietnam. Although massive investments have been made in briquetting in SSA, very few commercial success stories have been documented (Mwampamba et al., 2013). The quality, availability, convenience, and price of briquettes appear to be major factors hindering widespread adoption of briquetting technologies in the region. In addition, dependency on importation of equipment, spare parts, and after-sales service limits the scale at which briquetting production can occur and, to a large extent, explains why there are few briquetting factories in the region (Grover et al., 1994; Mwampamba et al., 2013).

Although the potential to use briquettes as fuel in SSA is high, the low price of fuelwood, punitive legal and fiscal requirements for briquette producers, and supply-driven approaches to industry development have limited the growth of fuel briquettes in the region (Mwampamba et al., 2013). Consumers prefer briquettes that are sufficiently hard with good burning characteristics (low moisture content, easy to light, high burning rate, low specific fuel consumption, low ash content, high flame temperature, and long burning time). Briquettes currently sold in SSA are hard to light, slow to burn, crumble easily when put out, and require additional ventilation of the stoves (Mwampamba et al., 2013). The production of briquettes of acceptable quality from rice-milling by-products at rice milling sites using affordable technologies is crucial to adding value to rice husk or husk–bran mixtures in SSA. Production of briquettes from rice husk or husk–bran mixtures with sufficient hardness and acceptable burning properties is a big problem, especially when using low-cost equipment. This paper presents the production and analysis of briquettes using different combinations of materials, methods, and low-cost equipment with the hope of getting briquettes with optimum performance (hardness and burning characteristics).

Material and methods

Construction of the briquetting machine

A multi-piston briquetting hydraulic press with nine cylinders was constructed at the Africa Rice Center (AfricaRice), Cotonou, Benin. All materials used for construction were acquired from local vendors.

The total pressure (P) and pressure exerted on each briquette (Pc) were derived from Eq. (1) which was subsequently used to develop Eqs. (2) and (3).

$$P = \frac{F}{S} \tag{1}$$

$$P - \frac{4F}{\pi\left(D^2 - d^2\right)} \tag{2}$$

$$Pc = \frac{P}{9} \tag{3}$$

where F is force in newtons, S is total surface area in square meters, D is the diameter of the cylinder in millimeters, d is the diameter of the central rod in the cylinder in millimeters, and 9 is the number of cylinder and piston systems per machine.

Biomass

Two types of rice residues produced in SSA were used in this study: pure husk from rubber-roll type mills and husk–bran mixtures from Engelberg type mills (Ndindeng et al., 2014). The bulk density of husk was 120 kg/m^3, and its moisture content was 12.6%.

Sample preparation

Separate rice husk and bran from rubber-roll type mills were collected from the AfricaRice Grain Quality and Postharvest Unit. The husk and bran were ground separately using a commercial hammer mill (Songhai Center, Porto Novo, Benin) to reduce the size of the particles. Each sample was separated into three particle sizes (large = particle sizes ≥ 1 mm; medium = 0.301–0.99 mm; fine ≤ 0.300 mm) using mesh 18 and mesh 50. The samples were first sieved with mesh 18 and then with mesh 50. Particles remaining in sieve mesh 18 were large, while those that remained in sieve mesh 50 were of medium size, and those that passed through sieve mesh 50 were the fine particles. Husk–bran mixtures were also ground and sieved with sieve mesh 18 to get a mixture of fine and medium-sized particles.

Production of briquettes

Description of the briquetting machine

The main components of the rice-husk briquetter (Fig. 1) are a frame assembly that holds together a hydraulic jack, plates, and a system of cylinders and pistons. The force generated by the jack drives the pistons sitting on the vertical mobile plate through the cylinders and compresses the biomass in the cylinders against the horizontal mobile plate. When the material to be briquetted is put in the cylinders, the upward-moving piston compresses the material against the horizontal mobile plate. When the material is fully compressed, the pressure on the horizontal mobile plate is eased by slightly releasing the force applied by the jack using the force-easing key. This action allows the

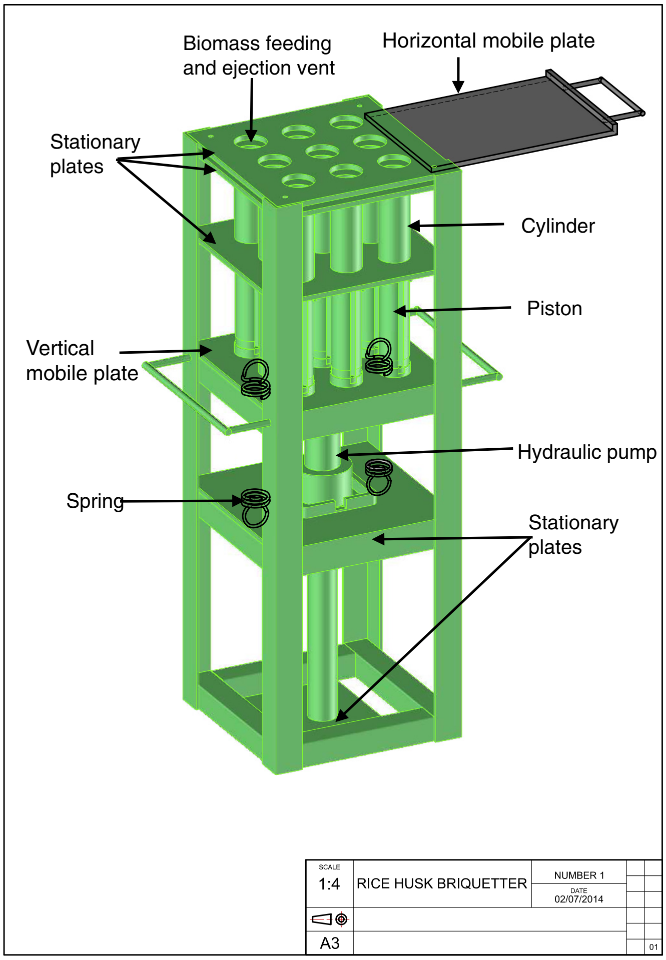

Fig. 1. Technical drawing for rice-husk briquetter.

