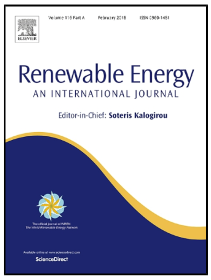
Accepted Manuscript



Characteristics of briquettes developed from rice and coffee husks for domestic cooking applications in Uganda

Michael Lubwama, Vianney Andrew Yiga

PII: S0960-1481(17)31096-0

DOI: 10.1016/j.renene.2017.11.003

Reference: RENE 9405

To appear in: *Renewable Energy*

Received Date: 26 December 2016

Revised Date: 03 August 2017

Accepted Date: 01 November 2017

Please cite this article as: Michael Lubwama, Vianney Andrew Yiga, Characteristics of briquettes developed from rice and coffee husks for domestic cooking applications in Uganda, *Renewable Energy* (2017), doi: 10.1016/j.renene.2017.11.003

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

ACCEPTED MANUSCRIPT

Highlights

- Rice and coffee husk briquettes were developed with cassava starch and clay as binders
- The type of binder affected the physical properties, calorific values and drop strengths
- Heating values for briquettes developed with cassava starch binder ranged from 21.9-23.0 MJ/kg for coffee husks and 15.9-16.6 MJ/kg for rice husks.
- For coffee and rice husk briquettes developed with clay binder, average higher heating values ranged from 13.0-19.5 MJ/kg and 9.5-13.8 MJ/kg, respectively.
- Cassava starch binder imparted higher drop strengths (over 94%) onto the briquettes than clay binder material.

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

Characteristics of briquettes developed from rice and coffee husks for domestic cooking applications in Uganda

Michael Lubwama*, Vianney Andrew Yiga
Department of Mechanical Engineering, Makerere University, P.O. BOX 7062, Kampala, Uganda
*Corresponding Author
Email: mlubwama@cedat.mak.ac.ug
Tel: +256784111042

Abstract

The goal of this study was to develop briquettes from coffee and rice husks agricultural wastes as sustainable fuel sources for domestic cooking applications. Clay and cassava starch were used as binders. Physial properties of the coffee husks and rice husks as well as the developed briquettes were determined using Thermogravimetric analysis. Higher heating value (HHV) results were determined using bomb calorimetry. Drop test method was used to determine the mechanical and storage integrity of the developed briquettes. The results showed that the type of binder used in the development of the briquettes significantly affected both their physical properties and calorific values. Average higher heating values for briquettes developed with cassava starch binder ranged from 21.9-23.0 MJ/kg for coffee husks and 15.9-16.6 MJ/kg for rice husks. For coffee and rice husk briquettes developed with clay binder, average higher heating values ranged from 13.0-19.5 MJ/kg and 9.5-13.8 MJ/kg, respectively. Generally, cassava starch binder imparted higher drop

ACCEPTED MANUSCRIPT

strengths (over 95%) onto the briquettes than clay binder material. The characteristics were influenced by the physical properties of the raw biomass material as well as the high SiO_2 ash in the clay binder.

Key words: Binder; Briquettes; Coffee and Rice husks; Physical Properties; Drop strength

1. Introduction

Fuel for domestic cooking applications in Uganda, like most of sub-Saharan Africa, is dominated by firewood (31.0%-Urban; 85.2%-Rural) and charcoal (58.2%-Urban; 11.8%-Rural) (Uganda Bureau of Standards (UBOS), 2016). This has resulted in a 46% loss in Uganda's forest cover between 1990 and 2013 (UBOS, 2015). The effect of this has been a change in the climatic pattern which has affected farming communities due to either extended droughts or excessive flooding and rainfall variability (Brown et al. 2011; Shiferaw et al. 2014). Uganda's deforestation rate now stands at 1.8% per annum (UBOS, 2015). This implies that carbondioxide (CO_2) capture and storage provided by forest cover will continue to substantially decline, hence promoting climate change and its negative impacts (Okello et al., 2013a; Okello et al., 2013b). Uganda's population is growing at a rate of 3% per annum. Demand for biomass energy is expected to increase in the short term to match this growth. This increase in demand is typical for developing countries where biomass represents 80% of the total energy supply mix. Therefore, there is an increasing need to source alternative fuels, especially for cooking so as to reduce deforestation as a result of trees being cut for both charcoal production and firewood (Yank et al., 2016).

One potential fuel source that is yet to be exhaustively tapped in Uganda are wastes from agricultural production and processing. These wastes can be used to produce modern energy of comparable or better heating value than both charcoal and firewood (Government of Uganda (GoU), 2007; Yank et al., 2016). A decade old Government of Uganda report documents that over 1.2 million tons of agricultural wastes are generated annually (GoU, 2007). This figure is expected to have increased as agricultural production has become both more commercialized and mechanized. Two agricultural wastes are the focus of this study: (1) Rice husks; and, (2) Coffee husks. Rice has become a staple food in Uganda and coffee remains one of Uganda's main cash crops (UBOS, 2015). Therefore, their production is expected to increase for the foreseeable future. Rice production has grown at a rate of over 9% per annum (Food and Agriculture Organization (FAO), 2015); whereas, coffee continues to play a leading role in the economy of Uganda, contributing 18% of export earnings between the year 2000 and 2010 (Ahmed 2012). However, the disposal of rice and coffee husks agricultural residues generated during processing is problematic. The most common method of dipsosal is burning in open fields which has negative ecological impacts (Lim et al., 2012; Thao et al., 2011).

Therefore, the utilization of rice and coffee husks agricultural wastes in the development of an alternative domestic cooking fuel will: (1) reduce on the rate of deforestation for charcoal production and firewood for domestic cooking applications; and, (2) enhance waste management by the utilization of the rice and coffee husks (Das et al., 2016). These advantages in combination enhance climate change mitigation and reduce environmental degradation and pollution (Okello et al., 2013a; Thao et al., 2011). Additionally, rice and coffee husks generated in Uganda have an energy potential of 0.58PJ/year and 2.86PJ/year, respectively (Okello et al., 2013a). Therefore, the

ACCEPTED MANUSCRIPT

development of rice and coffee husk briquettes provides a sustainable way of utilizing this energy potential in the production of a domestic cooking fuel that will provide potentially more energy per unit volume when compared to both charcoal and firewood (Ndindeng et al., 2015).

The technological process involved in briquetting is relatively well known (Bhattacharya et al., 1989). Over the last decade a number of studies have demonstrated the development of briquettes from agricultural wastes (Amaya et al., 2007; Barargan et al., 2014; Blesa et al., 2001; Chen et al., 2009; Chou et al., 2009a; Chou et al., 2009b; Gangil, 2014; Haykiri-Acma et al., 2013; Hu et al., 2015; Kaliyan and Morey, 2009a; Kaliyan and Morey, 2009b; Kaliyan and Morey, 2010a; Kaliyan and Morey, 2010b; Liu et al., 2013; Liu et al., 2014; Lu et al., 2014; Lubwama and Yiga, 2017; Muazu and Stegemann, 2015; Mwampamba et al., 2013; Oladeji, 2010; Srivastava et al., 2014; Stelte et al., 2011; Stolarski et al., 2013; Wilaipon, 2007; Wilaipon, 2008; Wilaipon, 2009). Even yet, these and more studies remain few given the amount of wastes generated from agricultural production and processing. Differences in hydrogeological conditions from one region to another imply that physical properties of agricultural wastes must be geo-specific (Muazu and Stegemann, 2015; Vassilev et al., 2010). Due to biomass variability, a continuous effort must be applied to development and characterization of biomass briquettes for sustainable energy development (Muazu and Stegemann, 2015).

Typical agrobased fibers like rice husks and coffee husks are three dimensional bio-polymers composed mainly of cellulose, hemicellulose and lignin (Bekalo and Reinhardt, 2010; Vassilev et al., 2012). Inorganic consitituents of chemical ash compositions show the dominant presence of silicon dioxide (SiO_2) and potassium oxide (K_2O) (Vassilev et al., 2010). A comparison of the organic and dominant chemical constituents between Rice husks and coffee husks is shown in Table 1. Cellulose content is generally higher for rice husks compared to coffee husks. Higher percentages of cellulose is generally associated with a rigid structure and stiffness. Rice husk ash also have a higher percentage of SiO_2 at 94.38% compared to that of coffee husks at 14.65% (Vassilev et al., 2010). Silica is also associated with the formation of rigid micro-structures that enhance structural stability and rigidness of the plant structure (Vassilev et al., 2012). These differences imply that the properties of briquettes developed from rice and coffee husks will be affected by these inherent differences in the raw materials under consideration.

More specifically, extremely few studies have been done on briquettes developed from rice husks and coffee husks. Arewa et al., (2016) characterized and compared rice husk briquettes developed with cassava peels and cassava starch as binders. Burning rate and water boiling test results indicated that rice husk briquettes combustion was improved with the use of both binders. However, properties of the rice husk briquettes made with cassava peels as a binder resulted in better performance. Ndindeng et al., (2015) produced briquettes from rice husks in combination with rice bran using palm press fiber, palm press sludge and clay as binders. Briquettes with rice husks and rice bran only were also developed. Results showed that incorporation of bran and other forms of binders produced rice husk briquettes with sufficient hardness and calorific value for cooking applications. However, inclusion of clay binder during rice husk briquette development had negative performance indicators including lower calorific value, higher ash content, lower flame temperature and higher specific fuel consumption (Ndindeng et al., 2015). Yank et al., (2016) investigated the effect of binders, water content and bran content on physical properties of briquettes developed from rice husks. Briquettes made with rice dust (a waste by-product produced

ACCEPTED MANUSCRIPT

when rice kernals are milled to produce flour) as binder had the highest durability and compressive strength, while briquettes made with cassava starch as binder had the greatest density (Yank et al., 2016). Oladeji (2010) characterized briquettes produced from corncobs and rice husk residues. Results showed better performance for briquettes developed from corncobs compared to those developed from rice husks. Corncob briquettes had higher volatile matter percentages (86.53) and higher heating values (20890 kJ/kg) whereas volatile matter and heating values for rice husk briquettes were 67.98% and 13389 kJ/kg, respectively. Amaya et al., (2007) developed activated carbon briquettes from wood and rice husks. Addition of low quantities of rice husk were observed to improve the mechanical properties of the prepared briquettes. However, thermogravimetric analysis indicated that the addition of rice husks in briquette development decreased their combustibility (Amaya et al., 2007). Hu et al., (2015) developed briquettes from rice husk char using different binders. Briquettes developed with starch binder showed good hydrophobicity, but exhibited low volume density and mechanical strength. Briquettes developed with sodium hydroxide (NaOH) as binder showed highest compressive strength and hydroscopicity. Briquettes developed with lignin and calcium hydroxide ($Ca(OH)_2$) exhibited more desirable characteristics for use as biofuels (Hu et al., 2015). Muazu and Stegemann (2015) developed composite briquettes from rice husks and corn cobs with a mixture of starch and water as binder. Starch and water addition were were required for attaining adequate briquette strength. Chou et al., (2009a) characterized briquettes made from rice straw with rice bran used as binding material. An optimized development process using different types of binders has also been described (Chou et al., 2009b). Liu et al., (2013) investigated the properteis of briquettes made by mixing bamboo and rice straw. With regards to briquettes made from coffee husks even fewer studies have been done. The potential of coffee husk briquettes has been documented for countries in South America, particularly, Brazil and Cuba (Felfi et al., 2011; Suarez et al., 2003). However, Gil et al., (2010) noted that briquettes developed from coffee husks had the least durability of all the raw material sources used. These limited studies indicate that further research should be done on briquettes developed from rice and coffee husks.