horizontal mobile plate to be removed by sliding it out. The jack is then pumped upward to release the briquettes. The briquettes at this stage are soft and need to be dried to harden them. This upward collection method allows the briquettes that are held in that position by the pistons to be easily and safely removed and placed on drying boards. The force produced by the jack is then completely released using the force-easing key and the springs pull the pistons downward in preparation for loading the next batch of briquetting material. The complete technical drawings of the briquetter are provided as Supplementary information.

Optimization of briquette hardness

The aim of the optimization process was to get briquettes that were hard enough to withstand transportation. Four experiments were performed to determine the best husk–bran ratio, drying method, particle sizes, and water temperature for briquetting. For each of these experiments, variable classes and fixed factors were selected (Table 1a). For each variable class, two machines were used and two replications were done giving a total of 36 briquettes per class. The mixture to be introduced into the briquetting machine was prepared by adding water to the biomass in the ratio of 3:5 weight basis and then homogenized. When required, heated water was used to raise the temperature of the mixture to 97 °C. Fifty (50) grams of the mix was placed in each biomass-feeding vent and the same amount of pressure (7.74 MPa) was applied to compress the biomass. To ensure that the same pressure was applied to all the briquettes, the same quantity of biomass was fed into the vents and the piston was made to travel an optimum predetermined fixed distance. The briquettes were then ejected after a holding time of 30 s and dried to a moisture content of 20%.

Table 1a
Sequential optimization of the hardness of briquette.

Factor being optimized	Class variables	Fixed factors		
Husk–bran ratio	Husk–bran ratio	Particle size	Water temperature for briquetting	Drying method
	1:1	Fine	97 °C	Sun only
	1:2	Fine	97 °C	Sun only
	1:0	Fine	97 °C	Sun only
	0:1	Fine	97 °C	Sun only
	2:1	Fine	97 °C	Sun only
Drying method		Particle size	Water temperature for briquetting	Husk–bran ratio
	Oven only	Fine	97 °C	1:1
	Sun only	Fine	97 °C	1:1
	Sun and oven	Fine	97 °C	1:1
Particle size	Particle size	Water temperature for briquetting	Husk–bran ratio	Drying method
	Fine	97 °C	1:1	Sun only
	Medium	97 °C	1:1	Sun only
	Large	97 °C	1:1	Sun only
Water temperature for briquetting	Water temperature for briquetting	Husk–bran ratio	Drying method	Particle size
	97 °C	1:1	Sun only	Fine
	27 °C	1:1	Sun only	Fine

Production of fuel briquettes from rice-milling by-products

Four types of fuel briquettes—husk–bran only (HBO), husk–bran–palm press fiber (HBF), husk–bran–palm press sludge (HBS), and husk–biochar–clay (HBC)—were produced for this set of experiments (Table 1b). The husk–bran mixture used for this experiment was collected from Engelberg type mills in Glazoué, Benin. These mills do not produce separate bran and husk, rather the husk and bran are coarsely ground during the rice milling process, making it impossible to separate the husk and bran. Palm press fiber and palm press sludge were collected from a local artisanal palm oil extraction company. Palm press waste is used as a fire-lighting material in rural communities in SSA and was added to the fuel briquette formulation to improve ignition and burning characteristics. Husk biochar was a waste product from husk gasifier stoves. For HBF and HBS briquettes, 0.5 kg of palm press fiber or palm press sludge were added to husk–bran mixtures (4.5 kg) of particle sizes ≤ 0.99 mm (medium and fine) and then homogenized. HBC briquettes were produced by adding 0.5 kg of fine clay to 4.5 kg of rice biochar, followed by thorough mixing. Water (3 L) at ambient temperature was then added and the mixtures homogenized by hand mixing. The optimum quantity of palm press fiber, palm press sludge, and clay for the production of HBF, HBS, and HBC briquettes had been predetermined (data not shown). For each briquette mix, two machines were used and two replications were done giving a total of 36 briquettes per briquette type. Two hundred (200) grams of the mix was placed in each biomass-feeding vent and the same amount of pressure (7.74 MPa) applied to compress the biomass. The briquettes were then ejected after a holding time of 30 s and dried for 21 days.

Table 1b
Production of different types of fuel briquettes from rice-milling by-products using water at 27 °C, particle size ≤ 0.9 mm, and sun drying.

Briquette type	Rice by-product	Binder
HBF	Husk–bran mixture from Engelberg type mill	Palm press fiber
HBS	Husk–bran mixture from Engelberg type mill	Palm press sludge
HBO	Husk–bran mixture from Engelberg type mill	
HBC	Husk biochar from husk gasification	Clay

HBF = rice husk–bran–palm press fiber; HBS = rice husk–bran–palm press sludge; HBO = rice husk–bran only; HBC = rice husk char.

Determination of moisture content during drying

The moisture content was determined on wet weight basis. The weight of briquettes was recorded daily for 7 days for samples dried in the oven and for 21 days for samples dried under ambient conditions (temperature = 16 °C–34 °C; relative humidity = 41%–100%). The daily moisture content of the sample was calculated as shown in Eq. (4).

$$Mc = \frac{Mo - Mt}{Mt} \times 100 \tag{4}$$

where Mc is the percent moisture content, Mo is the mass immediately after briquette is ejected from machine, and Mt is the mass of the briquette after drying for time t.

Determination of hardness of briquettes

The hardness of the briquettes was determined with a Kiya hardness tester (Fujirara Seisakusho, Ltd., Tokyo, Japan). The hardness of a briquette was the force required to break a briquette that was 20 mm thick using a 5 mm diameter plunger. The hardness of the briquettes was determined at a moisture content of 20%, usually after 7 days for samples dried in the oven and 21 days for samples dried under ambient conditions.

Determination of densification factor of rice-husk briquettes

Two (2) types of rice husk were used to produce briquettes for this experiment (husk-only and husk–biochar). Husk-only was either fine (≤0.300 mm) or a mixture of fine and medium (≤0.99 mm). An equal weight of rice husk or rice husk–biochar was placed in a measuring cylinder, shaken to remove voids, and the volume measured.

The length, diameter, and height of the briquette were measured using vernier calipers. The density of the briquette and husk were determined from Eqs. (5) and (6), respectively.

$$\text{Density of briquette}(D_b) = \frac{M_b}{\pi h (r_1^2 - r_2^2)} \tag{5}$$

$$\text{Density of husk}(D_h) = \frac{M_h}{V_h} \tag{6}$$

where D_b is the density of the briquette, D_h is the density of the husk, M_b is the mass of the briquette, M_h the mass of husk, V_h the volume of husk, h the height of the briquette, r_1 the radius of the briquette, and r_2 the radius of the orifice in the briquette.

The densification factor was then estimated using Eq. (7).

$$\text{Densification factor}(d) = \frac{D_b}{D_h} \tag{7}$$

Durability of briquettes

The drop resistance test (Al-Widyan and Al-Jalil, 2001) was used to determine the durability of the husk briquettes. For this test, briquettes were produced using particle sizes ≤ 0.9 mm, hot water (97 °C), husk–bran ratios of 1:1, 1:2, 2:1, and sun-dried for 21 days. Briquettes were dropped from a height of 1.85 m onto a metal plate four times. The final weight as a percentage of the initial weight was taken as the briquette durability.

Characterization of fuel briquettes from rice-milling by-products

The moisture content of the fuels was determined after drying for 24 h in an oven (Fisher Scientific 750 F, USA) at 104 °C based on the ASABE Standard S358.2 (ASABE, 2006). Total lipid and ash content were estimated according to AOAC methods (AOAC International, 2002). A bomb calorimeter (Parr Oxygen Bomb 1341 EB, Calorimeter Thermometer 6772, IL, USA) was used to measure the higher heating value (HHV) according to the American Society for Testing and Materials (ASTM) standard D5865-11a (ASTM, 2010). The start-up time of the fire was the time that elapsed for the flame temperature to reach 400 °C after lighting. The burning rate and specific fuel consumption were determined during the cold-start high-power phase of the Water Boiling Test (WBT) protocol version 4.2.2 (Bailis et al., 2003) with slight modifications. The modification was on the volume of water used (10 L) and the local boiling point (99 °C). The stove used was a SALMAR briquette–charcoal stove. Charcoal was used as the reference fuel. The amount of fuel used for each test was 4 kg and each test was carried out in triplicate. The data were entered in the WBT data calculation sheet version 4.2.2 (Aprovecho Research Center, 2013).

The burning rate measured the average number of grams of fuel burned per minute during the test, while the specific fuel consumption measured the amount of fuel required to boil 1 L of water. For each fuel type, the flame temperature was determined by burning 4 kg of fuel in the SALMAR briquette–charcoal stove and the flame temperature recorded every 5 min for 55 min using a traceable double thermometer (VWR-USA) equipped with thermal probes that can withstand up to 1200 °C.

Statistical analysis

Data obtained were analyzed using the Statistical Package for Social Sciences version 10.1.4 (SPSS, 2002) at a 5% significance level. The generalized linear model-univariate (GLM-Univariate) analysis was used to study the effect of husk–bran ratio, drying method, particle size, and water temperature for briquetting on the hardness of briquettes. The marginal estimated mean hardness for each class is reported. The means were further compared using the multiple comparison tests (LSD). The characteristics of the different types of fuel tested were compared using LSD. Pearson's correlation was used to determine the relationship between different briquette characteristics. Graphs were produced for flame temperature against time for the different types of fuel tested.

Results and discussion

Briquette production rate and briquette densities

The rate of briquette production depends on the time it takes to load the biomass and the time to fully compress the material. The average time for making nine briquettes (loading, compressing, ejection, and transfer to drying tray) was 3.6 min (150 briquettes/h). The compression and ejection time was significantly reduced from 55 to 18 s when the Stargold hydraulic jack was replaced with a Yale hydraulic jack. When the Stargold jack was used, the machine compressed and ejected 47.12 kg briquettes/day (589 briquettes at 11.4% moisture content), compared with 144 kg briquettes/day (1800 briquettes) when the Yale hydraulic jack was used. Conventional briquette making requires about 0.25 KWh/kg of briquettes to generate heat during the briquette-making process (Toan et al., 2000). In the heated die screw briquetting press (Ahiduzzaman and Islam, 2013), 77 kg/h was used to yield a gross output of 88 kg/h; resulting in a net output of 11 kg/h. However, this was a high input of briquettes for the net production. The operation of the multi-piston briquetting machine described in this paper is completely manual after grinding and a single person produced at least 12 kg of briquettes/h at 11.4% moisture content.