Therefore, in this study briquettes were developed from rice and coffee husks using cassava starch and bentonite clay as binder material. Cassava starch is composed of amylose and amylopectin and both play a role in enhancing strength of briquettes following gelatinization and retrogradation (Dureja et al., 2011; Muazu and Stegemann, 2015; Oladunmoye et al., 2014). Previous studies have utilized clay as a binder for the purpose of increasing the density and hardness of the developed briquette (Ndindeng et al., 2015). When dispersed in water, bentonite clay breaks down into small plate-like particles that become negatively charged on the surface and positively charged on the edges. This unique ion exchange is responsible for their binding action (Lu et al., 2014). The briquettes were developed using both low pressure after carbonization and high pressure development techniques. Thermogravimetric analysis was used to determine the physical properties and the weight loss-time profiles for the briquettes. The higher heating values for the briquettes were determined using bomb calorimetry. Drop strength results were used to evaluate the mechanical integrity and durability of the briquettes. The total cumulative time for ignition and water boiling were also determined for application to domestic cooking.

2. Experimental

2.1 Briquette Development

ACCEPTED MANUSCRIPT

Coffee husks and Rice husks raw material were sun dried for 6 - 8 hours. The dried coffee and rice husks were then fed into a carbonizer. The carbonizer was made from a steel drum onto which holes of 0.02m diameter were inserted . The holes serve an air regulation purpose. The carbonizer drum was of 200 litre volume capacity with height 1m and diameter 0.5m. These drums are locally available on the market. Ignition of the waste raw material takes place from the top of the carbonizer drum after which the top of the drum was covered (Lubwama and Yiga, 2017). During the carbonization process these holes were covered with mud/clay to limit the amount of air available for complete combustion in the carbonizer as the waste material reduces due to pyrolytic processes until bio-char was formed (Bazargan et al., 2014; Hu et al., 2015; Lubwama and Yiga, 2017; Tsai et al., 2012). Schematic drawings of the briquetting process have been presented elsewhere (Lubwama and Yiga, 2017)

Bio-char was then measured into 1000g portions which were mixed with 30, 40, 50, 60 and 100g of cassava starch binder; Bio-char was also measured into 1000g portions which were mixed with 100, 200, 300, 400 and 500g of clay binder. The starch binder was prepared by mixing 30, 40 50, 60 and 100g of cassava flour in water and bringing to boil in order to obtain a uniform starchy binder (Lubwama and Yiga, 2017; Rezania et al., 2016; Yank et al., 2016). The clay binder was prepared by adding 100g of water to each of the grams of solid clay and stirring to obtain a uniform solution. The cassava starch and clay binder were then mixed with the biochar and placed in cylindrical molds. The resulting briquette was a black solid of 0.05m diameter and 0.05m height.

For high pressure briquette development, rice and coffee husk raw material were first sun dried for 6-8 hours. Materials were dried to 10%-15% moisture content before being fed into an automated feed section that transferred it to the hopper by a screw mechanism run by an electric motor (Lubwama and Yiga, 2017). From the hopper the raw material flows to meet a shaft of 5.5 cm diameter and 40 cm length. The shaft is connected to a piston that gets mechanical energy from the rotary motion of wheels that are run by a motor at 1470 rpm. A compaction pressure of 230 MPa was maintained throughout the entire process. The formed briquette passed through a cooling conveyor (Lubwama and Yiga, 2017). High pressure briquette development was used to produce briquettes using coffee husks (1000g) without any binder. Development of rice husk briquettes under high pressure completely failed because of its high ash content. Processing parameters used in the development of rice husk and coffee husk briquettes are shown in Table 2.

2.2 Thermogravimetric analysis (TGA) and bomb calorimetry.

An Eltra Thermostep Thermogravimetric analyzer was used to determine the physical properties of the developed briquettes. Thermogravimetric analysis (TGA) was used to determine the moisture content, ash content, fixed carbon and volatile matter content for the developed briquettes (Fernandez et al., 2012; Lubwama and Yiga, 2017). TGA analysis was also used to represent the weight loss, first derivative and temperature evolution profiles versus time for each of the rice and coffee husk briquettes developed (Avelar et al., 2016; Gil et al., 2010; Hu et al., 2015; Liu et al., 2014; Virmond et al., 2012). Higher heating values for the rice and coffee briquettes were determined using an oxygen bomb calorimeter (IKA C 2000) (Lubwama and Yiga, 2017).

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

2.3 Mechanical Characterization

Drop test method was used to determine the compaction integrity of the briquettes for the purpose of gaining an understanding about their durability. In order to determine the drop strength, the briquettes were elevated up to 2m and then dropped onto a thick steel plate (Fengmin and Mingquan, 2011; Ndindeng et al., 2015). The ratio of the weight after dropping to the weight before dropping was recorded as the drop strength. Drop strength is an indicator as to whether the briquettes will retain their form during packaging, storage and transportation (Fengmin and Mingquan, 2011; Finney et al., 2009).

2.4 Water boiling tests

In order to evaluate the performance of the developed briquettes for domestic cooking supply the total time taken to ignite the briquettes and boil 1 liter of water using 200g of briquettes was determined (Chen et al., 2016; Lubwama and Yiga, 2017; Tumutegyereize et al., 2016). A traditional cook stove (locally called a '*sigiri*' or '*jiko*') was used.

3. Results and discussion

Structural characteristics between the pre-carbonized raw material and resulting bio-char after carbonization are very similar, though more particle disintegration was observed for coffee husks (See Figure 1). This observation is not surprising due to the high reactivity reported for coffee during the mass loss stage characterized by oxidative degradation (Gil et al., 2010). Also, coffee

ACCEPTED MANUSCRIPT

husks have higher percentages of volatile matter and lower percentages of ash content compered to rice husks which affects structural evolution during carbonization (Vassilev et al., 2010). For rice husks similarity in the structural morphology is typical for carbonization processes for rice husk samples where the reaction ratio of pyrolysis is low (Hu et al., 2008).

Some samples of briquettes developed under both low pressure after carbonization and high pressure techniques are shown in Figure 2. Only coffee husk briquettes were developed under high pressure without any binding material. The development of rice husk briquettes under high pressure was unsuccessful. In previous studies where rice husks briquettes were developed under high pressure either a binder was used or heated water was applied during the process (Amaya et al., 2007; Hu et al., 2015; Muazu & Stegemann, 2015; Ndindeng et al., 2015). The major limitation in the briquetting of rice husks is the high ash content consisting of mainly SiO_2 (see Table 1 and Table 3). For the coffee husk briquettes developed under high pressure it was observed that the surface of the briquettes generally had a smooth texture but lateral cracks were evident along the circumferential diameter of the briquettes along their entire length. However a cross-sectional view of the coffee husk briquettes developed under high pressure showed relatively good internal bonding. The smooth surface finish, lateral cracking notwithstanding, was expected as a result of the high pressure utilized during densification. Solid bridge bonding mechanisms are expected to have occurred as a result of the influence of both high instantaneous pressure and temperature during the compression stage of briquette development. Crystallization and chemical reactions of the lignin in the coffee husk raw material due to instantaneous high pressure and temperature ensure that solid bridges are developed to permeate any gaps between the coffee husks (Kaliyan and Morey, 2009a; Kaliyan and Morey, 2010a). However the formation of lateral cracks clearly indicates that the solidification of melted components during the cooling phase was irregular from the center of the briquette to its circumferential exterior, hence the formation of the circumferential lateral cracks (Kaliyan and Morey, 2010a; Kong et al., 2012). Briquettes developed after carbonization generally had micro-pores across the entire circumferential area. This is expected because the pressures exerted during their formation are low implying that mircro-spaces between the raw materials are not completely filled with the binder material. This bonding is characterized by short range forces due to intermolecular hydrogen bonds between amylose and amylopectin components of starch, van der Waals' forces and mechanical locking (Kaliyan and Morey, 2009a; Kaliyan and Morey, 2010a; Muazu and Stegemann, 2015; Stelte et al., 2011; Tako and Hizukuri, 2002).

In order to gain an in-depth understanding of the thermal degradation behaviour of the developed briquettes, TGA was used to obtain weight loss vs. time profiles as shown in Figure 3 to Figure 8. Results for the weight loss for both coffee and rice husk raw materials are shown in Figure 3a) and 3b) respectively. Initial weight loss of about 13% and 11% were recorded for coffee and rice husk raw materials, respectively. This is attributable to the loss of adsorbed moisture related to the moisture content in the raw materials being expended (Saegnar et al., 2001; Vassilev et al., 2013; Werther et al., 2000). The following rapid increase in weight loss corresponded to initiation of thermal degradation of the raw material. This weight loss corresponds to combustion of organic matter and burning of some residual char (Vassilev et al., 2013). During this period the drying phase changes to biomass volatization where volatile matter, due to hemicellulose (190 ºC – 320 ºC), cellulose (280 ºC – 400 ºC) and lignin (320 ºC – 450 ºC) decomposition, is released (Avelar et al., 2016; Chen et al., 2012; Fernandez et al., 2012).

The measured weight losses during the develotilzation phase in Figure 3a) and 3b) correspond exactly to the percentage of volatile matter in the coffee and rice husks. The residual mass corresponds to the ash content of coffee and rice husks (See Table 3). A very interesting trend in weight loss was observed for coffee husk briquettes with cassava starch binder as shown in Figure 4. The specific weight loss during the volatization stage was much lower in comparison to the mass loss for the coffee husk raw material. Therefore, it is possible to attribute the reduction of volatile matter in the briquettes to the carbonization pre-treatment process prior to briquetting (Fernandez et al., 2014; Liu et al., 2013; Park et al., 2012). No significant difference in weight loss was observed for coffee husk briquettes with 30-60g of cassava starch binder. However, for coffee husk briquettes with 100g of cassava starch binder a higher weight loss margin was observed because of the lower ash content in these briquettes due to the significance of the amount of binder present which reduces on the ash content of these briquettes (See Table 3) (Tharise et al., 2014).

The thermal degradation behaviour for rice husk briquettes with cassava starch binder is shown in Figure 5. The results clearly show that the presence of cassava starch binder in the rice husk briquettes and prior carbonization precesses reduce the devolatization stage significantly when compared to the thermal degradation of rice husk raw material. However, when the thermal degradation of the rice husk briquettes was compared to ascertain the influence of increasing the cassava starch binder from 30-100g very minimal changes to weight loss were observed. This suggests that carbonization pre-treatment is highly responsible for the reduction of weight loss during devolatilization. This behaviour is explained by the increase in ash content (see Table 3) as well as high level of SiO_2 in rice husks inherently (Vassilev et al., 2010). Heating rice husks may produce several effects that hinder combustion such as formation of silica ash, formation of silicon carbide and the strengthening of Silica-Carbon bonds (Amaya et al., 2007).