The briquetting technology increased the density of rice husk from 120 kg/m^3 to 600 kg/m^3 when the holding time was 30 s. Chin and Siddiqui (2000) demonstrated that holding time in the range of 20–40 s produced briquettes with the least percentage relaxation with time. The density of the briquettes was within the optimal range of biomass products after densification (600–800 kg/m^3) (Lim et al., 2012a) since this is directly related to the energy–volume ratio (Maiti et al., 2006). The densification factors for husk of fine and medium particle sizes were 1.51 and 1.50, respectively. These values were significantly lower than for husk biochar (5.91) because the husk biochar briquetting resulted in complete grinding of the carbonized husk into very fine particles.

Effects of particle size, husk–bran ratio, drying method, and water temperature for briquetting on the hardness of briquettes

Particle size, husk–bran ratio, drying method, and water temperature for the preparation of the biomass mix all influenced the hardness of rice-husk briquettes (Table 2). Briquettes were produced using fine and medium-sized particles, as large-particle briquettes crumbled when they were ejected from the machine due to the elastic nature of the husk. Particle size is an important factor affecting the durability of briquettes. Generally, the finer the particle size, the greater the durability. Fine particles usually absorb more moisture than large particles and, therefore, undergo a higher degree of conditioning (Kaliyan and Morey, 2009). In this study, the hardness of briquettes correlated positively with their durability ($R^2 = 0.55$; $P = 0.0001$).

Briquettes produced using fine particles were harder than those from medium-sized particles ($P < 0.001$). In addition, the density was higher for fine (605 kg/m^3) than for medium-sized particles (506 kg/m^3). These findings agree with previous work on *Miscanthus* and refuse-derived fuel, for which Ryu et al. (2006) showed that particle size influenced the density of briquettes since smaller particles resulted in more dense packing of particles at constant pressure. Briquettes produced using fine particles (<0.3 mm), hot (97 °C) water, husk–bran ratios of 0:1, 1:2, 1:1, 1:0, 2:1, and dried in the sun for 21 days had calculated mean hardness values of 132, 89, 76, 62, and 31 N. Rice bran has been used as binder for briquetting (Chuo et al., 2009) and the higher the proportion of the binder, the harder the briquettes. In this study, briquettes produced from bran only (0:1) were the hardest, while those produced with 2:1 husk–bran ratio were the softest (Table 3). Using large quantities of pure bran as binder may not be advisable as this product is a valued animal feed.

In this study, briquettes dried under ambient conditions were harder than those dried at 70 °C (oven) only or first dried at 70 °C and then under ambient conditions ($P < 0.01$). The rate of moisture loss was greater for samples dried in the oven (moisture was 20% after 2 days of drying) than for those dried under ambient conditions (moisture was 20% after 7 days of drying). These results suggest that a faster rate of moisture loss may reduce the ability of the particles to bind effectively during drying (Kaliyan and Morey, 2009). Briquettes were produced with both hot and cold water, and those produced using hot water were harder than those with cold water ($P < 0.01$). Nonetheless, briquettes produced using water at ambient temperature and husk–bran mixtures of fine and medium-sized particles from Engelberg mills were sufficiently hard (101 N). This suggested that heating water for the production of briquettes from husk–bran mixtures from Engelberg type mills was not necessary. Hot water gave much harder briquettes probably due to the gelatinization of the starch in bran (20%) (Saunders and Betschart, 1979).

Table 2
Main and interacting effect of factors that affect the hardness of rice-husk briquettes at constant pressure.

Term	F-value
Model	106.3***
Husk–bran ratio (HBR)	66.0***
Particle size (PS)	40.6***
Water temperature (WT)	12.1**
Drying method (DM)	6.3**
HBR × PS	0.5
HBR × WT	3.3*
HBR × DM	2.8*
PS × WT	9.1*
PS × DM	4.3*
WT × DM	4.4*
HBR × PS × WT	ns
PS × WT × DM	ns
HBR × PS × DM	ns
HBR × PS × DWT × DM	ns
R-square	0.87

*** $P < 0.001$; ** $P < 0.01$; * $P < 0.05$.

Table 3
Effects of factor combinations on the hardness of rice-husk briquettes.

Husk–bran ratio	Particle size	Water temperature (°C)	Drying method	Estimated mean hardness (N)
2:1	Fine	97	Oven + sun	24
			Sun	31
	Medium		Oven	4
	Fine	27	Oven + sun	8
			Sun	16
1:2	Fine	97	Oven	55
			Oven + sun	86
			Sun	89
	Medium		Oven	31
	Fine	27	Oven	30
			Oven + sun	63
1:1	Fine	97	Oven	42
			Oven + sun	64
			Sun	76
	Medium	97	Oven	09
			Oven + sun	03
			Sun	34
	Fine	27	Oven	41
			Oven + sun	14
			Sun	23
	Medium	27	Oven	35
1:0	Fine	97	Sun	62
	Medium	97	Oven	01
0:1	Fine	97	Sun	132
	Medium	97	Oven	38

Characteristics of fuel briquettes made from husk–bran mixtures from Engelberg type mills and rice-husk char

The four types of fuel briquettes—HBF, HBS, HBO, and HBC—produced in this study are shown in Fig. 2a. Briquettes made using husk–bran mixtures collected from Engelberg type mills and mixed with different palm press waste showed differences in hardness ($P < 0.05$) (Table 4). HBF briquettes were the hardest (170 N), followed by HBO (101 N), while HBS and HBC were the softest (20 and 21 N, respectively), although they were all produced using water at ambient temperature (27 °C). Palm press fiber contributed to the hardness of HBF by increasing mechanical interlocking. High lipid content recorded in HBS briquettes may have played a role in reducing the forces of attractive, interlocking, cohesiveness, and adhesiveness (Manickam et al., 2006) in these briquettes and thus reduced their hardness. Although it was possible to make very hard HBC briquettes with higher-quantity clay, these briquettes showed poor burning characteristics (data not shown).

The briquettes burned well in two natural draft stoves: a Salmar briquette–charcoal stove and an improved rocket stove previously developed for rice parboiling in SSA (Ndindeng et al., in press) (Fig. 2b).

HBF, HBS, HBO, and HBC briquettes had shorter start-off times (<5 min) than charcoal (10 min). Briquettes produced in SSA have been rated as hard to light compared to charcoal (Mwampamba et al., 2013), thus the briquetting technology described in this paper provides an opportunity for the production of briquettes that are easy to light and start a fire.

HBF, HBS, and HBO briquettes burned with a yellow flame, while HBC burned with a mixture of blue and red flames as did charcoal.

Fig. 2. (a) Different types of briquettes produced from husk–bran mixtures from Engelberg type mills and rice husk char; (b) burning of rice-husk briquettes in rocket and Salmar briquette–charcoal stoves.

HBF, HBS, and HBO briquettes produced some smoke especially when ventilation in the combustion chamber was poor (data not shown). HBO briquettes had the highest burning rate (145 g/min), while HBC briquettes had the lowest burning rate (67 g/min). Charcoal, HBS, and HBF briquettes had similar burning rates—120, 109, and 126 g/min, respectively. The briquettes produced crumbled when the fire was put out and so could not be re-used. This is a common problem in the briquetting industry worldwide (Mwampamba et al., 2013). HBC briquettes had the highest specific fuel consumption (701 g/l), while HBS briquettes had the lowest. HBC briquettes also recorded the largest ash content and the lowest calorific value. A positive correlation was observed between the ash content and specific fuel consumption ($R^2 = 0.917$; $P = 0.0001$), while negative correlations were observed between the ash content and the calorific value, lipid content, and burning rate ($R^2 = -0.65$, $P = 0.05$; $R^2 = -0.845$, $P = 0.001$; and $R^2 = -0.781$, $P = 0.001$, respectively) for the different types of fuel briquettes produced. The calorific values of HBF, HBS, and HBO briquettes were 18.47, 19.23, and 16.87 MJ/kg, respectively. These values are lower than the range reported for charcoal briquettes produced elsewhere (22–29 MJ/kg) (Mwampamba et al., 2013).

Briquettes made from husk–bran mixtures had flame temperatures above 800 °C after ~4–5 min of combustion in the Salmar briquette–charcoal stove (Fig. 3). This temperature stayed above 700 °C between 18 and 48 min of combustion and then started to drop. This drop in flame temperature coincided with the depletion of fuel biomass and an increase in the quantity of ash produced. For HBC briquettes, the maximum flame temperature (650 °C) was recorded after 20 min of combustion, but it stabilized and stayed above 490 °C until after 55 min. The flame temperature for charcoal started very low but peaked at 930 °C after 30 min, remaining above 800 °C even after 55 min. The average flame temperature over the 55 min burning time was not significantly different among the different fuel types tested ($P > 0.05$; Table 3). After loading the stove with 4 kg of fuel, briquettes made from husk–bran mixtures took 9 min to boil 10 L of water, while charcoal took 14.2 min. Briquettes made from rice-husk char boiled 5 L of water, but were unable to boil 10 L of water even after 1 h (data not shown).

These results indicate that HBF, HBS, and HBO are suitable for cooking operations that require high heat intensities from the onset of cooking, such as for boiling water during paddy soaking and steaming in the rice parboiling industry.

Table 4
Characteristics of fuel briquettes from rice-milling by-products and palm press waste burnt in a Salmar briquette–charcoal stove in comparison with charcoal. HBF = rice husk–bran–palm press fiber; HBS = rice husk–bran–palm press sludge; HBO = rice husk–bran only; HBC = rice husk char; CHA = charcoal; ND = not determined.

Fuel type	Hardness (N)	Lipid content (g/100 g)	Higher heating value (MJ/kg)	Ash content (g/100 g)	Start-up time (min)	Burning rate at cold start high power (g/min)	Specific fuel consumption at high power (g/liter of water boiled)	Flame temperature (°C) during a period of 55 min
HBF	$170 \pm 3^{a*}$	04.11 ± 0.13^{b}	18.47 ± 0.04^{b}	19.79 ± 0.25^{c}	2^{b}	126 ± 8^{b}	121 ± 07^{d}	684.3 ± 163.4^{a}
HBS	20 ± 0.3^{c}	10.58 ± 0.01^{a}	19.23 ± 1.67^{b}	17.64 ± 0.00^{e}	3^{b}	109 ± 6^{c}	107 ± 06^{e}	725.5 ± 199.5^{a}
HBO	101 ± 2^{b}	02.27 ± 0.04^{b}	16.87 ± 1.63^{b}	21.33 ± 0.06^{b}	3^{b}	145 ± 8^{a}	136 ± 09^{c}	728.5 ± 188.1^{a}
HBC	21 ± 0.9^{c}	0.250 ± 0.02^{c}	09.66 ± 1.02^{c}	68.80 ± 1.17^{a}	4^{b}	67 ± 8^{d}	701 ± 07^{a}	518.0 ± 113.5^{a}
Charcoal	ND	ND	31.14 ± 2.14^{a}	03.51 ± 0.91^{d}	10^{a}	120 ± 6^{bc}	195 ± 15^{b}	679.5 ± 260.1^{a}

*Means with different superscript letters implies least significant difference at the 0.05 level of significance using the multiple comparison test.