The influence of clay binder on coffee husk and rice husk briquettes is shown in Figure 6 and Figure 7, respectively. From Figure 6 it is clearly observed that as the amount of clay binder is increased from 100-500g, devolatization reduces. Clay itself is a mainly inorganic material, which implies that the volatile content contribution from the clay binder is very small (Onchieku et al., 2012). It is also expected that the presence of ash in the briquettes will increase as the amount of clay binder increases. This combination of factors combines to reduce on the weigth loss recorded for coffee husk briquettes with clay binders during the devolatization stage. A similar trend is observed for rice husk briquettes with clay binder. Devolatization is reduced further and ash content is expected to increase due to the combination of SiO_2 in rice husks and clay binder (Ndindeng et al., 2015; Onchieku et al., 2012). The thermal degradation results of the non-carbonized coffee husk briquettes developed under high pressure (see Figure 8) were very similar to the thermal degradation behaviour of coffee husk raw material.

The results of the thermal degradation investigation tally very well with the results obtained for the physical properties for rice and coffee husk briquettes shown in Table 3. A number of general observations can be made. Firstly, the moisture content in both the coffee and rice husk briquettes with both cassava starch and clay binder is lower than the moisture content percentage in coffee and rice husk raw material. Carbonized briquettes adsorb less moisture due to the destruction of hydroxyl groups, which are hydrophilic, in the carbonization process (Liu et al., 2013). The carbonization process inhibits moisture adsorption which is a necessary aspect for increased shelf life and storage of the briquettes by preventing rotting and decomposition (Fernandez et al., 2013; Liu et al., 2013). Secondly, the developed briquettes have a lower percentage of volatile matter compered to the coffee and rice husk raw material. Low volatile matter implies that the ignitability of the briquettes will be reduced, but once they ignite, then combustion will produce little or no smoke with a clean flame (Ivanov et al., 2003). Thridly, all of the developed briquettes had higher percentages of ash content compared to their respective parent raw material. Fouthly, all of the briquettes developed after carbonization have higher fixed carbon percentages as a result of volatization processes that occur during pyrolysis and reactions between steam and carbon leading to elimination of heteroatoms and an increment in the relative amount of ash (Amaya et al., 2007). These results are similar to results obtained in previous studies where rice and coffee husk briquettes were developed (Amaya et al., 2007; Muazu and Stegemann, 2015; Ndindeng et al., 2015; Yank et al., 2016).

More specific observations can be made from Table 3. Moisture content is lower for the rice husk briquettes compared to the coffee husk briquettes irrespective of the binder material used. Also, volatile matter percentage was higher for coffee husk briquettes with both cassava starch and clay binder compared to rice husk briquettes with cassava starch and clay binder. These results are directly related to the moisture content and volatile matter in the parent raw material as shown in Table 3. The percentage of ash is highest for rice husk briquettes with clay binder. Although ash content was also high for rice husk briquettes with cassava binder and coffee husk briquettes with clay binder. This is due to SiO_2 ash in both rice husks and clay binder (Ndindeng et al., 2015; Onchieku et al., 2012). The highest percentage of fixed carbon was observed for coffee husk briquettes with cassave starch binder followed by rice husk briquettes with cassava starch binder.

Briquettes developed with clay binder had lower percentages of fixed carbon. This result is similar to other studies where clay binder was also used (Onchieku et al., 2012). However, the presence of the clay binder may be advantageous in prolonging cooking time by its low heat release and fuel saving effects (Onchieku et al., 2012).

The results for the heating values for the developed briquettes are shown in Table 4. The highest heating value (HHV) results were obtained for coffee husk briquettes with cassava binder at 23 MJ/kg. The results suggest that as the amount of cassava starch binder is increased to 100g, the heating value drops to an average of 21.0 MJ/kg. This value is still higher than the heating value recorded for all of the other briquettes. Cassava flour has low amounts of ash content (Tharise et al., 2014). However as the amount of cassava starch binder is increased then a cumulative increment in the amount of ash is expected. Hence the drop in heating value for coffee husk briquettes when 100g of cassava starch binder is considered. Coffee husk briquettes with 100g and 200g of clay binder had the next average higher heating values at 19.5 MJ/kg and 17.2 MJ/kg. These results imply that utilization of up to 200g of clay binder in coffee husk briquettes could be acceptable for domestic cooking applications with greater values of clay binder not very useful (Onchieku et al., 2012). These results were followed by rice husk briquettes with cassava starch as binder. The lowest values for heating values were obtained for rice husk briquettes with clay binder. This is due to the high levels of ash content in these briquettes which negatively affects their energy content (Amaya et al., 2007; Ndindeng et al., 2015; Onchieku et al., 2012). The HHV for non-carbonised coffee husk briquette developed under high pressure was 15.2 MJ/kg. This implies that it is possible to develop low cost carbonized briquettes that have higher energy content than more costly high pressurized briquettes. This result is of extreme importance in sub-Saharan countries where cost limitations and lack of data are noted as reasons for low uptake of briquette production (Mwampamba et al., 2013).

Nested single factor analysis of variance (ANOVA) was used to determine the statistical significance of the effect of binder proportion on the physical properties and HHV. Statistical analysis showed that there was a high level of significance ($p < 0.05$) in the relationship between binder proportion and most response factors. This included results for the effect of binder proportion of fixed carbon and volatile matter percentages in both coffee and rice husk briquettes with cassava starch and clay binders where all P-values were below 0.05 at 95% confidence interval (see Table 5). High levels of significance were also shown for the effect of binder proportion on; Moisture content in both coffee and rice husk briquettes with clay binder; Ash content in coffee briquettes with clay binder; Ash content in rice husk briquettes with both cassava starch and clay binder; and, HHV for coffee husk briquettes with clay binder. The lack of statistical significance in the effect of binder proportion to HHV for all of the developed briquettes, except for coffee husks with clay binder, is due to comparable energy content of the developed briquettes. There was no statistical significance for the effect of binder proportion on moisture content for rice and coffee husk briquettes with cassava starch binder as well as ash content for coffee husks with cassava starch binder. This is similar to results obtained by Tumutegyereize et al. (2016) and Akowuah et al., 2012.

The drop strength results for the developed briquettes are shown in Figure 9. The results clearly indicate that briquettes developed with cassava starch as binder had higher drop strengths (over 94%) than the briquettes developed with clay binder. This implies that the increment of starch

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

provided by the cassava starch binder allowed for better compaction. Starch is a polysaccharide and is a good binding agent due to its chemical and structural properties (Muazu and Stegemann, 2015). Addition of water and heat to starch granules causes swelling, which results in the formation of intermolecular hydrogen bonds between amylose and amylopectin components of starch, followed by the loss of the individual crystalline structure of the two components (Tako and Hizukuri, 2002). This leads to the formation of a viscous solution that undergoes retrogradation during cooling or storage. The viscosity of hydrated starch increases its shear and tensile strengths and gives it the ability to occupy void spaces present within and between biomass particles, thus forming solid briges that increase in strength during air cooling and storage (Muazu and Stegemann, 2015; Tako and Hizukuri, 2002). It is also observable that the drop strength increases as the amount of clay binder is increased in both coffee and rice husk briquettes. This was also noted by Ndindeng et al., (2015). However a marginally better drop strength performance was observed for rice husk briquettes with clay binder than coffee husk briquettes with clay binder. This is due to Silica in the rice husk, which is also associated with the formation of rigid micro-structures that enhance structural stability and rigidness of the plant structure (Vassilev et al., 2012). The drop strength for the non-carbonised coffee briquette developed under high pressure was 90% and less than the drop strength for the carbonized briquettes. This indicates that the pressure applied during densification was inadequate for the complete formation of solid bridges to occur. The circumferential crack observed on the surface of the non-carbonized briquettes were obvious points for failure to occure once the drop test was applied. Suarez et al., (2003) developed coffee husk briquettes using a vertical 10 tonne hydraulic press for applying a load to a heated die of 80 mm internal diameter and 140 mm length in which the briquette was formed. This implies that if no binder is to be used then considerations on application of heat, extremely high loads or a combination of both have to be made.

The results for the total ignition and water boiling time for 1 liter of water using 200g of developed briquette are shown in Table 4. The tests were performed using a traditional cook stove because they are majorly used for domestic cooking applications in Uganda due to the perceived notion that improved cook stoves are expensive despite efforts to enhance their diffusion among rural communities (Shrimali et al., 2011). Additionally, performance of field studies of improved cook stoves are inconclusive mainly due to the numerous designs on the market (Jetter and Kariher, 2009). Lowest total times for ignition and boiling 1 liter of water were observed for coffee husk briquettes with 60g cassava starch binder at 13 minutes and rice husk briquettes with 100g clay binder at 15 minutes. Ndindeng et al. 2015 noted that 4 kg of rice husk char boiled 5 liter of water but were unable to boil 10 liters even after 1 hour. Tumutegyereize et al. (2016) recorded times of between 31.5 to 52.5 minutes to boil 8 to 10 liters of water in 2 liter intervals using briquettes developed from matooke peels. The results obtained in the water boiling test were influenced by the amount of briquettes used that were less than what is described in other similar studies. This meant that the total cumulative heat energy generated was less. The use of a traditional cook stove in order to align the study with what consumers actually use also affected the results because traditional cook stoves do not conserve heat and heat loss due to conduction, convection and radiation occurs much faster to the environment. However, the results for total times for ignition and water boiling highlight the possibility of applying less amounts of briquettes for cooking which translates into savings in domestic energy use.

ACCEPTED MANUSCRIPT

4. Conclusions

The utilisation of agricultural wastes is very important for sustainability of domestic cooking fuels in Uganda and sub-Saharan Africa. This study investigated the physical properties, thermal degradation weight loss behaviour, heating values and drop strengths of briquettes developed from rice and coffee husk agricultural wastes with cassava starch and clay as binders. Thermal degradation results showed a decrease in mass loss for all of the developed carbonized briquettes. The physical properties showed that the moisture content and volatile matter in the carbonized briquettes were lower than the moisture content percentage in coffee and rice husk raw material. All of the carbonized briquettes had higher percentages of ash content and fixed carbon compared to their respective parent raw material. These results were due to devolatization processes having occurred during pyrolysis pre-treatment prior to briquette development. The highest heating value results were obtained for coffee husk briquettes with cassava binder at 23 MJ/kg. Also, as the amount of cassava starch binder is increased to 100g, the heating value drops to an average of 21.0 MJ/kg. Coffee husk briquettes with 100g and 200g of clay binder had the next average higher heating values at 19.5 MJ/kg and 17.2 MJ/kg. These results imply that utilization of up to 200g of clay binder in coffee husk briquettes could be acceptable for domestic cooking applications with greater values of clay binder not very useful. The lowest values for heating values were obtained for rice husk briquettes with clay binder. This is due to the high levels of ash content in these briquettes which negatively affects their energy content. The HHV for non-carbonised coffee husk briquette developed under high pressure was 15.2 MJ/kg. Briquettes developed with cassava starch as binder had higher drop strengths (over 94%) than the briquettes developed with clay binder. This implies that the increment of starch provided by the cassava starch binder allowed for better compaction. The drop strength for the non-carbonised coffee briquette developed under high pressure was 90% and less than the drop strength for the carbonized briquettes. This indicates that the pressure applied during densification was inadequate for the complete formation of solid bridges to occur. Lowest total times for ignition and boiling 1 liter of water were observed for coffee husk briquettes with 60g cassava starch binder and rice husk briquettes with 100g clay binder. The results for total times for ignition and water boiling highlight the possibility of applying less amounts of briquettes for cooking which translates into savings in domestic energy use.