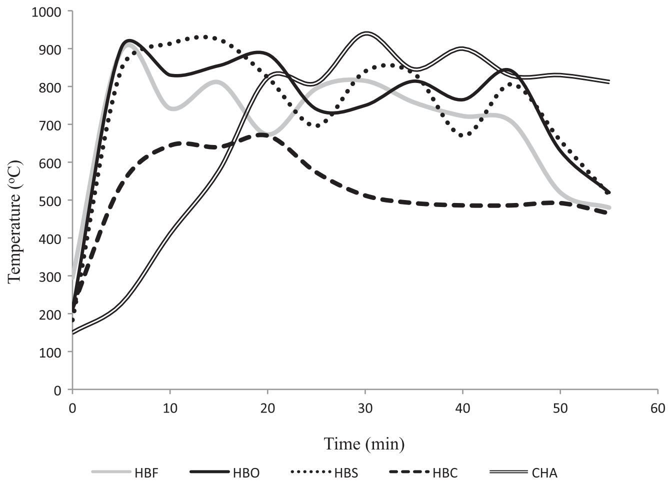

Fig. 3. Flame temperature of different types of briquettes and charcoal during combustion in a Salmar briquette–charcoal stove for a period of 55 min. HBF = rice husk–bran–palm press fiber; HBS = rice husk–bran–palm press sludge; HBO = rice husk–bran-only; HBC = rice husk char; CHA = charcoal.

Conclusions

Briquettes currently produced in SSA are hard to light and difficult to burn because existing stoves require additional ventilation. This paper reports the production and characterization of different types of briquettes using different combinations of raw materials, methods, and an affordable briquetting technology. The paper demonstrates that particle size, husk–bran ratio, drying method, and water temperature for briquetting are the main factors that influence the hardness of the briquettes at constant pressure. Using bran or other forms of binders is necessary to produce rice-husk briquettes with sufficient hardness. HBF and HBO briquettes produced for fuel from husk–bran mixtures from Engelberg type mills showed the best fuel briquette quality in terms of hardness, ease of lighting, calorific value, ash content, burning rate, specific fuel consumption, and flame temperature. Although HBS was not hard enough, HBF, HBS, and HBO should be suitable for cooking operations that require high heat intensities from the onset of cooking such as for boiling water during paddy soaking and steaming in the rice parboiling industry.

The high volumes of firewood used for rice parboiling represent as much as 30% of operating costs and contribute to local deforestation and landscape degradation. Targeting millers who also parboil rice is expected to increase the adoption rate of these briquettes, as this will reduce their dependence on firewood, which is becoming scarce, especially with increasing urbanization. Briquettes produced using husk only could be of added advantage, as the ash by-product could be used for building and construction (Khan et al., 2012; Yuzer et al., 2013) or in the local ceramic industry (Prasad et al., 2001; Andreola et al., 2013). Rice-husk briquettes can also be produced for companies that require rice husk as raw material. However, further research is needed to understand consumer perception and willingness to pay for the different types of briquettes made from rice-milling by-products.

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Appendix A. Supplementary data

Technical drawings of the different parts of the rice-husk briquetter showing (02) frame assembly, (03) frame assembly view, (04) plate and piston system, (05) plates, (06) cylinders, (07) piston, and (08) horizontal mobile plate. Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.esd.2015.09.003.

References

Adkins E, Oppelstrup K, Modi V. Rural household energy consumption in the millennium villages in sub-Saharan Africa. Energy Sustain Dev 2012;16(3):249–59. http://dx.doi.org/10.1016/j.esd.2012.04.003.

Ahiduzzaman M, Islam AKM. Development of biomass stove for heating up die barrel of rice husk briquette machine. Procedia Eng 2013;56:777–81. http://dx.doi.org/10.1016/j.proeng.2013.03.194.

Al-Widyan MI, Al-Jalil HF. Stress-density relationship and energy requirement of compressed olive cake. Appl Eng Agric 2001;17(6):749–53.

Amissah JGN, Ellis WO, Oduro I, Manful JT. Nutrient composition of bran from new rice varieties under study in Ghana. Food Control 2003;14(1):21–4. http://dx.doi.org/10.1016/S0956-7135(02)00047-6.

An D, Guo Y, Zou B, Zhu Y, Wang Z. A study on the consecutive preparation of silica powders and active carbon from rice husk ash. Biomass Bioenerg 2011;35(3):1227–34. http://dx.doi.org/10.1016/j.biombioe.2010.12.014.

Andreola F, Martín MI, Ferrari AM, Lancellotti I, Bondioli F, Ma Rincón J, et al. Technological properties of glass–ceramic tiles obtained using rice husk ash as silica precursor. Ceram Int 2013;39:5427–35. http://dx.doi.org/10.1016/j.ceramint.2012.12.050.

AOAC International. Official methods of analysis of AOAC International No. 920.05, 920.39. AOAC International; 2002.