Acknowledgements

The authors would like to acknowledge the research grant provided by International Foundation for Science (IFS) (Grant Number: C/5663-1) that facilitated the research presented in this paper.

References

Ahmed M. 2012. Analysis of incentives and disincentives for coffee in Uganda. Technical notes series. MAFAP, FAO, Rome.

Akowuah JO, Kemausuor F, Mitchual SJ. Physico-chemical characteristics and market potential of sawdust charcoal briquette. International Journal of Energy and Environmental Engineering 2012; 3(1):1-6

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

Amaya A, Medero N, Tancredi N, Silva H. Deiana C. Activated Carbon Briquettes from Biomass Materials. Bioresource Technology 2007; 98(8): 1635-1641.

Arewa ME, Daniel IC, Kuye A. Characteristics and comparison of rice husk briquettes with cassava peels and cassava starch as binders. Biofuels 2016; 7(6): 671-675

Avelar NV, Rezende AAP, Carneiro ADCO, Silva CM. Evaluation of briquettes made from textile industry solid waste. Renewable Energy 2016; 91: 417-424.

Bazargan A, Rough SL, McKay G. Compaction of palm kernel shell biochars for application as solid fuel. Biomass and Bioenergy 2014; 70: 489-497.

Bekalo SA, Reinhardt H-W, Fibers of coffee husk and hulls for the production of particleboard. Materials and Structures 2010; 43: 1049-1060

Bhattacharya SC, Sett S, Shrestha RM. State of the art for Biomass Densification. Energy Sources 1989; 11(3): 161-182.

Blesa MJ, Fierro V, Miranda JL, Moliner R, Palacios JM. Effect of the pyrolysis process on the physiochemical and mechanical properties of smokeless fuel briquettes. Fuel Processing Technology 2001; 74(1): 1-17.

ACCEPTED MANUSCRIPT

Brown C, Meeks R, Hunu K, Yu W. 2011.Hydro climate risk to economic growth in sub-Saharan Africa. Climate Change 106, 621-647.

Chen WH, Lu KM, Tsai CM. An experimental analysis on property and structural variations of agricultural wastes undergoing torrefaction. Applied Energy 2012; 100: 318-325.

Chen Y, Shen G, Su S, Du W, Huangfu Y, Liu G, Wang X, Xing B, Smith KR, Tao S. Efficiencies and pollutant emissions from forced-draft biomass-pellet semi-gasifier stoves: Comparison of International and Chinese water boiling test protocols. Energy for Sustainable Development 2016; 32: 22-30

Chou C, Lin S, Peng C, Lu W. Preparation and characterization of solid biomass fuel made from rice straw and rice bran. Fuel Processing Technology 2009a; 90(7): 980-987.

Chou C, Lin S, Peng C, Lu W. The optimum conditions for preparing solid fuel briquette of rice straw by a piston-mold process using the Taguchi Method. Fuel Processing Technology 2009b; 90(7): 1041-1046.

Das O, Sarmah AK, Bhattacharyya D. Biocomposites from waste derived biochars: Mechanical, thermal, chemical, and morphological properties. Waste Management 2016; 49: 560-570.

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

Dureja H, Khatak S, Khatak M, Kalra M. Amylose Rich Starch as an aqueous based pharmaceutical coating Material - Review. International Journal of Pharmaceutical Sciences and Drug Research 2011; 3(1): 8-12

Fengmin L, Mingquan Z. Technology Parameters of Biomass Briquetting of Macrophytes in Nansi Lake, Energy Procedia 2011; 5: 2449-2454

Food and Agriculture Organization 2015. Food and Agriculture Policy Design Analysis-Uganda. Country Fact Sheet on Food and Agriculture Policy trends.

Felfi FF, Mesa JM, Rocha JD, Filippetto D, Luengo CA, Pippo WA. (2011), Biomass briquetting and its perspectives in Brazil. Biomass and Bioenergy 2011; 35: 236-242

Fernandez RG, Garcia CP, Lavin AG, Bueno de las Heras JL. Influence of physical properties of solid biomass fuels on the design and cost of storage installations. Waste Management 2013; 33(5): 1151-1157.

Fernandez RG, Garcia CP, Lavin AG, Bueno de las Heras JL. Study of main combustion characteristics for biomass fuels used in boilers. Fuel Processing Technology 2012; 103: 16-26.

Fernandez RG, Garcia CP, Lavin AG, Bueno de las Heras JL. Spanish biofuels heating value estimation. Part II: Proximate analysis data. Fuel 2014; 117: 1139-1147

Finney KN, Sharifi VN, Swithenbank J. Fuel Pelletization with a Binder: Part I-Identification of a Suitable Binder for Spent Mushroom Compost-Coal Tailing Pellets. Energy & Fuels. 2009; 23(6): 3195-3202.

Gangil S. Beneficial transitions in thermogravimetric signals and activation energy levels due to briquetting of raw igeon pea stalk. Fuel 2014; 128: 2-13.

Gil MV, Oulego P, Casal MD, Pevida C, Pis JJ, Rubiera F. Mechanical durability and combustion characteristics of pellets from biomass blends. Bioresource Technology 2010; 101(22): 8859-8867.

Government of Uganda (GoU), 2007. Renewable Energy Policy, Kampala, Uganda

Haykiri-Acma H, Yaman S, Kucukbayrak S. Production of biobriquettes from carbonized brown seaweed. Fuel Processing Technology 2013; 106: 33-40.

Hu S, Xiang J, Sun L, Xu M, Qui J, Fu P. Characterization of char from rapid pyrolysis of rice husk. Fuel Processing Technology 2008; 89: 1096-1105

Hu Q, Shao J, Yang H, Yao D, Wang X, Chen H. Effects of binders on the properties of bio-char pellets. Applied Energy 2015; 157: 508-516.

ACCEPTED MANUSCRIPT

Ivanov IP, Sudakova IG, Kuznetsovv B. Manufacture of briquetted and granulated fuels from lignite with biobinders and heated die. Chem. Sustai. Devel. 2003; 11: 847-852.

Jetter JJ, Kariher P. Solid-fuel household cook stoves: Characterization of performance and emissions. Biomass and Bioenergy 2009; 33: 294-305

Kaliyan N, Morey VR. Factors affecting strength and durability of densified biomass products. Biomass and Bioenergy 2009a; 33(3) 337-359.

Kaliyan N, Morey VR. Constitutive model for densification of corn stover and switch grass. Biosystems Engineering 2009b; 104(1) 47-63.

Kaliyan N, Morey VR. Natural binders and solid bridge type binding mechanisms in briquettes and pellets made from corn stover and switch grass. Bioresource Technology 2010a; 101(3): 1082-1090.

Kaliyan N, Morey VR. Densification characteristics of corn cobs. Fuel Processing Technology 2010b; 91(5): 558-565.

Kong L, Tian S, He C, Du C, Tu Y, Xiong Y. Effect of waste wrapping paper fiber as a "solid bridge" on physical characteristics of biomass pellets made from wood sawdust. Applied Energy 2012; 98: 33-39.

ACCEPTED MANUSCRIPT

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 2012; 16(5): 3084-3094.

Liu Z, Jiang Z, Cai Z, Fei B, Yu Y, Liu X. Effects of carbonization conditions on properties of bamboo pellets. Renewable Energy 2013; 51: 1-6

Liu Z, Quek A, Balasubramanian, R. Preparation and characterization of fuel pellets from woody biomass, agro-residues and their corresponding hydrochars. Applied Energy 2014; 113: 1315-1322.

Lu D, Tabil LG, Wang D, Wang G, Emani S. Experimental trials to make wheat straws pellets with wood residue and binders. Biomass and Bioenergy 2014; 69: 287-296

Lubwama M, Yiga VA. Development of groundnut shells and bagasse briquettes as sustainable sources for domestic cooking applications in Uganda. Renewable Energy 2017; 111:532-542

Muazu RI, Stegemann JA. Effects of operating variables on durability of fuel briquettes from rice husks and corn cobs. Fuel Processing Technology 2015; 133: 137-145.

Mwampamba TH., Owen M, Pigaht M. Opportunities, challenges and way forward for the charcoal briquette industry in Sub-Saharan Africa, Energy for Sustainable Development 2013; 17(2): 158-170.

ACCEPTED MANUSCRIPT

Ndindeng SA, Mbassi JEG, Mbacham WF, Manful J, Graham-Acquaah S, Moreira J, Dossou J, Futakuchi K. Quality optimization in briquettes made from rice milling by-products, Energy for Sustainable Development 2015; 29: 24-31.

Okello C, Pindozzi S, Faugno S, Boccia L. Bioenergy potential of agricultural and forest residues in Uganda. Biomass and Bioenergy 2013a; 56: 515-525.

Okello C, Pindozzi S, Faugno S, Boccia L. Development of bioenergy technologies in Uganda: A review of progress. Renewable and Sustainable Energy Reviews 2013b; 18: 55-63.

Oladunmoye OO, Aworh OC, Maziya-Dixon B, Erukainure OL, Elemo GN. Chemical and functional properties of cassava starch, Durum wheat, semolina flour and their blends. Food Science and Nutrition 2014; 2(2): 132-138.

Oladeji M. Fuel Characterization of Briquettes Produced from Corncob and Rice Husk Residues. The Pacific Journal of Science and Technology 2010; 11(1): 101-106.

Onchieku JM, Chikamai BN, Rao MS. Optimum parameters for the formation of charcoal briquettes using bagasse and clay as binder. European Journal of Sustainable Development 2012: 1 (3) 477-492

Park YK, Yoo ML, Lee HW, Park SH, Jung SC, Park SS, Kim SC. Effects of operation conditions on pyrolysis characteristics of agricultural residues. Renewable Energy 2012; 42: 125-130

ACCEPTED MANUSCRIPT

Rezania S, Din MFM, Kamaruddin SF, Taib SM, Singh L, Yong EL, Dahalan FA. Evaluation of water hyacinth (Eichhornia crassipes) as a potential raw material source for briquette production. Energy 2016; 111: 768-773.

Saenger M., Hartge E.-U., Werther J., Ogada T. Combustion of coffee husks. Renewable Energy 2001; 23(1): 103-121.

Shiferaw B, Tesfaye K, Kassie M, Abate T, Prasanna BM, Menkir A. Managing vulnerability to drought and enhancing livelihood resilience in sub-Saharan Africa: Technological, institutional and policy options. Weather and Climate Extremes. 2014; 3: 67–79.

Shrimali G, Slaski X, Thurber MC, Zerriffi H. Improved stoves in India: A study of sustainable business models. Energy Policy. 2011; 39: 7543-7556

Srivastava NSL, Narnaware SL, Makwana JP, Singh SN, Vahora S. Investigating the energy use of vegetable market waste by briquetting. Renewable Energy 2014; 68: 270-275.

Stelte W, Holm JK, Sanadi AR, Barsberg S, Ahrenfeldt J, Henriksen UB. A study of bonding and failure mechanisms in fuel pellets from different biomass resources. Biomass and Bioenergy 2011; 35(2): 910-918.

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

Stolarski MJ, Szczukowski S, Tworkowski J, Krzyzanial M, Gulczynski P, Mleczek M. Comparison of quality and production cost of briquettes made from agricultural and forest origin biomass. Renewable Energy 2013; 57: 20-26.

Suarez JA, Beaton PA, Luengo CA, Felfi FF. Coffee husk briquettes: A new renewable energy source. Energy Sources 2003; 25: 961-967

Tako M, Hizukuri S. Gelatinization mechanism of potato starch, Carbohydrate Polymers 2002; 48(4): 397-401.

Thao P.T.M., Kurisu K.H., Hanaki K. Greenhouse gas emission mitigation potential of rice husks for An Giang province, Vietnam. Biomass and Bioenergy 2011; 35(8): 3656 -3666.

Tharise N, Julianti E, Nurminah M. Evaluation of physico-chemical and functional properties of composite flour from cassava, rice, potato, soybean and xanthan gum as alternative of wheat flour. International Food Research Journal 2014; 21(4): 1641-1649

Tsai WT, Liu SC, Hsieh CH. (2012) Preparation and fuel properties of biochars from the pyrolysis of exhausted coffee residue, J. Anal. Appl. Pyrolysis 2012; 93: 63–67

Tumutegyereize P, Mugenyi R, Ketlogetswe C, Gandure J. A comparative performance analysisof carbonized briquettes and charcoal fuels in Kampala-urban, Uganda. Energy for Sustainable Development 2016; 31: 91-96

ACCEPTED MANUSCRIPT

Uganda Bureau of Statistics (UBOS) 2015. Statistical Abstract. Kampala, Uganda.

Uganda Bureau of Statistics (UBOS) 2016. The National Population and Housing Census 2014- Main Report. Kampala, Uganda

Virmond E, Sena RF, Albrecht W, Althoff CA, Moreira RFPM, Jose HJ. Characterization of agroindustrial solid residues as biofuels and potential application in thermochemical processes. Waste Management 2012; 32(10): 1952-1961.

Vassilev SV, Baxter D, Andersen LK, Vassileva CG. An overview of the chemical composition of biomass. Fuel 2010; 89(5): 913-933.

Vassilev SV, Baxter D, Andersen LK, Vassileva CG. Morgan TJ. An overview of the organic and inorganic phase composition of biomass. Fuel 2012; 94: 1-33.

Vassilev SV, Baxter D, Vassileva CG. An overview of the behavior of biomass during combustion: Part 1: Phase mineral transformations of organic and inorganic matter. Fuel 2013; 112: 391-449.

Werther J, Saenger M, Hartge EU, Ogada T, Siagi Z. Combustion of agricultural residues. Progress in Energy and Combustion Science 2001; 26(1): 1-27.

ACCEPTED MANUSCRIPT

Wilaipon P. Physical Characteristics of Maize Cob Briquettes under Moderate Die Pressure. American Journal of Applied Science 2007; 4(12): 995-998.

Wilaipon, P. Density Equation of Bio-Coal Briquette and Quantity of Maize Cob in Phitsanulok, Thailand. American Journal of Applied Sciences 2008; 5(12): 1808-1811.

Wilaipon, P. The Effects of Briquetting Pressure on Banana Peel Briquette and the Banana Waste in Northern Thailand". American Journal of Applied Sciences 2009; 6(1): 167-171

Yank A, Ngadi M, Kok R. Physical properties of rice husk and bran briquettes under low pressure densification for rural applications. Biomass and Bioenergy 2016; 84: 22-30

Figures

Figure 1: Picture of rice husk and coffee husk raw material, before (a and c) and after (c and d) carbonization

Figure 2: Samples of briquettes developed under low pressure after carbonization (a) and non-carbonized under high pressure development

Figure 3: Weight loss, first derivative and temperature build up for TGA analysis of coffee husk (a) and rice husk (b) raw material

Figure 4: Weight loss, first derivative and temperature build up for TGA analysis of coffee husk briquettes with 30 g (a), 40 g (b), 50 g (c), 60 g (d) and 100 g (e), of cassava starch binder

Figure 5: Weight loss, first derivative and temperature build up for TGA analysis for rice husk briquettes with 30 g (a), 40 g (b), 50 g (c), 60 g (d) and 100 g (e), of cassava starch binder

Figure 6: Weight loss, first derivative and temperature build up for TGA analysis for coffee husk briquettes with 100 g (a), 200 g (b), 300 g (c), 400 g (d) and 500 g (e), of clay binder

Figure 7: Weight loss, first derivative and temperature build up for TGA analysis for rice husk briquettes with 100 g (a), 200 g (b), 300 g (c), 400 g (d) and 500 g (e), of clay binder

Figure 8: Weight loss, first derivative and temperature build up for TGA analysis of non-carbonized high pressure developed coffee husk briquettes

Figure 9: Drop strength for different developed briquettes

ACCEPTED MANUSCRIPT

Figure 1: Picture of rice husk and coffee husk raw material, before (a and c) and after (c and d) carbonization

ACCEPTED

Figure 2: Samples of briquettes developed under low pressure after carbonization (a) and non-carbonized under high pressure development

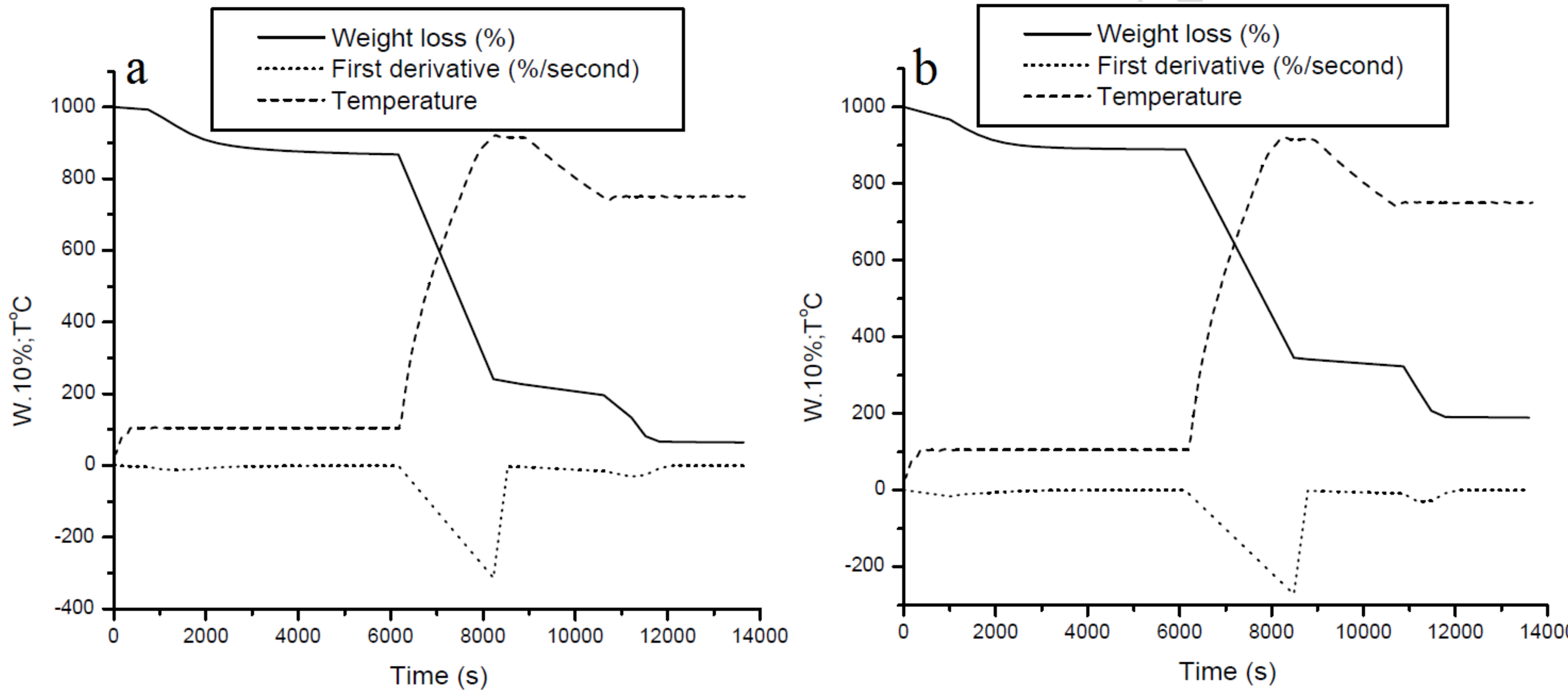


Figure 3: Weight loss, first derivative and temperature build up for TGA analysis of coffee husk (a) and rice husk (b) raw material

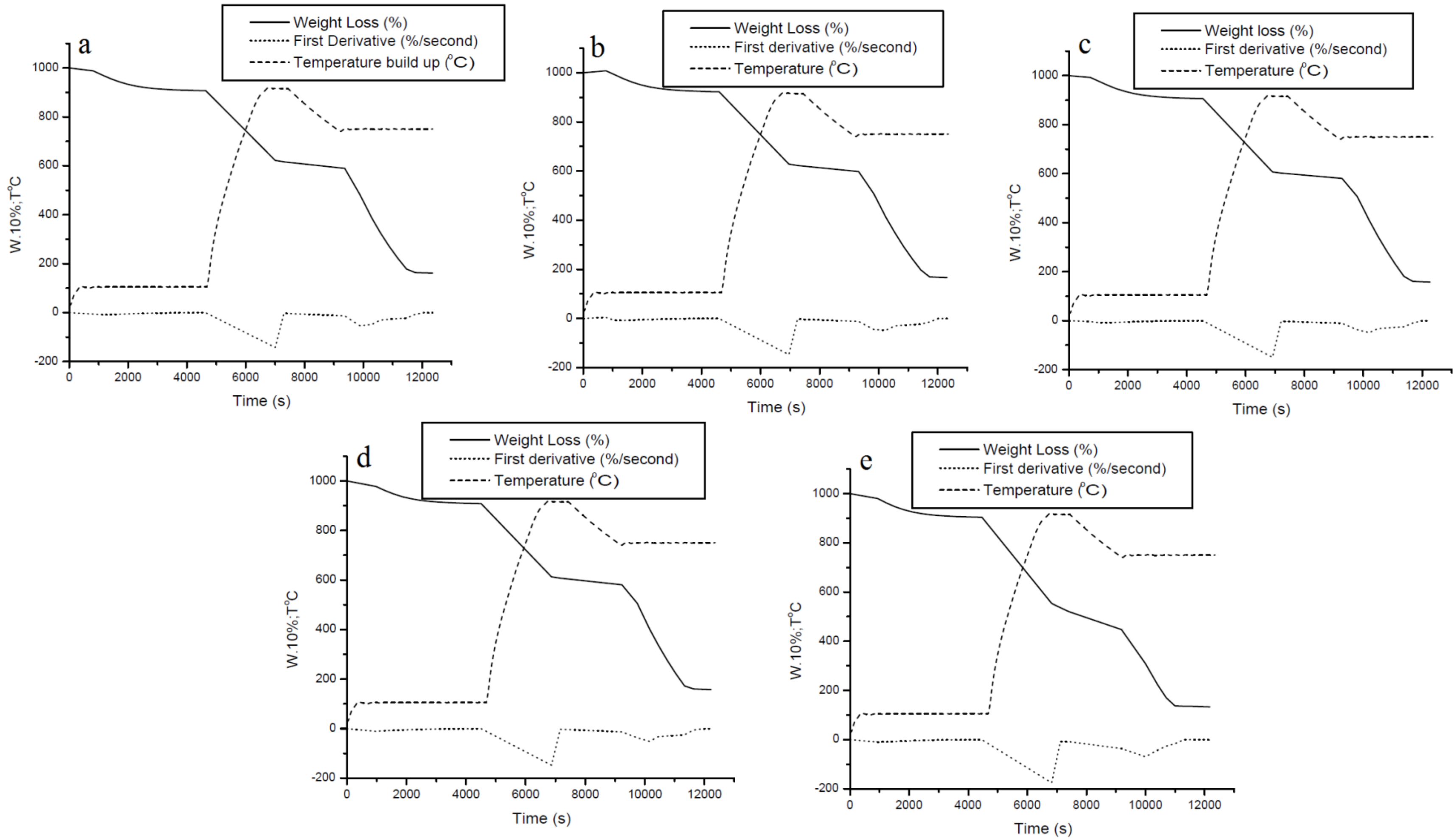


Figure 4: Weight loss, first derivative and temperature build up for TGA analysis of coffee husk briquettes with 30 g (a), 40 g (b), 50 g (c), 60 g (d) and 100 g (e), of cassava starch binder