Aprovecho Research Center. Testing & Protocols. Cottage Grove (OR): Aprovecho Research Center; 2013. http://www.aprovecho.org/lab/pubs/testing.

ASABE. Standard S358.2: Moisture measurement—Forages. St-Joseph (MI): American Society of Agricultural and Biological Engineering; 2006. p. 608–9.

ASTM. Standard D5865-11: Standard test method for gross calorific value of coal and coke. vol. 05.06. West Conshohocken (PA). : American Society for Testing and Materials; 2010. p. 628–44.

Bailis R, Ogle D, Maccarty N, Still D. The Water Boiling Test (WBT). version 4.12. Oregon, USA: Household Energy and Health Programme, Shell Foundation; 2003 [revised 2009].

Bhattacharya SC, Leon MA, Rahman MM. A study on improved biomass briquetting. Energy Sustain Dev 2002;6(2):67–71. http://dx.doi.org/10.1016/S0973-0826(08)60317-8.

Chin OC, Siddiqui KM. Characteristics of some biomass briquettes prepared under modest die pressures. Biomass Bioenergy 2000;18(3):223–8. http://dx.doi.org/10.1016/S0961-9534(99)00084-7.

Chou CS, Lin SH, Peng CC, Lu WC. The optimum conditions for preparing solid fuel briquette of rice straw by a piston-mold process using the Taguchi method. Fuel Process Technol 2009;90(7):1041–6. http://dx.doi.org/10.1016/j.fuproc.2009.04.007.

El-Shafey EI. Removal of Zn (II) and Hg (II) from aqueous solution on a carbonaceous sorbent chemically prepared from rice husk. J Hazard Mater 2010;175(1):319–27. http://dx.doi.org/10.1016/j.jhazmat.2009.10.006.

Faccin GL, Miotto LA, Vieira LDN, Barreto PLM, Amante ER. Chemical, sensorial and rheological properties of a new organic rice bran beverage. Rice Sci 2009;16(3):226–34. http://dx.doi.org/10.1016/S1672-6308(08)60083-9.

Goyal HB, Seal D, Saxena RC. Bio-fuels from thermochemical conversion of renewable resources: a review. Renew Sustain Energy Rev 2008;12(2):504–17. http://dx.doi.org/10.1016/j.rser.2006.07.014.

Grover PD, Mishra SK, Clancy JS. Development of an appropriate biomass briquetting technology suitable for production and use in developing countries. Energy Sustain Dev 1994;1(1):45–8.

Gunawan S, Maulana S, Anwar K, Widjaja T. Rice bran, a potential source of biodiesel production in Indonesia. Ind Crop Prod 2011;33(3):624–8. http://dx.doi.org/10.1016/j.indcrop.2010.12.027.

IRRI. World Rice Statistics Online Query Facility. Results generated on Sept 6, 2015 20:01. Los Baños: International Rice Research Institute; 2015 [http://ricestat.irri.org:8080/wrs2/entrypoint.htm].

Kaliyan N, Morey RV. Factors affecting strength and durability of densified biomass products. Biomass Bioenerg 2009;33(3):337–59. http://dx.doi.org/10.1016/j.biombioe.2008.08.005.

Kapilan R, Arasaratnam V. Paddy husk as support for solid state fermentation to produce xylanase from *Bacillus pumilus*. Rice Sci 2011;18(1):36–45. http://dx.doi.org/10.1016/S1672-6308(11)60006-1.

Khan R, Jabbar A, Ahmad I, Khan W, Khan AN, Mirza J. Reduction in environmental problems using rice–husk ash in concrete. Construct Build Mater 2012;30:360–5. http://dx.doi.org/10.1016/j.conbuildmat.2011.11.028.

Krishnani KK, Meng X, Christodoulatos C, Boddu VM. Biosorption mechanism of nine different heavy metals onto biomatrix from rice husk. J Hazard Mater 2008;153(3):1222–34. http://dx.doi.org/10.1016/j.jhazmat.2007.09.113.

Kumagai S, Sasaki J. Carbon/silica composite fabricated from rice husk by means of binderless hot-pressing. Bioresour Technol 2009;100(13):3308–15. http://dx.doi.org/10.1016/j.biortech.2009.02.001.

Li Z, Lu J, Yang Z, Han L, Tan T. Utilization of white rice bran for production of L-lactic acid. Biomass Bioenerg 2012;39:53–8. http://dx.doi.org/10.1016/j.biombioe.2011.12.039.

Lim JS, Abdul Manan Z, Wan Alwi SR, Hashim H. A review on utilisation of biomass from rice industry as a source of renewable energy. Renew Sustain Energy Rev 2012a; 16(5):3084–94. http://dx.doi.org/10.1016/j.rser.2012.02.051.

Lim SL, Wu TY, Sim EYS, Lim PN, Clarke C. Biotransformation of rice husk into organic fertilizer through vermicomposting. Ecol Eng 2012b;41:60–4. http://dx.doi.org/10.1016/j.ecoleng.2012.01.011.

Lin L, Ying D, Chaitep S, Vittayapadung S. Biodiesel production from crude rice bran oil and properties as fuel. Appl Energy 2009;86(5):681–8. http://dx.doi.org/10.1016/j.apenergy.2008.06.002.

Mai Thao PT, Kurisu KH, Hanaki K. Greenhouse gas emission mitigation potential of rice husks for An Giang province, Vietnam. Biomass Bioenerg 2011;35(8):3656–66. http://dx.doi.org/10.1016/j.biombioe.2011.05.023.