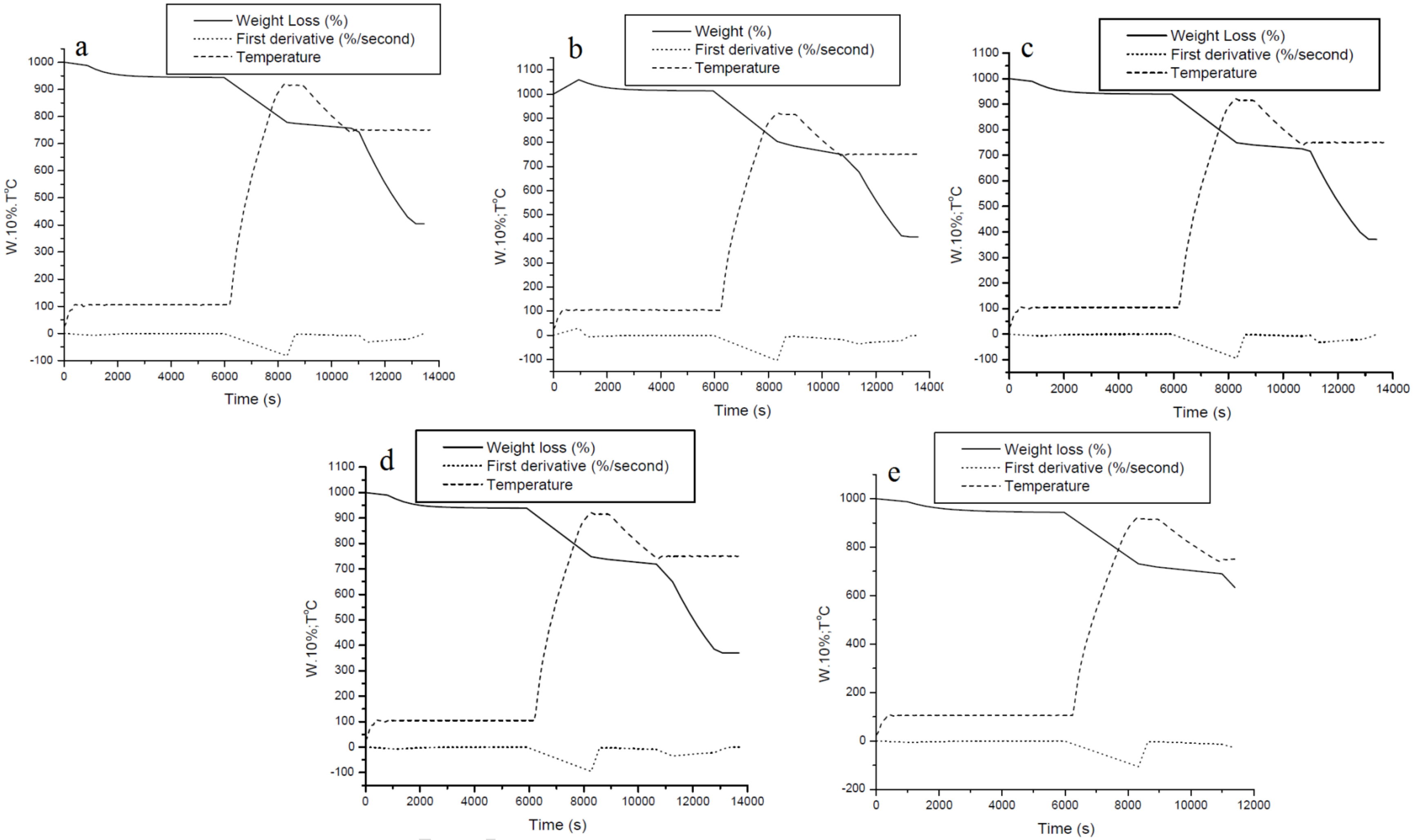


Figure 5: Weight loss, first derivative and temperature build up for TGA analysis for rice husk briquettes with 30 g (a), 40 g (b), 50 g (c), 60 g (d) and 100 g (e), of cassava starch binder

ACCEPTED MANUSCRIPT

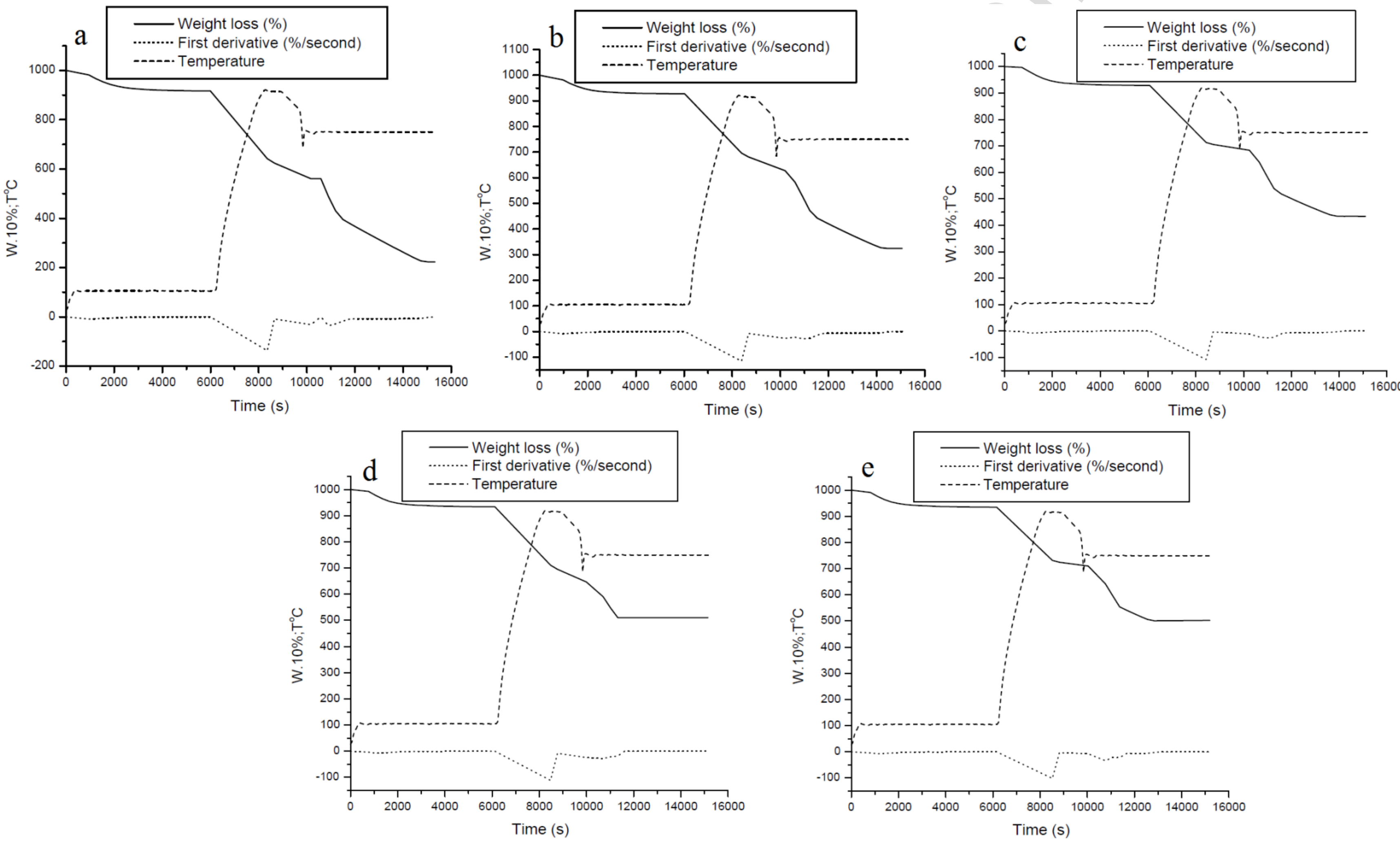


Figure 6: Weight loss, first derivative and temperature build up for TGA analysis for coffee husk briquettes with 100 g (a), 200 g (b), 300 g (c), 400 g (d) and 500 g (e), of clay binder

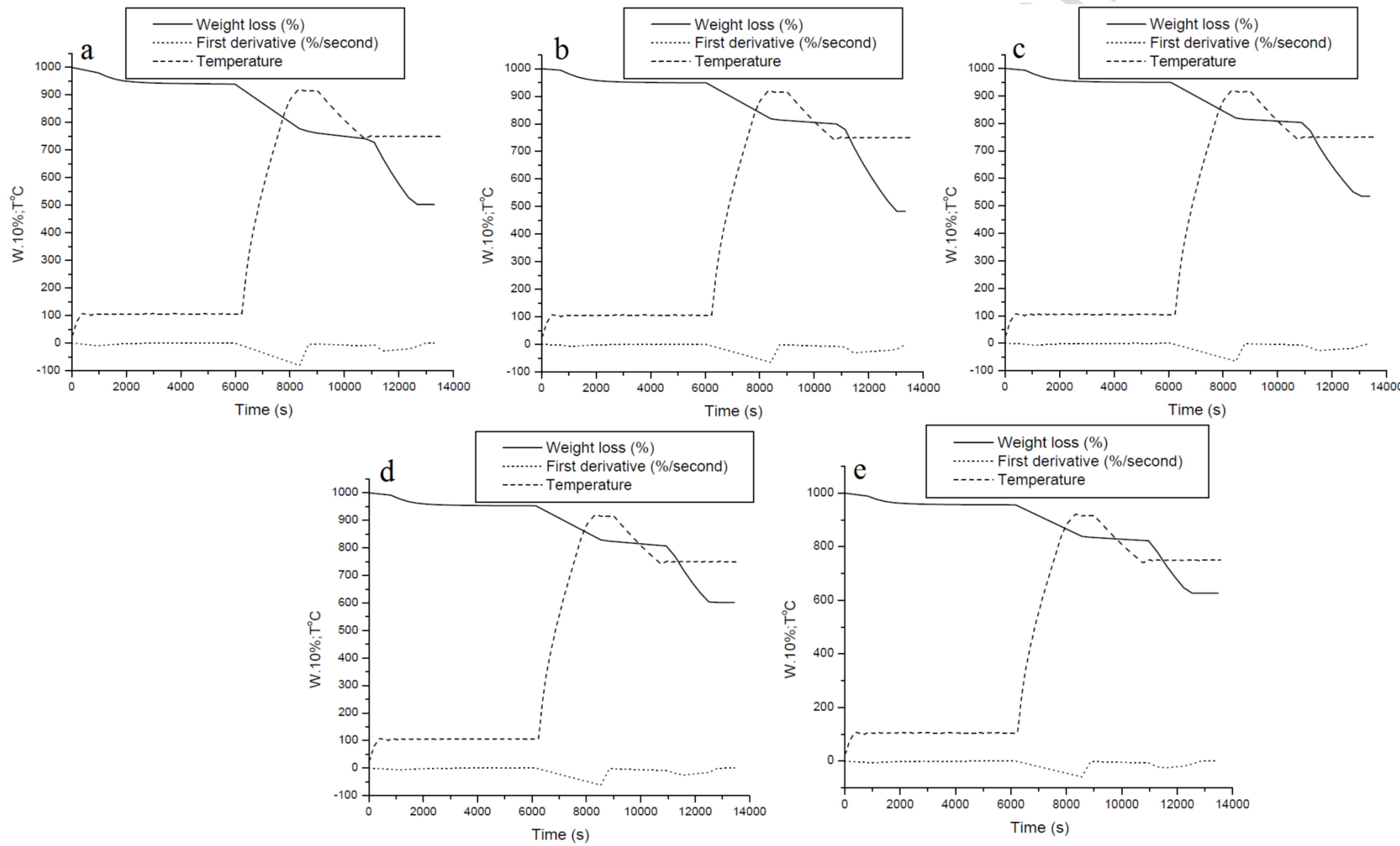


Figure 7: Weight loss, first derivative and temperature build up for TGA analysis for rice husk briquettes with 100 g (a), 200 g (b), 300 g (c), 400 g (d) and 500 g (e), of clay binder

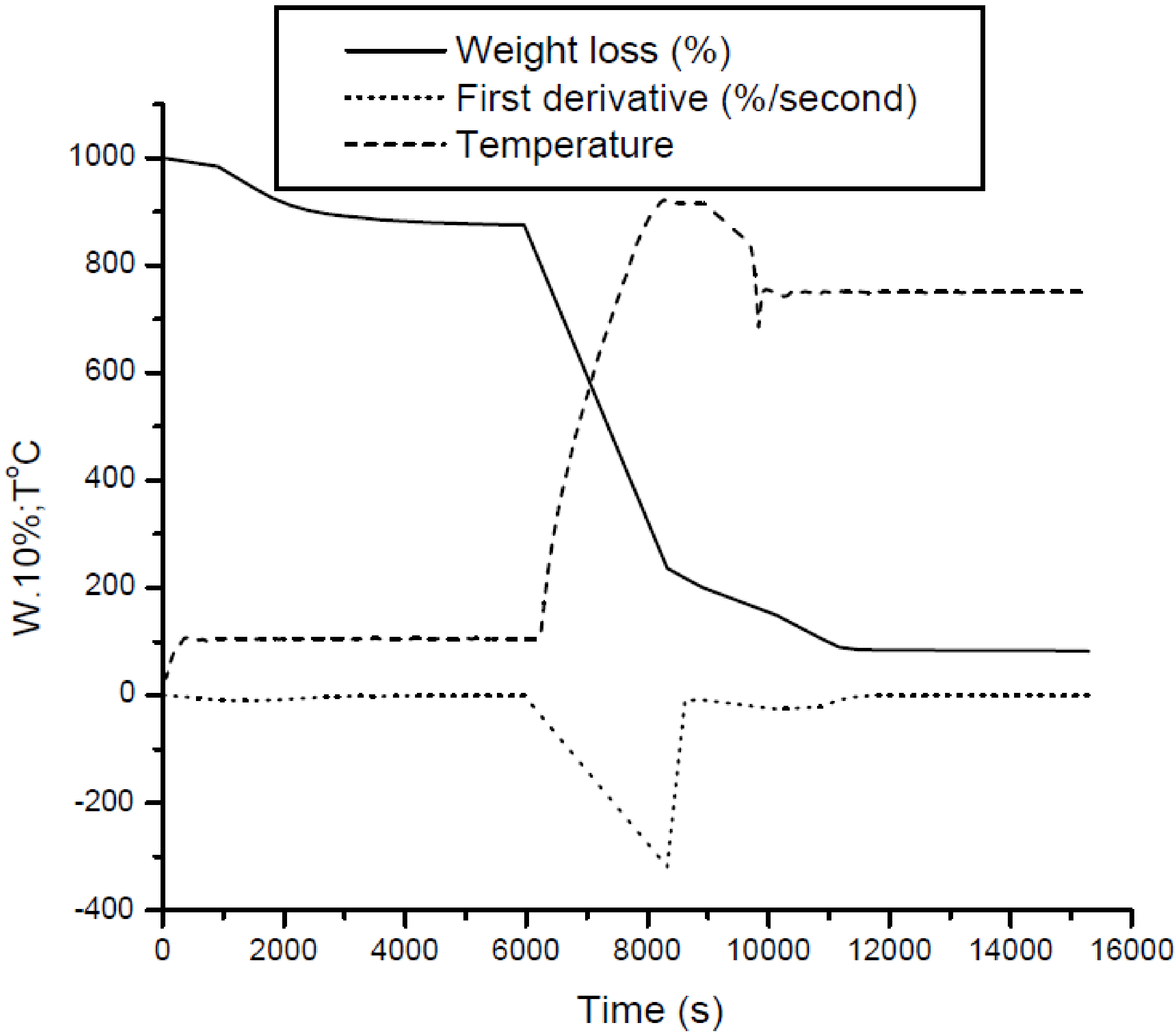


Figure 8: Weight loss, first derivative and temperature build up for TGA analysis of non-carbonized high pressure developed coffee husk briquettes

ACCEPTED

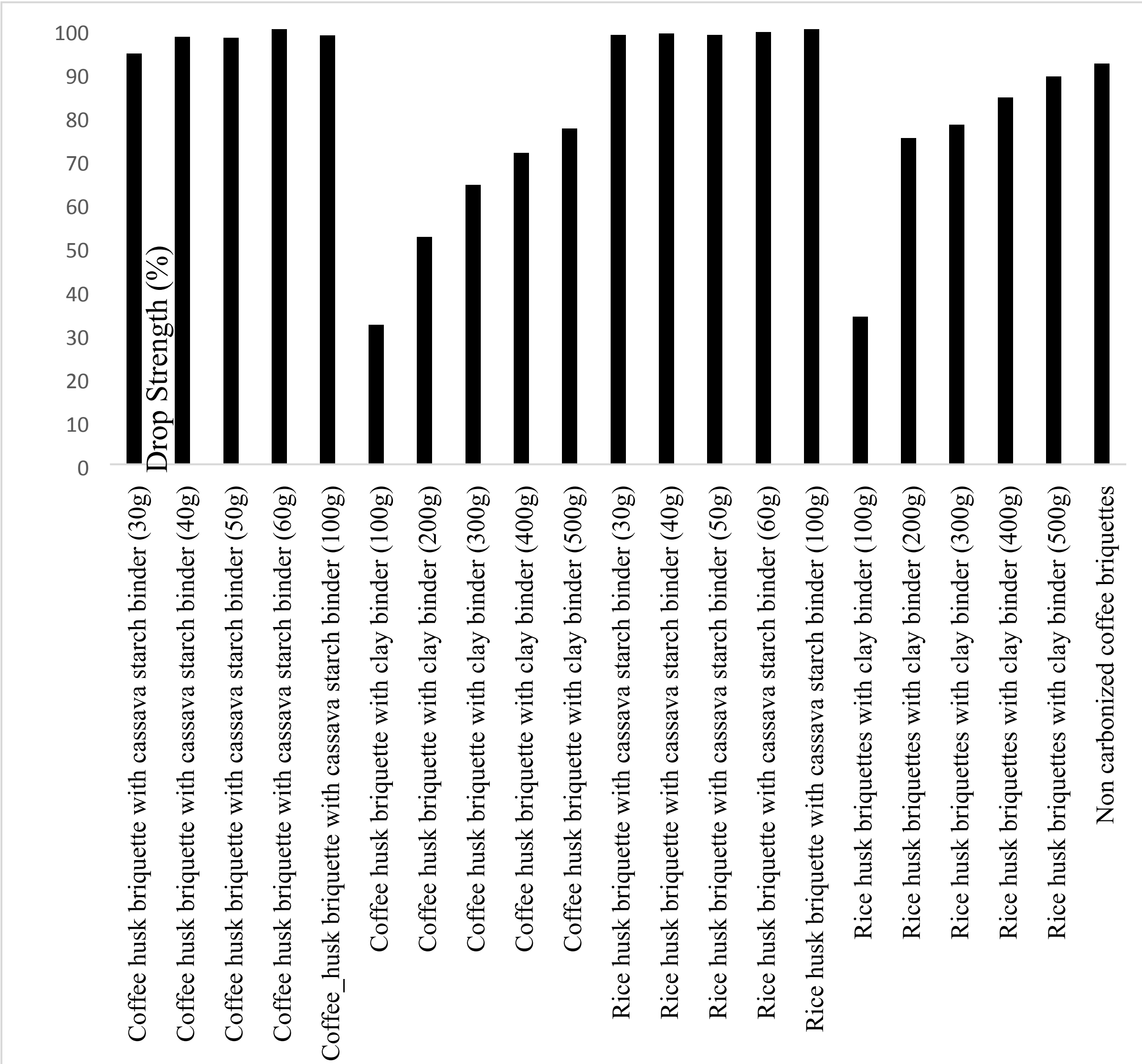


Figure 9: Drop strength for different developed briquettes

ACCEPTED

ACCEPTED MANUSCRIPT

List of Tables

ACCEPTED MANUSCRIPT

Table 1: Comparison between organic and dominant chemical ash constituents in rice husks and coffee husks

	Rice Husks	Coffee Husks
Cellulose	48.3*	19-26**
Hemi-cellulose	31.6*	24-45**
Lignin	24.6*	18-30**
SiO_2	94.38*	14.65*
K_2O	2.29*	52.45*

*Vassilev et al. 2010

**Bekalo & Reinhardt, 2010

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

Table 2: Processing parameters used in the development of rice husk and coffee husk briquettes