Maiti S, Dey S, Purakayastha S, Ghosh B. Physical and thermochemical characterization of rice husk char as a potential biomass energy source. Bioresour Technol 2006;97(16): 2065–70. http://dx.doi.org/10.1016/j.biortech.2005.10.005.

Manickam IN, Ravindran D, Subramanian P. Biomass densification methods and mechanism. Cogeneration & Distrib Generation J 2006;21(4):33–45. http://dx.doi.org/10.1080/15453660609509098.

Mwampamba TH, Owen M, Pigaht M. Opportunities, challenges and way forward for the charcoal briquette industry in sub-Saharan Africa. Energy Sustain Dev 2013;17(2): 158–70. http://dx.doi.org/10.1016/j.esd.2012.10.006.

Ndindeng SA, Mapiemfu DL, Fantong W, Nchinda VP, Ambang Z, Manful JT. Postharvest adaptation strategies to the effects of temperature variations and farmer–miller practices on the physical quality of rice in Cameroon. Am J Clim Chang 2014;3:178–92. http://dx.doi.org/10.4236/ajcc.2014.32017.

Ndindeng SA, Manful J, Futakuchi K, Mapiemfu DL, Akoa-Etoa JM, Tang EN, et al. Upgrading the quality of Africa's rice: a novel artisanal parboiling technology for rice processors in sub-Saharan Africa. Food Sci Nutr 2015. http://dx.doi.org/10.1002/fsn3.242. [in press].

Parmigiani SP, Vitali F, Lezzi AM, Vaccari M. Design and performance assessment of a rice husk fueled stove for household cooking in a typical sub-Saharan setting. Energy Sustain Dev 2014;23:15–24. http://dx.doi.org/10.1016/j.esd.2014.01.003.

Pourali O, Asghari FS, Yoshida H. Production of phenolic compounds from rice bran biomass under subcritical water conditions. Chem Eng J 2010;160(1):259–66. http://dx.doi.org/10.1016/j.cej.2010.02.057.

Prasad CS, Maiti KN, Venugopal R. Effect of rice husk ash in whiteware compositions. Ceram Int 2001;27(6):629–35. http://dx.doi.org/10.1016/S0272-8842(01)00010-4.

Rohman A. Rice bran oil's role in health and cooking. In: Watson RR, Preedy VR, Zibadi S, editors. Wheat and rice in disease prevention and health: benefits, risks and mechanisms of whole grains in health promotion. Elsevier, Academic Press; 2014. p. 481–90. http://dx.doi.org/10.1016/B978-0-12-401716-0.00037-4.

Ryu C, Yang YB, Khor A, Yates NE, Sharifi VN, Swithenbank J. Effect of fuel properties on biomass combustion: Part I. Experiments—fuel type, equivalence ratio and particle size. Fuel 2006;85:1039–46. http://dx.doi.org/10.1016/j.fuel.2005.09.019.

Saravanan SD, Senthil Kumar M. Effect of mechanical properties on rice husk ash reinforced aluminum alloy (AlSi10Mg) matrix composites. Procedia Eng 2013;64: 1505–13. http://dx.doi.org/10.1016/j.proeng.2013.09.232.

Saravanan S, Nagarajan G, Rao G, Sampath S. Feasibility study of crude rice bran oil as a diesel substitute in a DI–CI engine without modifications. Energy Sustain Dev 2007; 11(3):83–92. http://dx.doi.org/10.1016/S0973-0826(08)60580-3.

Saunders RM, Betschart AA. Rice and rice foods: chemistry and nutrition. Tropical Foods: Chemistry and Nutrition, 1. 1; 1979. p. 191–216.

So SJ, Jang IS, Han CS. Effect of micro/nano silica particle feeding for mice. J Nanosci Nanotechnol 2008;8(10):5367–71. http://dx.doi.org/10.1166/jnn.2008.1347. [5].

Sookkumnerd C, Ito N, Kito K. Financial viabilities of husk-fueled steam engines as an energy-saving technology in Thai rice mills. Appl Energy 2005;82(1):64–80. http://dx.doi.org/10.1016/j.apenergy.2004.09.012.

SPSS. Statistical Package for Social Sciences version 10.1.4. Chicago (IL): SPSS Inc.; 2002.

Suzuki RM, Andrade AD, Sousa JC, Rollemberg MC. Preparation and characterization of activated carbon from rice bran. Bioresour Technol 2007;98(10):1985–91. http://dx.doi.org/10.1016/j.biortech.2006.08.001.

Toan PK, Cuong ND, Quy NT, Sinh PK. Application of briquetting technology to produce briquettes from agricultural residues and by-products. World Renewable Energy Congress VI: Renewables—The Energy for the 21st Century; 2000. p. 1416–9. http://dx.doi.org/10.1016/B978-008043865-8/50295-6.

Vadiveloo J, Nurfariza B, Fadel JG. Nutritional improvement of rice husks. Anim Feed Sci Technol 2009;151(3):299–305. http://dx.doi.org/10.1016/j.anifeedsci.2009.03.002.

Wan Y, Prudente A, Sathivel S. Purification of soluble rice bran fiber using ultrafiltration technology. LWT- Food Sci Technol 2012;46(2):574–9. http://dx.doi.org/10.1016/j.lwt.2011.09.019.

Yuzer N, Cinar Z, Akoz F, Biricik H, Yalcin Gurkan Y, Kabay N, et al. Influence of raw rice husk addition on structure and properties of concrete. Construct Build Mater 2013; 44:54–62. http://dx.doi.org/10.1016/j.conbuildmat.2013.02.070.