Raw material	State of material at briquettes development	Briquette development pressure	Binder Used	Ratio of raw material to binder
Coffee husks	Carbonized	≤7MPa	Cassava starch	100:3
Coffee husks	Carbonized	≤7MPa	Cassava starch	100:4
Coffee husks	Carbonized	≤7MPa	Cassava starch	100:5
Coffee husks	Carbonized	≤7MPa	Cassava starch	100:6
Coffee husks	Carbonized	≤7MPa	Cassava starch	100:10
Coffee husks	Carbonized	≤7MPa	clay	100:10
Coffee husks	Carbonized	≤7MPa	clay	100:20
Coffee husks	Carbonized	≤7MPa	clay	100:30
Coffee husks	Carbonized	≤7MPa	clay	100:40
Coffee husks	Carbonized	≤7MPa	clay	100:50
Rice husks	Carbonized	≤7MPa	Cassava starch	100:3
Rice husks	Carbonized	≤7MPa	Cassava starch	100:4
Rice husks	Carbonized	≤7MPa	Cassava starch	100:5
Rice husks	Carbonized	≤7MPa	Cassava starch	100:6
Rice husks	Carbonized	≤7MPa	Cassava starch	100:10
Rice husks	Carbonized	≤7MPa	Clay	100:10
Rice husks	Carbonized	≤7MPa	Clay	100:20
Rice husks	Carbonized	≤7MPa	Clay	100:30
Rice husks	Carbonized	≤7MPa	Clay	100:40
Rice husks	Carbonized	≤7MPa	Clay	100:50
Coffee husks	Non- carbonized	250MPa	--	1000:0

ACCEPTED MANUSCRIPT

Table 3: Physical properties (Average ± standard deviation) for coffee and rice husk raw materials and coffee and rice husk briquettes with cassava starch and clay binder

Sample	Binder (Amount)	% Moisture Content	% Volatile Matter	% Analytical ash	% Volatiles on dry basis	% Ash on dry basis	% Fixed Carbon
Coffee Husks	-	13.0±0.6	65.4±1.0	5.9±0.3	73.9±1.1	6.6±0.4	15.7±1.4
Rice Husks	-	11.3±0.0	56.4±1.1	18.1±0.1	62.8±1.2	20.1±0.2	14.2±0.9
Coffee husks briquettes	Cassava (30g)	9.0±0.5	29.6±0.3	15.1±0.6	32.2±0.2	16.4±0.6	46.4±0.7
Coffee husks briquettes	Cassava (40g)	8.5±0.9	30.8±0.5	15.5±0.6	33.4±0.8	16.8±0.5	45.2±0.8
Coffee husks briquettes	Cassava (50g)	9.3±0.2	31.3±0.7	16.3±1.1	34.2±0.8	17.8±1.2	43.1±1.6
Coffee husks briquettes	Cassava (60g)	9.2±0.3	30.9±0.5	16.4±2.8	33.8±0.6	17.9±3.0	43.4±2.1
Coffee husks briquettes	Cassava (100g)	9.7±0.0	36.9±0.8	12.6±0.7	40.5±0.8	13.9±0.8	40.7±1.2
Rice husks briquettes	Cassava (30g)	5.8±0.1	18.2±0.7	38.7±1.5	19.2±0.7	40.9±1.5	37.3±0.7
Rice husks briquettes	Cassava (40g)	5.5±0.0	21.2±2.4	38.4±2.3	21.6±1.4	39.2±0.5	38.3±0.1
Rice husks briquettes	Cassava (50g)	6.2±0.0	19.7±0.5	36.6±0.2	20.9±0.5	38.9±0.2	37.4±0.3
Rice husks briquettes	Cassava (60g)	6.3±0.1	20.9±1.2	36.3±0.1	22.3±1.3	38.6±0.1	36.4±1.4
Rice husks briquettes	Cassava (100g)	6.1±0.3	23.1±0.7	36.9±2.3	24.5±0.8	39.2±2.3	33.9±1.3
Coffee husks briquettes	Clay (100g)	8.8±0.6	30.2±0.7	22.8±1.3	32.9±1.0	24.8±1.5	38.1±2.7
Coffee husks briquettes	Clay (200g)	8.2±0.8	24.7±0.9	32.2±2.0	26.7±1.0	34.8±2.1	35.0±1.1
Coffee husks briquettes	Clay (300g)	7.5±0.2	23.3±1.3	40.1±3.6	25.1±1.4	43.1±3.8	29.0±2.2
Coffee husks briquettes	Clay (400g)	6.5±0.5	22.1±1.7	47.4±3.7	23.6±1.7	50.5±4.1	23.9±4.7
Coffee husks briquettes	Clay (500g)	7.0±0.4	21.8±0.5	47.6±2.2	23.3±0.7	50.9±2.1	23.7±1.4
Rice husks briquettes	Clay (100g)	5.5±0.6	15.7±2.2	50.5±2.3	16.6±2.4	53.3±2.2	28.3±1.8
Rice husks briquettes	Clay (200g)	5.2±0.0	14.4±0.3	48.2±1.0	15.2±0.3	50.7±1.1	32.2±1.0
Rice husks briquettes	Clay (300g)	5.0±0.2	14.0±0.4	54.6±2.7	14.6±0.4	57.3±2.7	26.5±2.2
Rice husks briquettes	Clay (400g)	5.0±0.2	13.7±0.6	56.5±4.2	14.4±0.6	59.3±4.4	24.8±3.4
Rice husks briquettes	Clay (500g)	4.6±0.2	12.7±0.2	60.6±1.3	13.3±0.2	63.4±1.3	22.1±1.3

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

Table 4: HHV (Average ± standard deviation) for Coffee husk and rice husk briquettes with different amounts of cassava starch and clay binder.

Briquette	Binder (Amount)	Higher Heating Value (HHV) MJ/Kg	Total Time taken to ignite and boil 1 l of water (minutes)
Coffee husks briquettes	Cassava (30g)	23.0±0.8	40
Coffee husks briquettes	Cassava (40g)	23.5±0.5	34
Coffee husks briquettes	Cassava (50g)	22.0±0.1	20
Coffee husks briquettes	Cassava (60g)	22.6±1.4	13
Coffee husks briquettes	Cassava (100g)	21.9±0.9	17
Rice husks briquettes	Cassava (30g)	16.6±0.0	23
Rice husks briquettes	Cassava (40g)	16.5±0.1	35
Rice husks briquettes	Cassava (50g)	16.4±0.0	45
Rice husks briquettes	Cassava (60g)	15.9±0.9	32
Rice husks briquettes	Cassava (100g)	16.4±0.1	18
Coffee husks briquettes	Clay (100g)	19.5±0.6	26
Coffee husks briquettes	Clay (200g)	17.2±0.4	15
Coffee husks briquettes	Clay (300g)	13.8±1.4	29
Coffee husks briquettes	Clay (400g)	13.0±1.3	25
Coffee husks briquettes	Clay (500g)	13.6±0.9	24
Rice husks briquettes	Clay (100g)	12.0±0.2	15
Rice husks briquettes	Clay (200g)	13.8±0.3	36
Rice husks briquettes	Clay (300g)	12.0±0.3	43
Rice husks briquettes	Clay (400g)	10.2±0.8	44
Rice husks briquettes	Clay (500g)	9.5±1.1	44
Non-carbonized coffee briquettes	-	15.2±0.4	

ACCEPTED MANUSCRIPT

Table 5: Nested ANOVA for response factors including physical properties and HHV

Type of briquette	Type of binder	Response Factor	Source of Variation	SS	df	MS	F	P-value
Coffee husks	Cassava starch	Fixed Carbon	Binder proportion	71.411956	4	17.852989	6.126045363	0.009305478
			Error	29.14276331	10	2.9142763		
			Total	100.5547193	14			
Coffee husks	Clay	Fixed Carbon	Binder proportion	539.796916	4	134.949229	19.29209234	0.000107824
			Error	69.9505407	10	6.995054067		
			Total	609.747457	14			
Rice husks	Cassava starch	Fixed Carbon	Binder proportion	228.2362	4	57.05904	5.003889	0.01779
			Error	114.0294	10	11.40294		
			Total	342.2656	14			
Rice husks	Clay	Fixed Carbon	Binder proportion	201.7832	4	50.4458	8.426443	0.003045
			Error	59.86607	10	5.986607		
			Total	261.6493	14			
Coffee husks	Cassava starch	Moisture Content	Binder proportion	13.40067	4	3.350167	2.159718	0.14747
			Error	15.51206	10	1.551206		
			Total	28.91273	14			
Coffee Husks	Clay	Moisture Content	Binder proportion	11.51441	4	2.878603	9.893125	0.001667
			Error	2.9097	10	0.29097		
			Total	14.42411	14			
Rice husks	Cassava starch	Moisture Content	Binder proportion	0.765711	4	0.191428	2.994326	0.072652
			Error	0.639302	10	0.06393		
			Total	1.405013	14			
Rice husks	Clay	Moisture Content	Binder proportion	3.095791	4	0.773948	10.11524	0.001531
			Error	0.765131	10	0.076513		
			Total	3.860921	14			
Coffee husks	Cassava starch	Volatile Matter	Binder proportion	96.92809	4	24.23202	71.31192	2.60E-07
			Error	3.398033	10	0.339803		
			Total	100.3261	14			
Coffee husks	Clay	Volatile Matter	Binder proportion	147.0785	4	36.76962	31.79872	1.16E-05
			Error	11.56324	10	1.156324		
			Total	158.6417	14			
Rice husks	Cassava starch	Volatile Matter	Binder proportion	39.19587	4	9.798968	17.37456	0.000169
			Error	5.639835	10	0.563984		
			Total	44.83571	14			
Rice husks	Clay	Volatile Matter	Binder proportion	33.62506	4	8.406266	21.00183	7.45E-05
			Error	4.002635	10	0.400264		

ACCEPTED MANUSCRIPT

			Total	37.6277	14			
Coffee husks	Cassava starch	Ash Content	Binder proportion	27.62444	4	6.90611	3.441818	0.051375
			Error	20.06529	10	2.006529		
			Total	47.68974	14			
Coffee husks	Clay	Ash Content	Binder proportion	1322.798	4	330.6995	45.39514	2.22E-06
			Error	72.84909	10	7.284909		
			Total	1395.647	14			
Rice husks	Cassava starch	Ash Content	Binder proportion	195.2793	4	48.81983	5.71265	0.011705
			Error	85.45916	10	8.545916		
			Total	280.7385	14			
Rice husks	Clay	Ash Content	Binder proportion	371.5774	4	92.89434	13.77019	0.000448
			Error	67.46048	10	6.746048		
			Total	439.0379	14			
Coffee husks	Cassava starch	HHV (J/g)	Binder proportion	6798209	4	1699552	2.400206	0.181436
			Error	3540430	5	708085.9		
			Total	10338638	9			
Coffee husks	Clay	HHV (J/g)	Binder proportion	64106357	4	16026589	15.67081	0.004918
			Error	5113515	5	1022703		
			Total	69219872	9			
Rice husks	Cassava starch	HHV (J/g)	Binder proportion	479637	4	119909.3	0.753082	0.596772
			Within Groups	796123	5	159224.6		
			Total	1275760	9			
Rice husks	Clay	HHV (J/g)	Binder proportion	22952799	4	5738200	4.813435	0.057593
			Within Groups	5960608	5	1192122		
			Total	28913406	9			

ACCEPTED MANUSCRIPT